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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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Record 1993/54

An international conference on crustal evolution, metallogeny and exploration of the Eastern Goldfields

Extended Abstracts

Compiled by P R Williams and J A Haldane

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DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

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POSTER SESSION

Submarine volcanism: concepts, problems and significance

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Submarine volcanism is one of the most intriguing areas of modern volcanology because many of the processes occur sight unseen. The use of modern analogues to understand ancient processes and successions has limited application and much of our understanding of concepts has been derived from the careful study and interpretation of ancient volcanic successions, including Precambrian ones. However, there are still many poorly understood concepts, including:

1. The maximum water depths for submarine explosive volcanic eruptions. Calculations of equilibrium gas pressures for subaerially erupting magmas indicate that under the significant hydrostatic pressures of marine environments, magmatically driven explosive eruptions are likely to be suppressed at water depths of 1 km or more, although anomalously volatile rich magmas may erupt explosively in slightly deeper water. For phreatomagmatic/phreatic explosive eruptions, consideration of specific volume changes as a function of pressure indicate that explosively rapid expansion of superheated water is not possible at water depths of 1.0 km.

2. Pumice in deep water can be accounted for by deposition of water settled fall deposits originating from shallow water to subaerial explosive volcanic centres, or by mass flow resedimentation from shallow water settings, or by "slow", steady, non-explosive vesiculation of relatively volatile rich magmas under conditions of high hydrostatic pressures. Quench fragmentation of such vesiculated lava will produce non-explosive, quench fragmented pumice.

3. Factors controlling the formation of coherent lavas and hyaloclastites.

4. The likelihood for rising magmas to intrude seafloor sediment successions rather than erupt on the sea floor is enhanced where the sediment succession is thick, unconsolidated, lacks strength, the uprise rate of magma is relatively low and the density of the rising magma is higher than the intruded sediment succession.

5. The distinction between hyaloclastite and subaqueously deposited pyroclastic debris is becoming increasingly more difficult in the light of the possibility of pumiceous hyaloclastite forming.

6. Submarine fire fountaining is feasible driven purely by fluid pressure induced by lithostatic pressure. Clast fragmentation is due to shearing, extensional stretching and quench fragmentation. Fragmentation is not driven by explosive expansion of either magmatic volatiles or superheated seawater and is therefore not pyroclastic.

7. The nature of the interaction between pumiceous pyroclastic flows and the sea is still unclear. Low bulk density and low angles of incidence should favour flow over water rather than into water. High thermal potential should enhance explosive interaction with the sea. High volume eruption rate submarine pyroclastic eruptions may lead to near vent subaqueous pyroclastic flow deposits and welding.

8. Seafloor massive sulphide deposits will only form if boiling of host hydrothermal fluids is prevented in the sub-seafloor stock work system. Minimum confining pressures required to prevent boiling of hydrothermal fluids at 250°C and 350°C respectively, with 0.2 moles of CO_2 and 4.5 weight percent NaCl is 90 bars (=900m water depth) and 175 bars (=1750m water depth) respectively. This depth range is at the maximum water depth for explosive submarine eruptions. Prospective ancient submarine volcanic successions should therefore generally be dominated by coherent lavas, hyaloclastite, synvolcanic intrusives ± resedimented volcaniclastics, including pyroclastic debris from shallower water environments. In situ pyroclastics may occur associated with some deposits but should in general be rare.

Application of these principles to the interpretation of Precambrian volcanic successions provides constrained but not necessarily unequivocal interpretations. The Archaean Golden Grove succession consists of felsic lavas, autoclastics and intrusives, minor basaltic lavas, resedimented volcaniclastics, including pumiceous pyroclastic debris interpreted to be resedimented from shallow water to subaerial explosive centres. The ambient volcanism is represented by the lavas and autoclastics. This succession is interpreted as a relatively deep water volcanic succession erupted in a graben like basin. It hosts the Scuddles–Gossan Hill VMS mineralisation, which is consistent with the proposed water depths as outlined above.

The Archaean Black Flag Beds are an Archaean submarine felsic volcanic succession outcropping in the Kambalda–Kalgoorlie region. Although little studied until recently, we have found that the Black Flag Beds consist of rhyolitic lavas, hyaloclastites, resedimented volcaniclastics ambient black/dark grey mudstones and siltstones and resedimented polymictic sediments. These characteristics are consistent with sub-wave base volcanism and sedimentation. The presence of submarine felsic lavas, which represent the ambient volcanism, the Black Flag Beds should be considered prospective for at least VMS mineralisation.

By contrast the footwall rock succession to the Ni sulphide mineralisation at Kambalda, the Lunnon Basalt, is a wholly basaltic succession dominated by massive, pillowed and autoclastic (hyaloclastite, autobreccia) basaltic lavas. A possible thickness of at least 2 km indicates that the succession represents the tectonised, dismembered relics of either a submarine shield volcano, a ponded seafloor graben or half-graben pile of volcanics, or layer 2 basalts of the oceanic crust.

High–resolution dating of felsic magmatism in the Eastern Yilgarn

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Advances in technology

Technology for dating magmatic and metamorphic events has advanced rapidly over the last ten years and the impact of this is just now being felt in our understanding of the Yilgarn Craton. First there has been a move away from a reliance on Rb-Sr whole rock dating to a new faith in U-Pb geochronology based on zircons and to a lesser extent other uranium-bearing minerals such as titanite, allanite, monazite, rutile, cassiterite and apatite. A decade of high precision geochronology on zircon, baddeleyite, rutile, titanite and other minerals, using conventional analytical techniques, has resulted in major advances in the understanding of the Archaean history of the Canadian Shield. Very little comparable work has been carried out on the Yilgarn Craton but the advent of the ANU ion microprobe (SHRIMP) provides a quantum leap in the technology of U-Pb geochronology and promises a revolution in the geochronological understanding of the Archaean of Western Australia. At the time of writing this abstract a SHRIMP II is being installed at Curtin. It is anticipated that this instrument will be turned loose on Yilgarn problems later in 1993 but in the meantime it is necessary to use the limited database of zircon results on volcanic rocks to place at least preliminary constraints on models of the evolution of the Eastern Goldfields.

Available zircon ages

A summary of available zircon ages for the Norseman–Kalgoorlie region, made mainly with the ANU SHRIMP I, is provided by Swager & others (1992). An important result is the determination of an age of 2692 ± 4 Ma for volcanism at Kambalda (Claoué-Long & others, 1988). Also a ca 2900 Ma SHRIMP age on zircons from a felsic volcanic unit in the Penneshaw formation has been interpreted by Campbell & Hill (1988) as dating the basal unit of the greenstone succession in the Norseman terrane, suggesting a major time break in greenstone evolution in the southern Yilgarn Craton comparable to that identified in the Murchison Province by Pidgeon & Wilde (1990) using conventional zircon U-Pb techniques. Further results from SHRIMP I (Compston & others, 1986; Campbell & Hill, 1988; Claoué-Long & others, 1988; Hill & others, 1989) have identified widespread xenocrystic zircons in granitoids and some volcanic rocks with ages as old as 3400 Ma, suggesting that the greenstones in the southern part of the Eastern Goldfields Province are underlain by older sialic crust.

A small number of conventional zircon results on felsic volcanic rocks from the Eastern Goldfields region were reported by Pidgeon & Wilde (1990). If extremely discordant data sets are disregarded (results from Germatong and Kanowna) the remaining data (Fig.1) show a pattern of ages which, although preliminary, suggest a significant difference in the ages of volcanism between the Eastern Goldfields and Southern Cross Provinces. Zircon ages on felsic volcanics from Pig Well, Teutonic Bore, Ora Banda, and the Surprise Mine near Coolgardie in the Norseman–Wiluna Belt of the Eastern Goldfields Province give a consistent age of ca 2700 Ma. Conventional multigrain and single grain analyses on zircons from felsic volcanic rocks from the Koolyanobbing Greenstone Belt and the Marda Complex (Pidgeon & Wilde, 1990) give a consistent age of ca 2740 Ma (Fig.1). These zircon ages suggest that volcanism in the Southern Cross Province occurred about 40Ma earlier than volcanism in the Norseman–Wiluna Belt.

Timing of volcanism in the Eastern Goldfields and Southern Cross Provinces

Our preliminary interpretation of the age difference of zircons from the few samples of felsic volcanic rocks from the two provinces is that volcanism in the Southern Cross Province preceded that in the Kalgoorlie–Wiluna Greenstone Belts by

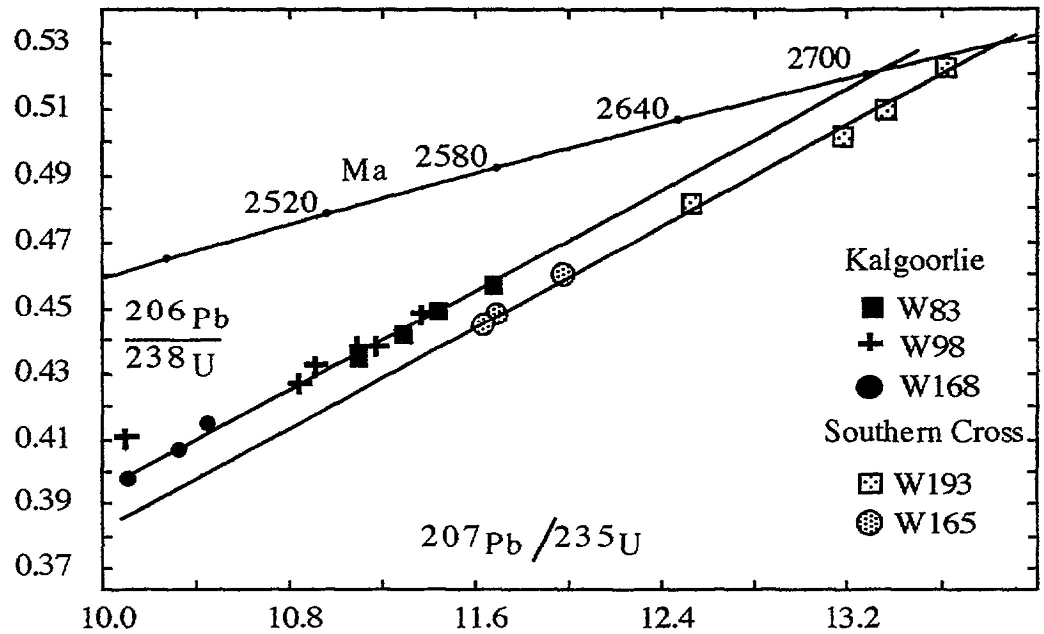

Fig. 1. Zircon U-Pb results from felsic volcanic rocks from W83 (Pig Well), W98 (Teutonic bore, and W168 (Surprise Mine, Coolgardie) from the Eastern Goldfields Province and W193 Koolyanobbing and W165 (Marda Complex) from the Southern Cross Province from Pidgeon and Wilde (1990).

about 40 Ma. This interpretation is supported by the differences in the stratigraphic sequences between the Eastern Goldfields and Southern Cross Provinces reported by Wyche (1993). However, it does not take account of finer subdivisions of the provinces into terranes (e.g. Swager & others 1992) which opens the possibility that unrelated blocks are present within each province with their own distinctive age patterns. The dated samples cannot be claimed to be representative of the span of volcanic activity within any one greenstone belt and an overlap of ages of volcanism between the two provinces cannot be ruled out. Also, the multi-grain measurements could be influenced by the presence of inherited zircons, and this will need to be tested by conventional single zircon measurements and by SHRIMP analyses. Despite these qualifications we believe the age difference is significant, and the proposal that volcanism in the two provinces represents two separate (in time) and possibly unrelated episodes provides constraints for current models of the evolution of the Yilgarn Craton. The plume model of granite-greenstone development (Hill & others,1992) envisages formation of the craton by remelting of older crust during a single thermal event and proposes that continued conduction of heat during this event may result in anatexis over a time interval of 30-50Ma. Nevertheless, there may be difficulties in accommodating a ca 40 Ma division in age of felsic volcanism between the Southern Cross Province and the greenstones of the Kalgoorlie–Wiluna region within this model. Alternatively a plate tectonic model, envisaging the accumulation of two island arc systems with ages separated by ca 40 Ma, might be a more acceptable explanation for the age difference. Witt & others (1989) suggested accretion of micro-plates to explain apparently diachronous deformation and metamorphism between the Kalgoorlie and Leonora regions. This model would explain the pervasive compressional structures observed in greenstone belts throughout the Yilgarn. Also, Swager & others (1992) favour this model in explaining the variety in stratigraphic and structural settings in terrane subdivisions of the Norseman–Kalgoorlie granite-greenstone terrain. Myers (1993) extended this model of crustal aggregation and crustal collision to explain granite-greenstone formation and observed tectonic relationships throughout the Yilgarn Craton.

The interpretation of the presently available limited data set from the Eastern Goldfields and Southern Cross Provinces as defining the ages of volcanism within these Provinces is no doubt an oversimplification. However, determination of the duration of volcanism within a province or terrane not only relies on the precision of analytical techniques, but depends critically on the distribution of dateable rocks in the successions, and the access, through drill core or relatively unweathered surface samples, to this material. In the final instance this may be the limiting factor constraining our ability to precisely date the sequence of igneous events in the Yilgarn Craton.

References

Claoué-Long, J.C., Compston, W., & Cowden, A. 1988, The age of the Kambalda greenstone resolved by ion-microprobe: implications for Archaean dating methods. *Earth and Planetary Science Letters* 89, pp 239-259.

Compston, W., Williams, I.S., Campbell, I.H., & Gresham, J.J. 1986, Zircon xenocrysts from the Kambalda volcanics: age constraints and direct evidence for older continental crust below the Kambalda-Norseman greenstones. *Earth and Planetary Science Letters* ,76, pp 299-311.

Campbell, I.H., & Hill, R.I. 1988, A two stage model for the formation of the granite-greenstone terrains of the Kalgoorlie-Norseman area, Western Australia. *Earth and Planetary Science Letters,* 90, pp 11-25.

Hill, R.I., Campbell, I.H., & Compston, W. 1989, Age and origin of granitic rocks in the Kalgoorlie-Norseman region of Western Australia: implications for the origin of Archaean crust. *Geochimica et Cosmochimica Acta,* 53, pp 1259-1275.

Hill,R.I., Campbell, I.H., & Chappell, B.W. 1992, Crustal growth, crustal reworking and granite genesis in the southwestern Yilgarn Block, Western Australia, in *The Archaean: terrains, processes and metallogeny* eds. J.E. Glover & S.E. Ho, Geology Department (Key Centre) and University Extension, University of Western Australia Publication 22, pp203-212.

Myers, J.S. 1993, Precambrian history of the West Australian Craton and adjacent orogens. Annual Review. *Earth and Planetary Science Letters,* 21, pp 453-485.

Pidgeon, R.T., & Wilde, S.A. 1990, The distribution of 3.0 Ga and 2.7 Ga volcanic episodes in the Yilgarn Craton of Western Australia. *Precambrian Research,* 48, pp 309-325.

Swager, C.P, Witt, W.K., Griffen,T.J., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J., & Wyche, S. 1992, Late Archaean granite-greenstones of the Kalgoorlie Terrane, Yilgarn Craton, Western Australia, in *The Archaean: terrains, processes and metallogeny* eds. J.E.Glover & S.E. Ho, Geology Department (Key Centre) and University Extension, University of Western Australia Publication 22, pp 107-122.

Witt, W.K., & Swager, C.P., Williams, P.R., & Etheridge, M.A. 1989, Accretionary tectonics in the Eastern Goldfields Province? in *Geoscience Mapping towards the 21st Century,* BMR Research Symposium, Canberra, 1989, 9pp.

Wyche, S. 1993, Contrasts between the Kalgoorlie and Barlee Terranes, East Yilgarn. *Procedings of-Second Annual Geology Symposium on Mineral Exploration and Mining Geology in the Eastern Goldfields,* May 1993. Publication of the Western Australian School of Mines. 91-93.

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Recent advances in the understanding of Komatiite Volcanology in the Norseman–Wiluna Greenstone Belt

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Komatiites in the Norseman–Wiluna Greenstone Belt show evidence for a complex spectrum of eruptive environments. Among these are analogues to lunar sinuous rilles, equivalents to recent voluminous submarine lava flows, and Archaean analogues to a number of features seen today on Hawaii such as lava channels, rivers, levees, tubes, and compound flows. The principal styles of eruptive environment are:

- the lenticular channel-fill dunite bodies flanked by extensive sheet-like orthocumulate sequences of the Agnew-Wiluna Belt,
- the thick sheet-like dunite body and layered ultramafic-gabbro sequences of the Walter Williams Formation,
- thin well-differentiated compound flows at Kambalda (Tripod Hill Member) and Marshall Pool,
- thick poorly differentiated flows with relatively thin spinifex zones (channel facies) flanked by well-differentiated spinifex-textured flows with interflow sediments, (sheet flow facies), Silver Lake Member, Kambalda.

Kambalda region

The Silver Lake Member of the Kambalda Komatiite Formation consists of one or more 25 m to 100 m thick high-Mg komatiite flows comprising thick lower cumulate BZones and thin upper spinifex-textured AZones. Lateral variations in internal structure and the distribution of interflow sediments define two time-equivalent volcanic environments: "channel" and "sheet flow" facies (fig. 1, after Cowden & Roberts, 1990).

The channel facies is characterized by thick units of up to 100 m of olivine orthocumulates with minor olivine harrisite layers, thin intervening spinifex zones and an absence of interflow sediments. Basal Fe/Ni sulphides are hosted by the lowermost and thickest of up to four flow units. The channel units occupy linear belts at least 10 km long but no more than 500 m wide (Cowden & Roberts, 1990).

The sheet flow facies komatiites occur gradational to and flanking the Channel domain. They are thinner, contain less olivine, and are well differentiated into A and B Zones. Thin interflow sediment units are common but pinch out in transitional zones between sheet flow and channel environments.

These komatiite volcanic domains are now generally accepted as the result of continuous but pulsing focussed lava flow down primary central feeder channels, which periodically spilled over channel 'banks' to produce thin ponded sheet flows (Lesher & others, 1984), which differentiated to form well developed cumulate and spinifex zones. The high proportion of cumulus olivine in the channel fill results either from the eventual accumulation of olivine-choked lava in channels capped by fragmented rafts of quenched lava, or by accretion of olivine from flowing lava within well-developed closed lava tubes. Thin spinifex and harrisite zones crystallized in the tubes or channels during periods of stagnation of the lava.

There is some controversy over whether the channel facies occupies primary topographic features (Lesher & others, 1984), thermal erosion channels (Lesher & others, 1984; Evans & others, 1989), or positive linear topographic features

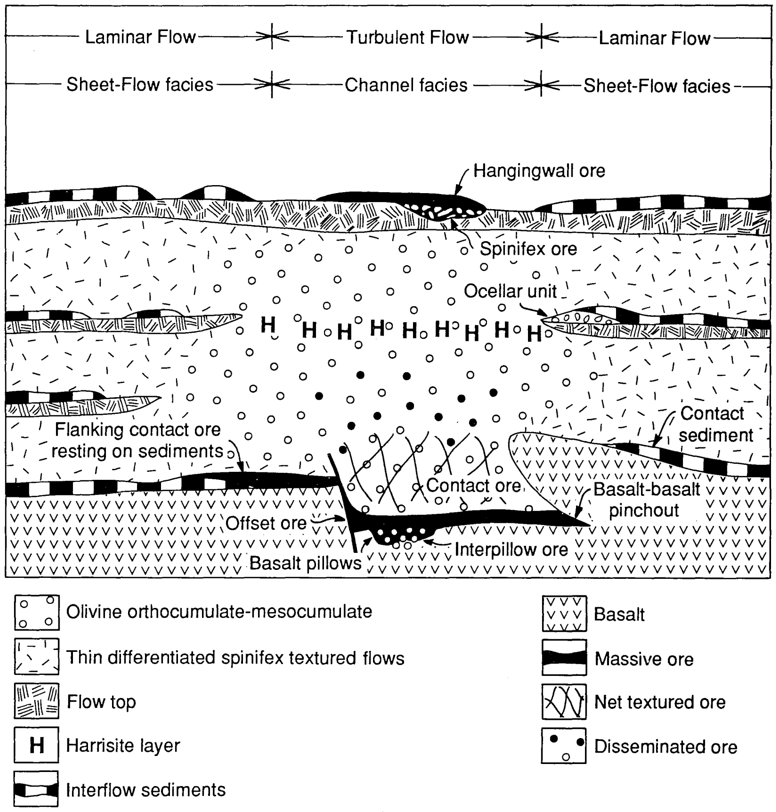

Fig. 1. Diagrammatic cross-section showing relationship between channel and sheet flow facies in the Silver-Lake Member of the Kambalda Komatiite Formation. After Cowden and Roberts, 1990.

constrained by solidified levees (Cowden, 1988). Modern analogues exist for all of these mechanisms, and a combination of these effects is most likely.

Komatiite lava rivers in the Agnew–Wiluna Greenstone Belt

The komatiite-bearing interval in the upper Greenstone Sequence of the Agnew–Wiluna Greenstone Belt is continuous for at least one hundred kilometres of strike length. The komatiites form several persistent stratigraphic units of variable thickness intercalated with felsic to intermediate volcaniclastic sediments, cherts or black shales. The komatiite units consist of concordant sheet-like bodies of layered olivine orthocumulates with minor spinifex-textured flow-tops, which flank substantially thicker trough-shaped pods or elongate lenses of layered, coarse-grained olivine adcumulates and mesocumulates up to 1 km thick and 5 km wide. Examples of these dunitic lenses occur at Perseverance, Six Mile Well, Betheno and Mt. Keith (Fig. 2).

Several of the dunite lenses are overlain and underlain by recognisably extrusive komatiites. They typically exhibit gradational contacts with the laterally equivalent spinifex-textured and orthocumulate rocks, and constitute an integral part of the volcanic stratigraphy. They contain mineralogical, textural, and compositional layering on scales of centimetres to several metres. In several places, for example Perseverance, the upper part of a dunite lens grades laterally into orthocumulates and differentiated flows, whereas the base cuts down through a sequence of felsic volcanic rocks to "bottom out" against an earlier komatiite sequence. Cryptic variation in olivine composition is a common feature. The dunites typically show upward trends of increasing forsterite content of olivine (Donaldson, 1982; Barnes & others, 1988; Hill & others, 1989), indicating crystallisation in an open magmatic system. These features, taken together, constitute evidence for an extrusive origin of the lenticular dunite bodies.

The characteristic rock type of the dunite lenses is coarse-grained olivine adcumulate, with or without accessory cumulus chromite. The presence of "poikilitic" chromite in some of these dunite bodies, together with fluid dynamic considerations, indicates that these rocks formed by in situ growth rather than by crystal settling or flow differentiation of crystal mushes. Adcumulates developed where conditions favoured the growth of existing crystals rather than the nucleation of new ones. This requires very low degrees of supercooling, and physical removal of the nutrient-depleted boundary layer which tends to develop around growing crystals and which inhibits continuing growth. Both these conditions are met by vigorous turbulent flow of lava, very slightly below its liquidus temperature, over a bed of growing crystals. Higher degrees of supercooling favour the nucleation and growth of olivine crystals at the top of the crystal pile, trapping the olivine depleted liquid boundary layer before it can be removed. If the cooling is sufficiently rapid that this liquid solidifies in place then an orthocumulate will be formed. Appropriate conditions may develop within thinner flows, or within thick sheet flows where the flow regime is laminar rather than turbulent.

The base of the Perseverance dunite lens has a discordant channel like geometry, and cuts down through at least 150 m of felsic country rocks (Barnes & others, 1988). This feature is interpreted as a thermal erosion channel, akin to lunar sinuous rilles, formed by melting of floor rocks beneath an extensive komatiite lava river. The ability of komatiites to melt the rocks over which they flow was predicted theoretically by Huppert and Sparks (1985), and arises from the combination of high liquidus temperatures and low viscosity, which induces turbulent flow. In the case of all the lenticular dunite bodies of the Agnew–Wiluna belt, parent lavas were erupted onto felsic metavolcanic rocks having liquidus temperatures well below the temperature of the komatiite lavas.

Figure 3 illustrates the general model for the origin of the olivine adcumulate lenses. Prolonged, rapid, and continuous eruption of komatiite lava occurred on a substrate of dominantly-felsic volcanic rocks. Portions of this flow became channellised between "levees" of solidified lava. Continued flow of superheated lava resulted in deepening of the channels by melting and assimilation of felsic volcanic flows and walls. At Agnew, over 100 m of felsic rocks were melted and assimilated beneath the thalweg (axis of maximum flow) of the main channel. As flow rates declined and the lava temperature dropped, thermal erosion ceased and crystallisation of olivine began on the floors and walls of the channels. At Perseverance and Honeymoon Well the dunite lenses bottom out against a lower sequence of refractory komatiites which acted as thermal barriers to further erosion. Heterogeneous nucleation and crystallisation of olivine at low degrees of supercooling on a heated substrate formed adcumulate bodies, as long sinuous ribbons with lenticular cross sections. Some bodies have a thin basal zone of olivine orthocumulate, particularly on channel walls (for example Six Mile, Mt. Keith, and Kathleen East) which reflect initial higher cooling rates through the channel substrate. Overflow of the channels or sheet

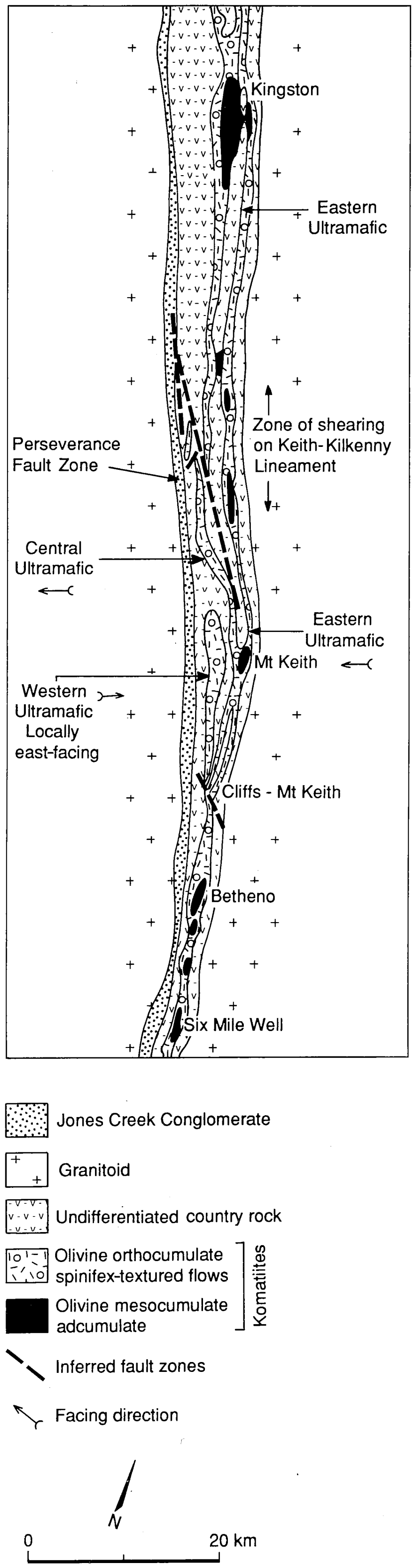

Fig. 2. Geology of the area between Six Mile Well and Kingston, showing volcanogenic style of komatiites and major stratigraphic units.

flow over lava shields produced the flanking rocks. These were emplaced as cooling units on a colder substrate, giving rise to orthocumulates and spinifex-textured flow units.

The "lava river" model provides an ex-

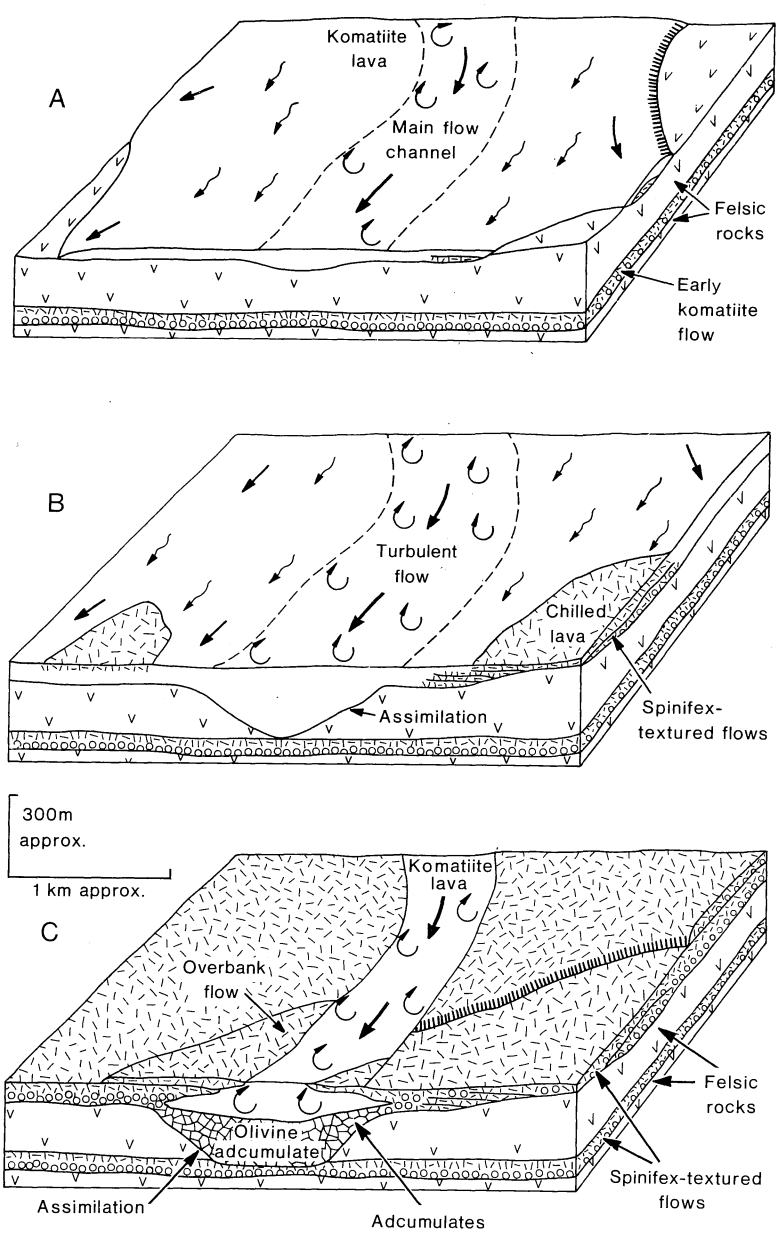

Fig. 3. Cartoons showing model for the development of olivine adcumulate lenses and flanking sequences within komatiite lava rivers.

planation for the large surplus of cumulus olivine relative to komatiitic liquid represented by the dunite lenses. The lava river mechanism allows for the parent magma to the olivine adcumulate to have drained away downstream. An intrusive mechanism would require initial emplacement of an extremely olivine-rich crystal mush, a difficult feat in view of the high density and extremely high viscosity involved, followed by highly efficient filter pressing to remove virtually all of the liquid component. This is inconsistent with current understanding of the origin of adcumulates. The coarse-grained nature of the dunite, a feature often taken as evidence for an intrusive origin, is an expected characteristic of crystallisation at low degrees of supercooling in a hot, long-lived lava flow channel. The scale of the channels involved is comparable with that of lunar sinuous rilles.

The Walter Williams Formation—extensive lava sheet

The Walter Williams Formation is 600-800 m thick, and occupies an area 60 km wide by 150 km long, from Ora Banda in the south to Copperfield in the north. It is a major component of the central zone of the Norseman–Wiluna Greenstone Belt.

The Formation is predominantly composed of olivine cumulate, with an upper zone of layered olivine orthocumulate-pyroxenite-gabbro units (Fig. 4). In the south the lower zone is predominantly layered coarse-grained olivine adcumulate

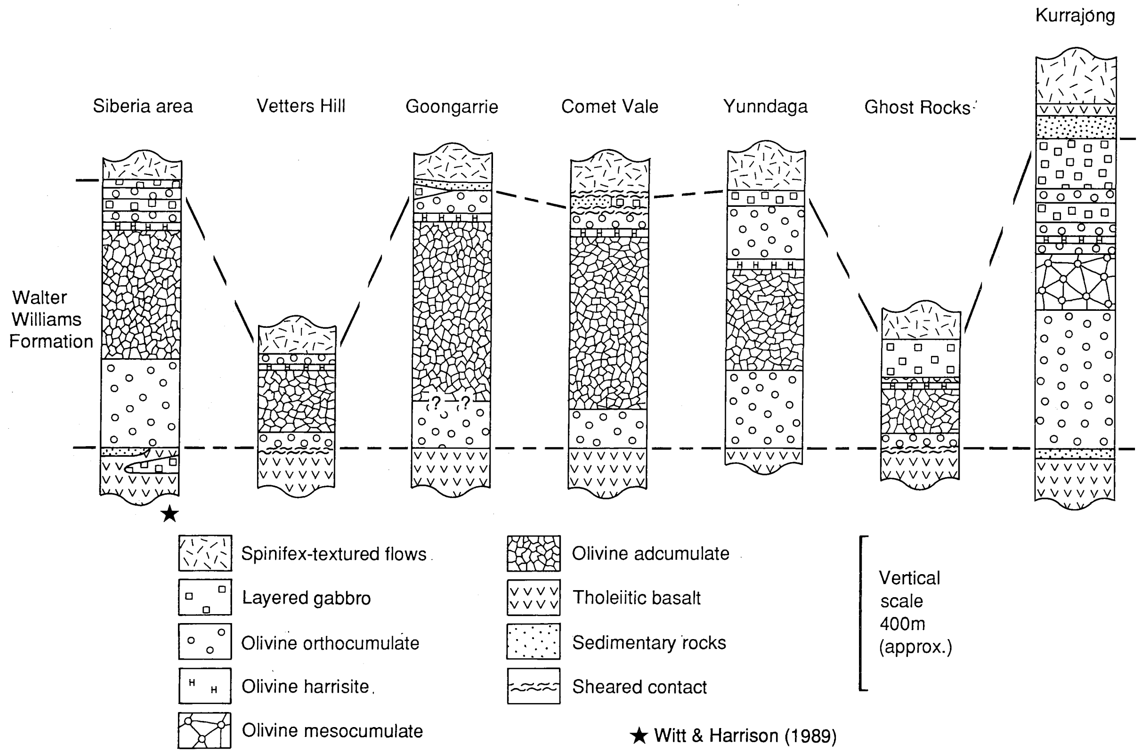

Fig. 4. Stratigraphic profiles through the Walter Williams Formation, spanning 150 km of strike length from Siberia and Vetters Hill in the south to Kurrajong in the north.

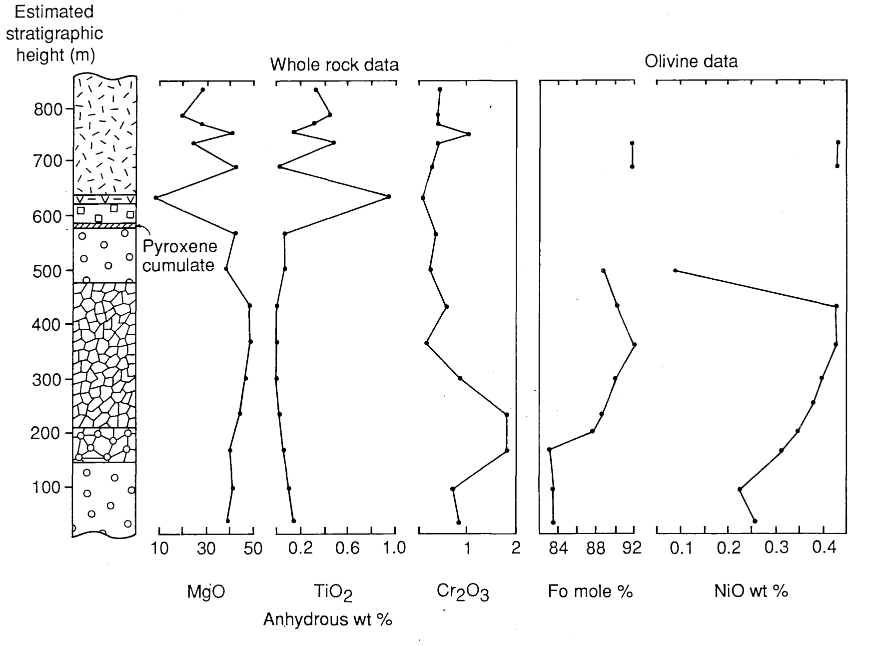

Fig. 5. Lithological and geochemical profiles through the Walter Williams Formation and the lower part of the Siberia Komatiitic Volcanics, Yunndaga.

but towards the north there is a change to rocks with more intercumulus liquid and the development of cyclic units capped by thin layers of Mgaugite. The basal unit of the lower zone is a loosely-packed olivine orthocumulate. Upwards there is a change to progressive mesocumulate and adcumulate textures and a concomitant increase in forsterite content of olivines (Fig. 5). A thin persistent olivine harrisite zone occurs at the top of the lower zone. The upper gabbroic zone is discontinuous and thin in the south but generally thickens northwards towards Kurrajong, where it is very prominent and is believed to have crystallized within an extensive lava lake.

Distal margins to the Walter Williams Formation have not been identified. However, the arguments presented for the volcanic origin of the laterally restricted olivine adcumulate bodies of the Agnew–Wiluna belt apply equally to the Walter

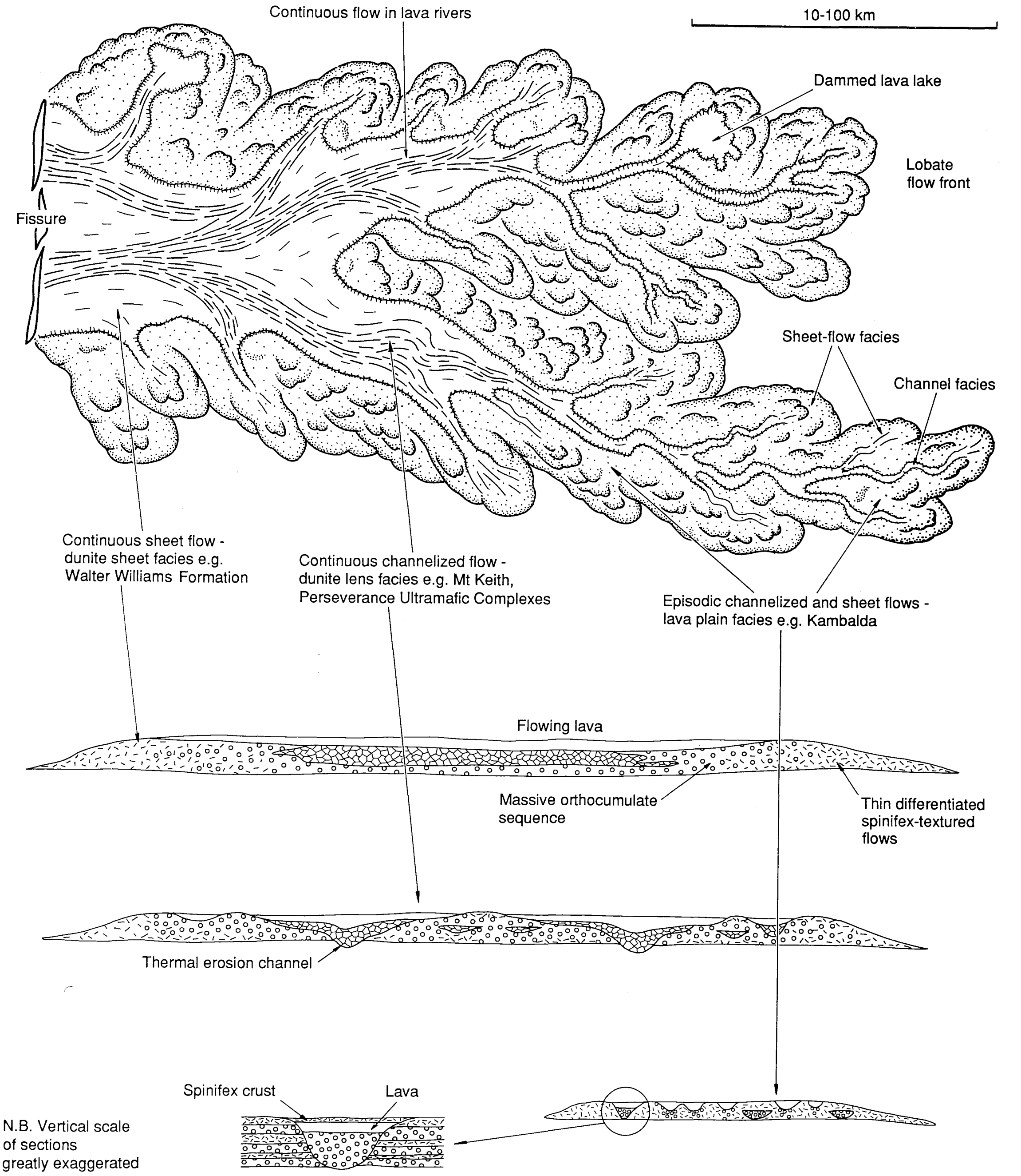

Fig. 6. Schematic illustration of a regional komatiite volcanic complex, formed by cataclysmic sustained eruption. Shows postulated relationship between sheet-like body such as the Walter Williams Formation and distal lava plain facies, formed by episodic channel switching. Schematic cross-sections show lateral distribution of rock types. Overall scale and relative proportions of sheet flow, channellised flow and lava plain facies are strongly dependent upon volume and rate of eruption, and the nature of the substrate. As eruption rate decreases, distal facies become dominant closer to the eruption site.

Williams Formation. It is believed to have crystallized from an unrestricted lava sheet, flowing turbulently over an extensive refractory tholeiitic basalt plain. Late-stage lava ponding, *in situ* fractionation, and periodic lava injection was responsible for the formation of the upper gabbroic zone.

The geometry of Komatiite Volcanic Complexes

Figure 6 is a highly schematic generalized representation of a portion of a large komatiite volcanic complex which incorporates different environments from vast dunite sheets at one end of the spectrum to thin differentiated and delicately layered flows at the other. The scale of the model could vary from a few kilometres to hundreds of kilometres. The entire complex can be regarded as a single, giant compound flow.

An essential property of the model is that the relative areas of rocks of different facies depend strongly upon the dominant imposed variable, the rate of eruption. At very high eruption rates, the sheet flow and channellised flow facies are likely to be dominant. A single voluminous eruption could give rise to "proximal" extensive dunite bodies, formed in regimes of continuous flow, with time-equivalent distal sequences of thin, differentiated flows forming lava plains. The occurrence of channellised *vis a vis* sheet flow also depends upon the "erodability" of the substrate, major channellised lava rivers being favoured by eruption on easily melted felsic volcanic or sedimentary floor rocks. The lava plain flows form in overlapping lobes as seen in modern day flows on Hawaii, generated by episodic switching of the locus of flow. At lower eruption rates, the continuous flow regime becomes relatively less extensive, and the regime of episodic channellised flow becomes dominant closer to the vent, potentially occupying the whole area of the complex. In general, very large rapid eruptions give rise to extensive dunite bodies with distal composite lava plains, while small eruptions generate the lava plain facies only. To put some semi-quantitative figures on the terms "rapid" and "extensive", thermal modelling calculations on rocks in the northern part of the Norseman–Wiluna Belt suggest that a thickness of several hundreds of metres of dunite lens facies cumulates could have accumulated within a time scale of the order of tens of years (Gole & others, 1990).

The model implies that komatiite volcanic complexes exhibit a property now widely recognised across a vast range of natural phenomena: that of fractal geometry, or self-similarity at a range of scales. If a small part of the lava plain facies was enlarged, it would show a similar geometry to that of the complex as a whole, as would individual cooling units from one small part of the lava plain. In general, rocks formed from flowing lava will be dominantly cumulates, while those generated in slow-moving or ponded lavas flanking the major flow channels will contain a relatively higher proportion of komatiite liquid to cumulus crystals, whatever scale is being considered. At the largest scale, the geometry of central channels and marginal sheet flow manifests itself as ribbons of adcumulate flanked by sheets of orthocumulate, as at Perseverance, Six Mile, Mt. Keith, etc. At a smaller scale, composite mesocumulate-orthocumulate units are flanked by sequences of spinifex-textured flows, as at Kambalda.

An important property of the model is that it collapses on itself during waning stages of the eruptive event, as the lava plain facies becomes dominant progressively closer to the site of eruption. Consequently, dunite bodies formed during the climax of eruptive activity are overlain first by layered, mixed orthocumulates formed by *in situ* fractionation of stagnant lava, then by lava-plain facies of thin compound flows. This is the stratigraphic relationship seen consistently in the Norseman–Wiluna belt. The consistency of field relationships throughout the belt lends support to the concept of enormous cataclysmic eruptions, comparable in volume to the largest known eruptions in continental flood basalt provinces. Such eruptions blanketed tens of thousands of square kilometres of Archaean ocean floor.

References

Barnes, S. J., Hill, R. E. T., & Gole, M. J. 1988, The Perseverance ultramafic complex, Western Australia: product of a komatiite lava river. *Journal of Petrology,* 29, pp 305-331.

Cowden, A. 1988, Emplacement of komatiite lava flows and associated nickel sulphides at Kambalda, Western Australia. *Economic Geology,* 83, pp 436-442.

Cowden, A., & Roberts, D. E. 1990, Komatiite hosted nickel sulphide deposits, Kambalda, in *Geology of mineral deposits of Australia and Papua New Guinea,* Editor F. E. Hughes Australian Institute of Mining and Metallurgy Monograph 14,. Melbourne: Australian Institute of Mining and Metallurgy, pp. 567-581

Donaldson, M. J. 1983, Progressive alteration of barren and weakly mineralised Archaean dunited from Western Australia: a petrological, mineralogical and geochemical study of some komatiitic dunites from the Eastern Goldfields Province, unpublished PhD thesis, University of Western Australia, Nedlands, W.A.

Evans, D. M., Cowden, A., & Barrett, R. M. 1989, Deformation and thermal erosion at the Foster nickel deposit, Kambalda St. Ives, Western Australia, in *Magmatic sulphides—the Zimbabwe Volume,* editors M.D. Prendergast, & M. J. Jones, London: Institute of Mining and Metallurgy, pp 215-219.

Gole, M. J., Barnes, S. J., & Hill, R. E. T. 1990, Partial melting and recrystallization of Archaean komatiites by residual heat from rapidly accumulated flows. *Contributions to Mineralogy and Petrology,* 105, pp 704-714.

Hill, R. E. T., Gole, M. J., & Barnes, S. J. 1988, Olivine adcumulates in the Norseman–Wiluna greenstone belt Western Australia: implications for the volcanology of komatiites, in *Magmatic sulphides - the Zimbabwe Volume,* editors M.D. Prendergast, & M. J. Jones, London.: Institute of Mining and Metallurgy, pp 189-206.

Lesher, C. M., Arndt, N. T., & Groves, D. I. 1984, Genesis of komatiite-associated nickel sulphide deposits at Kambalda Western Australia: a distal volcanic model, in *Sulphide deposits in mafic and ultramafic rocks,* editors D. L. Buchanan, & M. J. Jones, London: Institute of Mining and Metallurgy, pp 70-80.

Follows p. 13

Comparative geochemistry of stratigraphically equivalent volcanic units in the Eastern Goldfields

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In the Archaean Kalgoorlie Terrane of the Eastern Goldfields Province of Western Australia, mafic and ultramafic volcanic rocks are divided into a stratigraphic sequence of lower basalt unit, komatiite unit, and upper basalt unit. Of six tectonostratigraphic domains recognised in the Kalgoorlie Terrane (Swager & others, 1990), two of these (the Kambalda Domain and the Ora Banda Domain) contain all three units (Table 1A). The absolute age of the sequence is poorly constrained as published zircon geochronology is restricted to the Kambalda Domain, where Claoué-Long and Compston (1987) record an age of 2702 ± 4 Ma for a sedimentary layer on top of the lower-most flow in the komatiite unit at Kambalda. An age of 2692 ± 4 Ma is cited by Claoué-Long & others (1988) for the Kapai Slate, at the top of the komatiite unit.

Although komatiites in each domain are chemically similar, there are notable compositional differences between stratigraphically equivalent basalt units in the two domains, and any tectonic models put forward must explain both the chemical variations, and the timing and distribution of mafic and ultramafic volcanism.

Mafic lithologies of the Kambalda and Ora Banda Domains

The lower basalt unit in the Kambalda Domain (Lunnon Basalt) is a sequence of monotonous, pillowed and massive volcanic flows and high-level, co-magmatic intrusive rocks. The succession is at least 1700 m thick. The stratigraphically equivalent unit in the Ora Banda Domain consists of two parts (Witt, 1990). The lower part (Wongi Basalt) contains a small proportion of pillow lava, abundant pyroxene-spinifex textured basalt, and some variolitic units. In contrast, the overlying Missouri Basalt is pillowed, texturally more uniform, and notably more felsic.

The komatiite unit is up to 1000 m thick in the Kambalda Domain, and more than 3000 m thick in the Ora Banda Domain. In both domains, tholeiites and basaltic komatiites are developed at the top of the komatiite unit (Devon Consols Basalt and Big Dick Basalt; Table 1A).

The overlying upper basalt unit in the Kambalda Domain contains basalt, basaltic komatiite and several dolerite sills (Roberts & Elias, 1990; Clout & others, 1990). It reaches a stratigraphic thickness of about 1000 m. Witt (1990) has divided the upper basalt unit in the Ora Banda Domain into two parts, separated by a regionally extensive slate horizon. The lower part (Bent Tree Basalt) consists of tholeiitic basalts, whereas the overlying Victorious Basalt contains calc-alkalic basalts and andesites (Morris, 1993).

Chemistry of mafic units

Archaean volcanic rocks that have undergone polyphase deformation, greenschist to amphibolite facies regional metamorphism, and some degree of surface weathering, have also probably undergone some element mobilisation. In order to appreciate chemical variations between basalt sequences, it is important to assess the effects of this mobility. In both domains, the good preservation of igneous textures suggests limited mobility. However, studies of other Archaean rocks (e.g. Arndt & Jenner, 1986; Redman & Keays, 1985) have highlighted the mobility of low field strength elements (LFSE: K, Rb, Ba, Cs, Sr, Th, U, Pb), and the relative immobility of the high field strength elements (HFSE: Ti, P, Zr, Nb, Ta, Hf). Other studies (Saunders & others, 1979; Marsh, 1991) have argued for limited mobility of the rare earth elements (REE: La - Lu), Y, Cr, Ni, and V.

Immobile elements that directly reflect the composition of the source material are the most

Stratigraphy And Geochronology Of Mafic And Ultramafic Volcanic Rocks Of The Kambalda And Ora Banda Domains, Kalgoorlie Terrane

A

	Kambalda Domain	Ora Banda Domain
Upper basalt unit	Paringa Basalt	*Victorious Basalt* *Bent Tree Basalt*
	Kapai Slate (2692 ± 4 Ma)	
Komatiite unit	Devon Consols Basalt Kambalda Komatiite (2702 ± 4 Ma)	Big Dick Basalt Siberia Komatiite Walter Williams Formation
Lower basalt unit	*Lunnon Basalt*	*Missouri Basalt* Wongi Basalt

Italicised = Group1
Underlined = Group 2

B

Chemical Characteristics Of Groups 1 And 2

	Group 1	**Group 2**
Ti/Zr	about 106	about 76
$(La/Yb)_{CN}$	~1	~1, >1
Σ_{Nd}	>0	>0, <0
Zr/Y	~2.5	>3
Al_2O_3/TiO_2	~20	> =20

Table 1A. Stratigraphy, geochronology, and group assignation (see text and Table 1B) of mafic and ultramafic volcanic units in the Kambalda and Ora Banda Domains, Kalgoorlie Terrane. After Swager & others (1990) and Witt (1990).

1B. Geochemical characteristics of Groups 1 and 2 volcanic rocks identified in the Kambalda and Ora Banda Domains.

useful in comparing basalt sequences. Of the immobile elements, Ti and Zr are readily measurable by XRF, and have bulk distribution coefficients much less than 1 for most minerals, meaning that the ratio of such elements (e.g. Ti/Zr) is unaffected by either the degree of partial melting or the extent of fractional crystallization. As such, the ratio will reflect that of the mantle source if the melt is uncontaminated.

Lower basalt unit

The lower basalt unit (Lunnon Basalt) of the Kambalda Domain forms a coherent group in terms of Ti/Zr (Fig. 1A), defining a best-fit line with a slope of 106 ($r = 0.89$; $n = 46$). Chondrite-normalised REE patterns are flat, and La is about 10 x chondrite. Available Σ_{Nd} range between 2 and 4.

Samples from the Wongi Basalt in the Ora Banda Domain plot oblique to the Lunnon Basalt trend for Ti/Zr (Fig. 1A), and one basaltic andesite (GSWA 100113) has high Zr and low Ti. Missouri Basalt samples scatter about the Lunnon Basalt trend, and show only a weak overlap with the underlying Wongi Basalt. In terms of REE, basaltic andesite GSWA 100113 is strongly LREE-enriched, with La about 60 x chondrite, but other Wongi Basalt samples have flat patterns. Missouri Basalt samples have higher total REE, flat patterns with small negative Eu anomalies.

Basaltic upper part of the komatiite unit

Samples from both domains lie on a similar trend in terms of Ti/Zr (Fig. 1B), plotting at lower Ti than the lower basalt group of the Kambalda Domain. Chondrite-normalised REE plots for two basaltic komatiites from the Ora Banda Domain have flat patterns with La about 8 x chondrite.

Upper basalt unit

Samples of the upper basalt unit from Kambalda and Kalgoorlie, and some samples from Bluebush–Republican (Kambalda Domain) plot close to a Ti/Zr line with a slope of 76 (Fig. 1C), similar to samples from the upper part of the komatiite unit (Fig. 1B). The remaining samples plot close to the lower basalt unit samples of the Kambalda Domain (Fig. 1). Chondrite-normalised REE (Arndt & Jenner, 1986) are all LREE-enriched and two samples with steep $(La/Yb)_{CN}$ have 15.6 and 21.6 wt% MgO respectively. Two Bluebush samples have similar MgO contents but significantly different REE patterns Σ_{Nd} shows ranges from +4 to -3.

In terms of Ti/Zr, samples from both parts of the upper basalt unit in the Ora Banda Domain plot slightly off the trend for the lower basalt unit of the Kambalda Domain. This trend is similar to that for samples from the lower basalt unit at Dunnsville in the adjacent Coolgardie Domain (Morris, 1993).

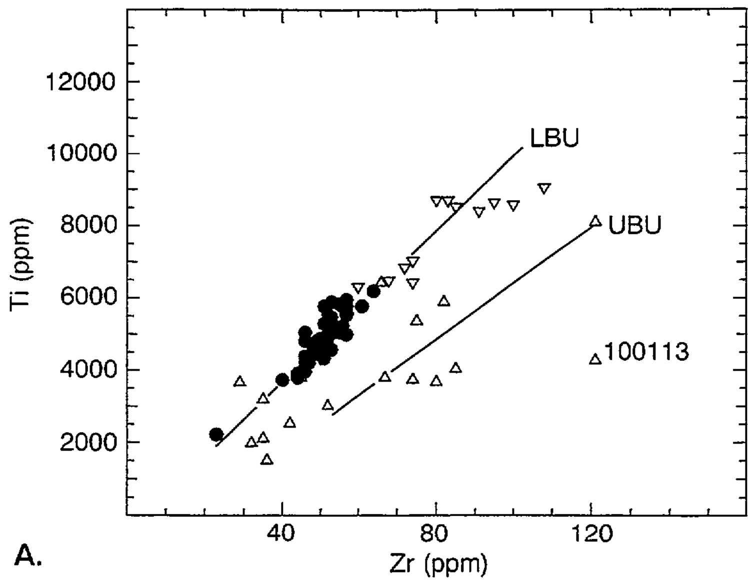
Summary of mafic geochemistry

Mafic volcanic rocks in the Kambalda and Ora Banda Domains can be divided into two broad groups on the basis of chemical and lithological criteria. The characteristics of each group are summarised in Table 1B. One group (informally named Group 1 here) comprises samples from the lower basalt unit of the Kambalda Domain, the Missouri Basalt of the Ora Banda Domain (lower basalt unit), some samples from the upper basalt unit at Bluebush-Republican in the Kambalda Domain, and the two members of the upper basalt unit of the Ora Banda Domain. Group 2 comprises samples of the upper basalt unit at Kambalda and Kalgoorlie, the remaining samples from Bluebush–Republican, and the Wongi Basalt (lower basalt unit of the Ora Banda Domain). Samples from the basaltic upper part of the komatiite unit are also placed in this group. It is clear that groups contain samples from various stratigraphic levels, although in one case (Bluebush–Republican upper basalt unit samples) complex folding and thrust stacking accounts for the juxtaposition of Group 1 and Group 2 lithologies.

Models for magma genesis

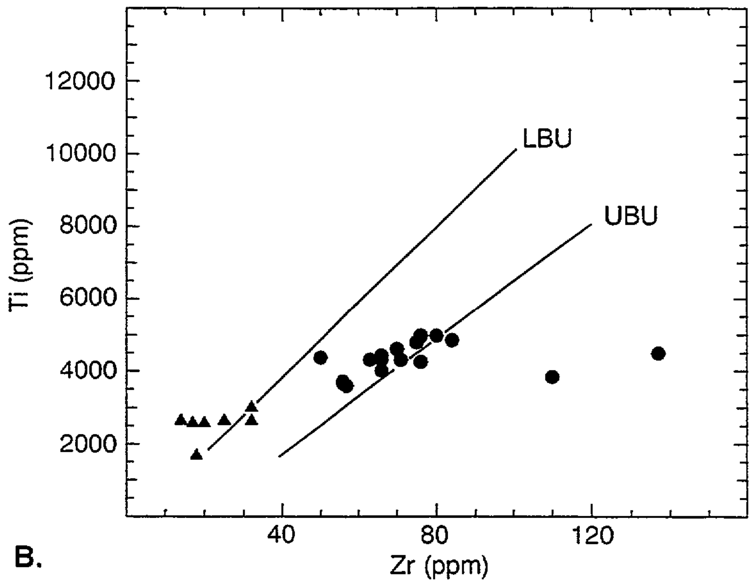
Ti/Zr, REE patterns and Σ_{Nd} of Group 1 samples are similar to modern mid-ocean ridge basalts (MORB: Sun & McDonough, 1989), which are derived from a depleted mantle source where garnet was not a residual phase. Within this group, samples with high Ti and Zr generally have low MgO, Ni and Cr, consistent with some low-pressure fractional crystallisation.

The strong divergence of Group 1 and 2 trends in terms of Ti/Zr, and the disparity of the two groups in terms of Σ_{Nd} indicates that the groups are not genetically related. Despite containing both basalts and basaltic komatiites, Group 2 samples lie on a well-defined Ti/Zr trend, which indicates some common petrogenetic thread. Some members of Group 2 have high MgO, Cr and Ni and are also LREE enriched, which indicates either an enriched mantle source region or contamination of komatiite by a LREE-enriched component such as continental crust (siliceous high MgO-series basalts (SHMSB) of Sun & others, 1989). A contamination and fractional crystallisation model is widely accepted for these rocks (e.g. Arndt and Jenner, 1986; Sun & others, 1989). Based on trace element and isotope



12000
10000
8000
6000
4000
2000
Ti (ppm)
LBU
UBU
100113
40
80
120
Zr (ppm)

A.



12000
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Ti (ppm)
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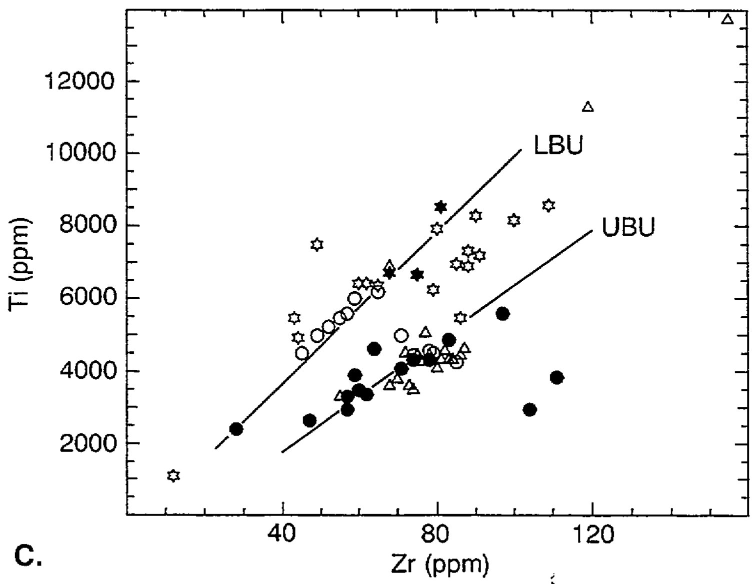
Zr (ppm)

B.



12000
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C.

modelling, Arndt & Jenner (1986) reproduced compositions of SHMSB from the upper basalt unit at Kambalda by incorporation of 24% modern upper crust composition by komatiite magma, followed by about 60% fractional crystallisation. They noted that an Archaean crustal contaminant could not reproduce the required incompatible element composition of SHMSB. Morris (1993) has carried out similar assimilation and fractional crystallisation modelling, and found that between 5 and 10% contamination of komatiite by a calcalkaline granitoid, followed by 10-20% fractional crystallisation produced a good fit to Group 2 compositions. A greywacke contaminant (i.e Archaean crust) did not produce the required LREE enrichment.

Models to account for the distribution and chemistry of mafic volcanic rocks in the two domains must account for the derivation of Group 1 rocks from a depleted mantle source, and Group 2 rocks by contamination and fractionation of a komatiite magma. In addition, models must satisfy other regional geological aspects (Morris, 1993), which are summarised as follows: in both domains, volcanism changes from basalt-dominated to komatiite-dominated, and back to basalt-dominated; mafic and ultramafic volcanic rocks in the Kalgoorlie Terrane show characteristics consistent with subaqueous, and continuous effusion; sedimentary rocks associated with volcanic rocks are fine grained and locally sulphidic; palaeoenvironmental reconstructions have indicated a southeasterly direction of lava flow; despite polyphase deformation (Swager & others, 1990), the northwest-southeast polarity of the Kalgoorlie Terrane is generally taken as near to the original distribution of greenstones.

Models for the magmatic evolution of these domains assume the stratigraphies are coeval, and have not undergone severe reorganisation. Models proposed to date follow two lines. Campbell and co-workers (e.g. Campbell & Hill, 1988) have argued that the transition from mafic to ultramafic volcanic activity can be explained by a komatiite mantle plume. Entrainment of mantle into the plume head would result in tholeiitic magma, such as the Kambalda Domain lower basalt unit. The komatiite unit would correspond to eruption of material from the plume axis. According to Griffiths and Campbell (1990), the plume axis would have a diameter of 600–800 km, flattening to a plume head of about 2000 km diameter. Although this model can explain the chemistry and stratigraphy of the lower basalt and komatiite units respectively of the Kambalda Domain, it cannot account for early komatiite-related magmatism in the lower basalt unit of the Ora Banda Domain, at a time when tholeiitic magma was being erupted at Kambalda. The dimensions of the plume axis and head mean that this model should account for volcanism in both domains simultaneously.

By considering the type and distribution of volcanic rocks in the Kalgoorlie Terrane, and greenstones to the east, Barley and co-workers (e.g. Barley & others, 1989; Barley & Groves, 1990) attribute the Kalgoorlie Terrane sequence to back arc extension. This model is attractive in that there are strong analogies in terms of volcanism, geochemistry, and sediment types between the Kalgoorlie Terrane and such well preserved back arc successions as the Jurassic–Cretaceous 'rocas verdes' of South America (Tarney & others, 1981; Alabaster & Storey, 1990) and the Miocene Sea of Japan (Matsuda, 1979; Morris & Kagami, 1989). These back arc basins are characterised by rapid effusions of mafic magma, sulphide mineralisation, basin polarity, and spatial relationship to arc-derived volcanic rocks. Two major problems arise from this model. Firstly, although intermediate and felsic rocks do occur in greenstones to the east of the Kalgoorlie Terrane, it is not generally accepted that these rocks result from subduction-related volcanism (e.g. Giles & Hallberg, 1982). Secondly, experimental work on komatiite genesis (e.g. Ohtani, 1990; Herzberg & Ohtani, 1989) indicates the locus of komatiite magma genesis is in excess of 400 km, well below the focus of arc magmatism.

The tectonic model adopted by Morris (1993) utilises parts of the plume and rift models. A northwest-southeast trending rift develops in continental crust. The rift opens at a greater rate to the north than the south. Coincident with this rifting, komatiite magma rises towards the surface in the

Fig. 1. (opposite page) Ti vs Zr (ppm) for mafic volcanic rocks of the Kalgoorlie and Ora Banda Domains, Kalgoorlie Terrane. Lines LBU and UBU on each plot are lines of best fit for the lower basalt unit of the Kambalda Domain (slope 106) and the upper basalt unit at Kambalda and Kalgoorlie in the Kambalda Domain (slope 76) respectively.

A. Lower basalt unit. Closed circles—Kambalda Domain. Open triangles—Wongi Basalt, Ora Banda Domain. Inverted open triangles—Missouri Basalt, Ora Banda Domain.

B. Upper part of komatiite unit. Closed circles—Kambalda Domain. Closed triangles—Ora Banda Domain.

C. Upper basalt unit. Closed circles—Kambalda area, Kambalda Domain. Open triangles—Kalgoorlie, Kambalda Domain. Open circles—Bluebush–Republican, Kambalda Domain. Open stars—Bent Tree Basalt, Ora Banda Domain. Closed stars—Victorious Basalt, Ora Banda Domain.

north and interacts with the crust to produce contaminated and fractionated magma (Wongi Basalt). At the same time, the komatiite acts as a heat source for melting of a depleted mantle in the south, and localised melting in the north, resulting in tholeiitic basalt (Lunnon Basalt and Missouri Basalt respectively). Accelerated rifting in the north allows the passage of uncontaminated komatiite magma to the surface, which flows southeast along the rift (komatiite unit of both domains). Extension stops, and komatiite interacts with crustal rocks to produce the basaltic upper part of the komatiite in both domains.

The rift now closes more rapidly to the north than the south, resulting in the eruption of variably contaminated magma in both domains (upper basalt unit).

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References

Alabaster, T., & Storey, B.C. 1990, Modified Gulf of California model for South Georgia, north Scotia Ridge, and implications for the Rocas Verdes back-arc basin, southern Andes, *Geology*, 18, pp 497-500.

Arndt, N.T., & Jenner, G.A. 1986, Crustally contaminated komatiites and basalts from Kambalda, Western Australia, *Chemical Geology*, 56, pp 229-255.

Barley, M.E., Eisenlohr, B.N., Groves, D.I., Perring, C.S., & Vearncombe, J.R, 1989, Late Archaean convergent margin tectonics and gold mineralization: A new look at the Norseman-Wiluna Belt, Western Australia, *Geology*, 17, pp 826-829.

Barley, M.E., & Groves, D.I. 1990, Deciphering the tectonic evolution of Archaean greenstone belts: the importance of contrasting histories to the distribution of mineralization in the Yilgarn Craton, Western Australia, *Precambrian Research*, 46, pp 3-20.

Campbell, I.H., & Griffiths, R.W. 1990, Implications of mantle plume structure for the evolution of flood basalts, *Earth and Planetary Science Letters*, 99, pp 79-93.

Campbell, I.H., & Hill, R.I. 1988, A two-stage model for the formation of granite-greenstone terrains of the Kalgoorlie-Norseman area, Western Australia, *Earth and Planetary Science Letters*, 90, pp 11-25.

Claoué-Long, J.C., & Compston, W. 1987, Precise geochronology in the Kambalda mineral belt, *Research School of Earth Sciences Annual Report*, 1987, pp 65-67.

Claoué-Long, J.C., Compston, W., & Cowden, A. 1988, The age of the Kambalda greenstones resolved by ion-microprobe: implications for Archaean dating methods, *Earth and Planetary Science Letters*, 89, pp 239-259.

Clout, J.M.F., Cleghorn, J.H., & Eaton, P.C. 1990, Geology of the Kalgoorlie Goldfield, in *Geology Of The Mineral Deposits Of Australia And Papua New Guinea*, ed. F.E. Hughes, Australasian Institute of Mining and Metallurgy Monograph, 14, pp 411-431.

Giles, C.W., & Hallberg, J.A. 1982, The genesis of the Archaean Welcome Well volcanic complex, Western Australia, *Contributions to Mineralogy and Petrology*, 80, pp 307-318.

Griffiths, R.W., & Campbell, I.H. 1990, Stirring and structure in mantle starting plumes, *Earth and Planetary Science Letters*, 99, pp 66-78.

Herzberg, C.T., & Ohtani, E. 1988, Origin of komatiite at high pressures, *Earth and Planetary Science Letters*, 88, pp 321-329.

Marsh, J.S. 1991, REE fractionation and Ce anomalies in weathered Karoo dolerite, *Chemical Geology*, 90, pp 189-194.

Matsuda, T. 1978, Collision of the Izu-Bonin arc with central Honshu: Cenozoic tectonics of the Fossa Magna, Japan, in *Advances In Earth And Planetary Sciences*, 6, eds. S. Uyeda, R.W. Murphy, & K. Kobayashi, Japan Scientific Societies Press, pp 409-421.

Morris, P.A. 1993, Physical volcanology and geochemistry of Archaean mafic and ultramafic volcanic rocks between Menzies and Norseman, Eastern Yilgarn craton, Western Australia, *Geological Survey of Western Australia Report*, 36.

Morris, P.A., & Kagami, H. 1989, Nd and Sr isotope systematics of Miocene to Holocene volcanic rocks from Southwest Japan: volcanism since the opening of the Japan Sea, *Earth and Planetary Science Letters*, 92, pp 335-346.

Ohtani, E. 1990, Majorite fractionation and genesis of komatiite in the deep mantle, *Precambrian Research*, 48, pp 195-202.

Redman, B.A., & Keays, R.R. 1985, Archaean basic volcanism in the Eastern Goldfields Province, Yilgarn Block, Western Australia, *Precambrian Research*, 30, pp 113-152.

Roberts, D.E., & Elias, M. 1990, Gold deposits of the Kambalda-St Ives region, in *Geology Of The Mineral Deposits Of Australia & Papua New Guinea*, ed. F.E. Hughes, Australasian Institute of Mining and Metallurgy Monograph 14, pp 479-491.

Saunders, A.D., Tarney, J., Marsh, N.G., & Wood, D.A. 1980, Ophiolites as ocean crust or marginal basin: A geochemical approach, in *Proceedings of the International Ophiolite Symposium, Cyprus 1979*, ed. A. Panayioutu, Ministry of Agriculture and Natural Resources Geological Survey Division, Republic of Cyprus, pp 193-204.

Sun, S.S., & McDonough, W.F. 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and process, in *Magmatism In The Ocean Basins*, ed. A.D. Saunders & M.J. Norry, Geological Society Special Publication, pp 313-345.

Sun, S.S., Nesbitt, R.W., & McCulloch, M.T. 1989, Geochemistry and petrogenesis of Archaean and early Proterozoic siliceous high-magnesian basalts, in *Boninites And Related Rocks*, ed. A.R. Crawford, Unwin Hyman, pp 148-173.

Swager, C., & Ahmat A. 1992, Greenstone terranes in the southern part of the Eastern Goldfields province, in *Mineral Exploration and Mining Geology in the Eastern Goldfields*, Department of Mineral Exploration and Mining Geology, Western Australian School of Mines, Kalgoorlie, pp 70-71.

Swager, C., Griffin, T.J., Witt, W.K., Wyche, S.W., Ahmat, A.L., Hunter, W.M., & McGoldrick, P.J. 1990, Geology of the Archaean Kalgoorlie Terrane - an explanatory note, *Geological Survey of Western Australia Record* 1990/12.

Swager, C.P., & Griffin, T.J. 1990, An early thrust duplex in the Kalgoorlie - Kambalda greenstone belt, Eastern Goldfields Province, Western Australia, *Precambrian Research*, 48, pp 63-73.

Tarney, J., Dalziel, I.W.D., & De Wit, M.J. 1981, Marginal basin 'Rocas Verdes' complex from South Chile: a model for Archaean greenstone belt formation, in *The Early History Of The Earth*, ed. B.F. Windley, John Wiley and Sons, New York, pp 131-145.

Witt, W.K. 1990, Geology of the Bardoc 1:100 000 sheet, Western Australia, *Geological Survey of Western Australia Record*, 1990/14.

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Mafic/ultramafic rocks of the Gindalbie Terrane: a review of the Bulong and Carr Boyd Complexes

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The Gindalbie Terrane (Fig. 1) is a tectonostratigraphic unit (160 x 40 km) in the centre of the Archaean Norseman–Wiluna Belt in the Kalgoorlie area and is separated from the Kalgoorlie Terrane to the west by the Mt Monger Fault and the Jubilee Terrane to the east by the Emu Fault (Swager & Ahmat, 1992). Part of the Gindalbie-Jubilee boundary is unconformably overlain by polymictic conglomerate, the Penny Dam Conglomerate (Ahmat, in prep., a). The three terranes are made up largely of mafic, ultramafic and felsic volcanic rocks but have different stratigraphic sequences and proportions of rock types. In contrast to the Kalgoorlie Terrane (Swager & others, 1990), which has a widely recognised sequence (from base to top) of basalt, komatiite, basalt and felsic volcanic/volcaniclastic rocks (Black Flag Group) overlain locally by polymictic conglomerate, the Gindalbie Terrane sequence consists of basalt, felsic volcanic/volcaniclastic rocks, komatiite, basalt and, locally, polymictic conglomerate. The main difference between the two terranes is the presence of the prominent felsic volcanic/volcaniclastic unit low in the Gindalbie Terrane sequence. Rocks of the Gindalbie Terrane are polydefomed (Archibald & others, 1978; Swager & others, 1990) and metamorphosed at greenschist or amphibolite facies (Binns & others, 1976). The felsic volcanic/volcaniclastic unit has a U-Pb zircon date of 2715 ± 14 Ma (Neal McNaughton, pers. comm., 1991) and a thin felsic volcanic layer in the upper basalt has a U-Pb zircon age of ~2700 Ma (Pidgeon & Wilde, 1990).

Mafic/ultramafic rocks make up ~65% of the Gindalbie Terrane and range in composition from tholeiitic to komatiitic. Broad zones dominated by mafic-ultramafic rocks (e.g. komatiitic basalt and komatiite) and mafic rocks (e.g. tholeiitic basalt, dolerite, gabbro) are recognised (Fig. 1). These zones show both structural and stratigraphic relationships to one another. Numerous thin (1-30 m thick) felsic volcanic/volcaniclastic-metasedimentary units are interbedded with the mafic/ultramafic rocks (Fig. 2) and indicate contemporaneous felsic-mafic and felsic-ultramafic volcanism as well as subaqueous deposition in many parts of the terrane. The mafic-ultramafic zones contain conformable layered bodies of predominantly high-MgO composition (15-18 wt%) (Williams & Hallberg, 1973) whereas the mafic zones contain conformable layered bodies of almost exclusively tholeiitic composition (~8 wt% MgO). Layered mafic-ultramafic bodies are up to 920 m thick and are variably differentiated from dunite and harzburgite through orthopyroxenite, norite, gabbronorite and gabbro to granophyre (Williams & Hallberg, 1973). Layered mafic bodies are variably differentiated from pyroxenite and melagabbro through gabbronorite and gabbro to granophyre (Ahmat, in prep. a,b). Although the layered bodies have been interpreted as high-level sills that formed contemporaneously with mafic/ultramafic volcanism (Williams, 1970; Williams & Hallberg, 1973; Moeskops, 1977), recent studies on Archaean gabbro genesis (e.g. Arndt, 1977; Hill & others, 1989), suggest that they can also be interpreted as the products of fractional crystallisation of thick or ponded flows. Mapping of the greater part of the Gindalbie Terrane (Ahmat, in prep., a,b) has revealed a complex gradational relationship between basalt, dolerite and gabbro in many of the mafic rock-dominated areas. Rock units are commonly too thin to represent at 1:25 000 scale and are seen to grade both vertically and laterally into one another. Such areas are designated by map symbols as Abd (basalt-dolerite) or Abg (basalt-dolerite-gabbro) (Fig. 2). The gradational feature of the basalt-dolerite-gabbro suite, in combination with intercalation of numerous thin units of felsic vol-

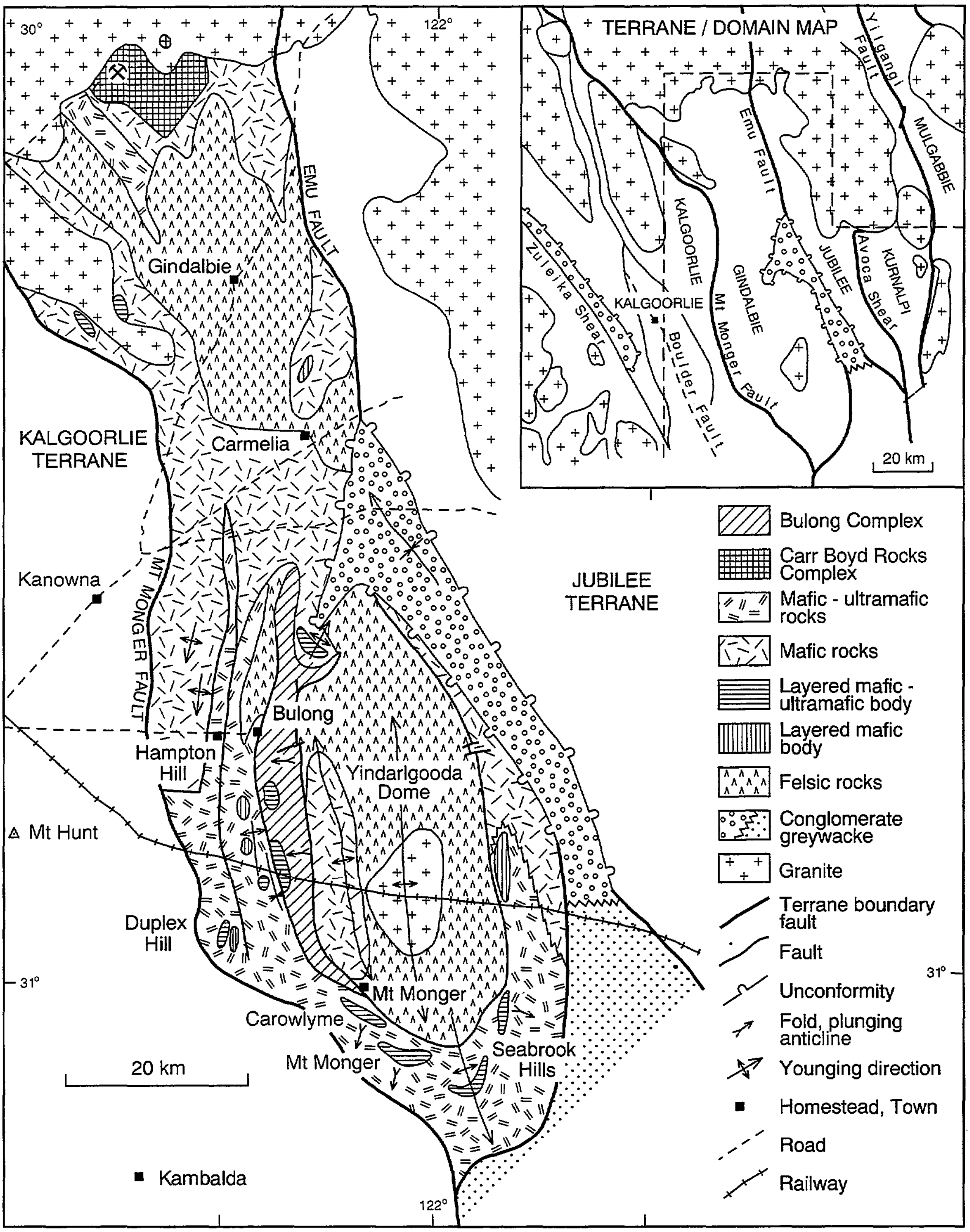

Fig. 1. General geology of the Gindalbie Terrane. Inset shows terranes/domains of the southern part of the Norseman–Wiluna Belt (after Swager, this volume).

canic/volcaniclastic rocks, is evidence that many of the dolerite and gabbro bodies, hitherto considered as intrusive, are actually extrusive in origin (Ahmat, in prep., b).

Bulong Complex

The Bulong Complex (>45 x 5 km) is a thick sequence of predominantly serpentinised peridotite that overlies the felsic volcanic/volcaniclastic

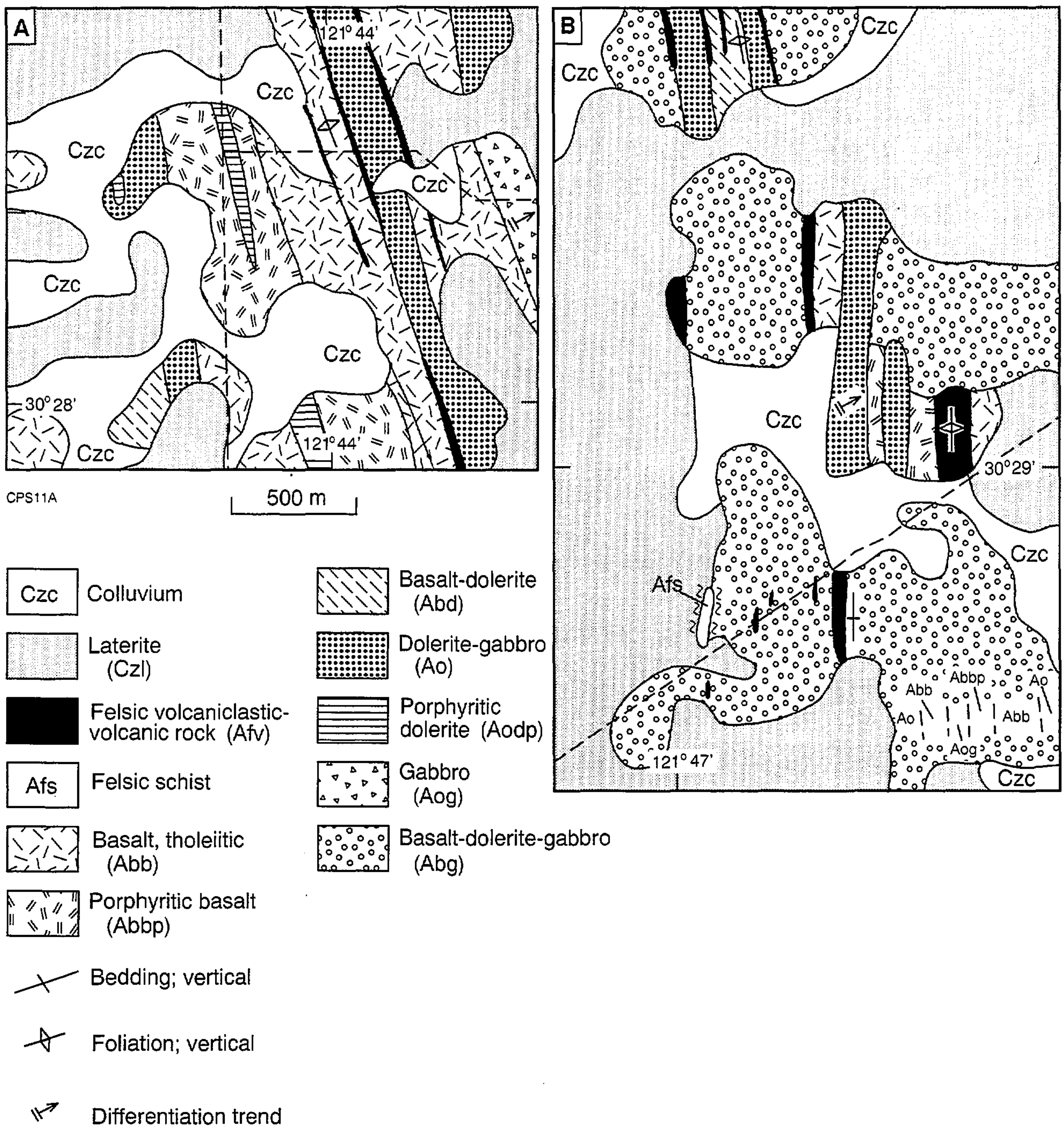

Fig. 2. Outcrop geology of areas in mafic-dominated rocks 11 km west-southwest (A) and 7 km southwest (B) of Carmella.

rocks on the western limb of the Yindarlgooda dome (Fig. 1). Although originally considered to be a differentiated ultramafic intrusive complex (Williams, 1970; Moeskops, 1973, 1977), it is now interpreted as a komatiite complex made up of proximal and distal deposits (Ahmat, in prep., a). The complex is fault-bounded, regionally west-younging, although folded in part, possibly reflecting the development of minor nappe structures during early thrusting. It is made up of numerous, variously differentiated units (up to 400 m thick) consisting of serpentinised peridotite (olivine ± chromite ortho-mesocumulates), pyroxenite, gabbronorite and, locally, leucogabbro and diorite. A layer of chromitite (10-20 cm thick) occurs in one of the differentiated units on the east side of the complex. Approximately 80-85% of the complex is composed of serpentinised, cumulus-textured peridotite and, in general, lacks spinifex-textured komatiite or high-MgO basalt. However, both of these rock types are more prevalent laterally and vertically. On a regional scale, the complex appears to grade along strike into tholeiitic rocks.

The serpentinised peridotite contains ~33-43 wt% MgO (volatile-free basis) with mg-values [100Mg/(Mg + Fe)] of 83.6-92.1; the pyroxenite contains ~17-31 wt% MgO with mg-values of 79.1-82.8; and the gabbro contains ~9-14 wt% MgO with mg-values of 64.9-81.3. Mineral compositional ranges for rare relict minerals in the serpentinised peridotite, determined by Moeskops (1973), are olivine $Fo_{87.5}$ to $Fo_{92.5}$ and clinopyroxene $Mg_{85.4}$ to $Mg_{92.6}$ [Mg = 100Mg/(Mg + Fe)]. The olivine compositions imply a magma with up to ~26 wt% MgO. Clinopyroxene typically contains ~22 wt% CaO and plots as endiopside. More fractionated mineral compositions are found in the pyroxenite and gabbroid rocks.

Carr Boyd Rocks Complex

The Carr Boyd Rocks Complex is an Archaean layered mafic-ultramafic complex about 80 km north-northwest of Kalgoorlie–Boulder. It is unique in the Norseman–Wiluna Belt in that it contains gabbroid-associated Ni-Cu deposits (1.36 Mt of 1.65 wt% Ni and 0.57 wt% Cu) (Purvis & others, 1972; Schultz, 1975). The complex (~75 km^2) is broadly lobate in outline with ultramafic rocks occupying mainly the western, southern and eastern margins; the northern part of the complex is intruded by granite. The geological setting is still poorly understood because of limited exposure but it is variously folded, faulted and metamorphosed. Previous studies by Purvis & others (1972) and Schultz (1975) have indicated that the body is an intrusive complex within Archaean basic and acid volcanic sequences. Purvis & others (1972) suggest it formed from a sequence of tholeiitic magmas which became progressively richer in normative plagioclase and poorer in normative orthopyroxene. Ni-Cu ore deposits are restricted to steep, west-plunging bronzite-sulphide pegmatoid rock units ("shoots") that are discordant to the main stratigraphy and have been interpreted as intrusive breccia pipes developed late in the crystallisation history of the complex (Purvis & others, 1972; Schultz, 1975).

Rock types range from dunite, harzburgite and bronzitite through olivine norite and norite to gabbronorite, with cyclic layering present in places. At the regional scale, the two dominant rock types are harzburgite-bronzitite (now tremolite-talc rock) and gabbronorite. The main cumulus minerals are olivine, orthopyroxene and plagioclase (intercumulus phase in the ultramafic rocks). Clinopyroxene is a common intercumulus mineral in most rocks but occurs as a cumulus phase in the gabbronorite. The dunite contains ~37 wt% MgO (volatile-free basis) and has an mg-value of ~78. Olivine ranges from Fo_{85} in the ultramafic rocks to Fo_{74} in the gabbroid rocks. Orthopyroxene ranges from En_{82} in the ultramafic rocks to En_{72} in the gabbroid rocks. Plagioclase compositions in the mafic rocks are mainly An_{75-85}. Intercumulus clinopyroxene in the mafic rocks has mg-values of ~78 to 83. The olivine compositions imply a magma with up to ~12 wt% MgO. The mineralized breccia pipes contain ~30% sulphides (pyrrhotite, pentlandite, chalcopyrite and pyrite) and have a bulk Ni:Cu ratio of 3.1. In comparison, komatiite-associated nickel deposits have Ni:Cu ratios >7 (Marston, 1984).

References

Ahmat, A.L. (in prep. a), Kanowna 1:100 000 geological map series, SH51-10-3236, *Geological Survey of Western Australia.*

Ahmat, A.L. (in prep. b), Gindalbie 1:100 000 geological map series, SH51-10-3237, *Geological Survey of Western Australia.*

Archibald, N.J., Bettenay, L.F., Binns, R.A., Groves, D.I. & Gunthorpe, R.J. 1978, The evolution of Archaean greenstone terrains, Eastern Goldfields Province, Western Australia, *Precambrian Research*, 6, pp 103-131.

Arndt, N.T. 1977, Thick, layered peridotite-gabbro lava flows in Munro Township, Ontario, *Canadian Journal of Earth Sciences*, 14, pp 2620-2637.

Binns, R.A., Gunthorpe, R.J. & Groves, D.I. 1976, Metamorphic patterns and development of greenstone belts in the eastern Yilgarn Block, Western Australia, in *The early history of the Earth*, ed. B.F. Windley, Wiley-Interscience, London, pp 303-313.

Hill, R.E.T., Gole, M.J. & Barnes, S.J. 1989, Olivine adcumulates in the Norseman-Wiluna greenstone belt, Western Australia: implications for the volcanology of komatiites, in *Magmatic sulphides - the Zimbabwe volume*, eds M.D. Prendergast & M.J. Jones, Institute Mining and Metallurgy, pp 189-206.

Marston, R.J. 1984, Nickel mineralization in Western Australia, *Western Australian Geological Survey, Mineral Resources Bulletin*, 14.

Moeskops, P.G. 1973, The Bulong serpentinite and environments of nickel mineralisation near Kalgoorlie, Western Australia, *Ph.D thesis, University of London (Imperial College).*

Moeskops, P.G. 1977, New type of igneous layering due to fractionation of Archaean ultramafic magma, *Nature*, 267, pp 508-509.

Pidgeon, R.T. & Wilde, S.A. 1990, The distribution of 3.0 Ga and 2.7 Ga volcanic episodes in the Yilgarn Craton of Western Australia, *Precambrian Research*, 48, pp 309-325.

Purvis, A.C., Nesbitt, R.W. & Hallberg, J.A. 1972, The geology of part of the Carr Boyd Rocks Complex and its associated nickel mineralization, Western Australia, *Economic Geology*, 67, pp 1093-1113.

Schultz, K. 1975, Carr-Boyd Rocks nickel-copper deposits, in *Economic geology of Australia and Papua New Guinea, 1. Metals*, ed. C.L. Knight, Australian Institute Mining and Metallurgy, Monograph series No. 5, pp 121-125.

Swager, C.P. & Ahmat, A.L. 1992, Greenstone terranes in the southern part of the Eastern Goldfields Province, in *Mineral Exploration and Mining Geology in the Eastern Goldfields*, Western Australia School of Mines, Geology Symposium, pp 70-72.

Swager, C.P., Griffin, T.J., Witt, W.K., Wyche, S., Ahmat, A.L., Hunter, W.M. & McGoldrick, P.J. 1990, Geology of the Archaean Kalgoorlie Terrane - an explanatory note, *Western Australian Geological Survey, Record 1990/12*.

Williams, D.A.C. & Hallberg, J.A. 1973, Archaean layered intrusions of the Eastern Goldfields region, Western Australia, *Contributions to Mineralogy and Petrology*, 38, pp 45-70.

Williams, I.R. 1970, Kurnalpi, Western Australia, *Bureau of Mineral Resources 1:250 000 geological series explanatory notes*.

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An overview of felsic volcanism within the Eastern Goldfields Province, Western Australia

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Historical perspective

Although felsic volcanic rocks were frequently discussed in the context of regional mapping (for example, Honman, 1916), the first detailed study specifically concerned with felsic volcanic and related rocks in the Eastern Goldfields Province was not undertaken until the mid-1960s (O'Beirne, 1968). Following the discovery of economic base metal mineralization in a mafic-felsic sequence near Teutonic Bore in 1976 (Greig, 1984), felsic volcanic rock types were the focus of a number of detailed studies providing field, petrographic and geochemical data (Fehlberg & Giles, 1983; Giles, 1982; Giles & Hallberg, 1982; Hallberg & Thompson, 1986). Much of this information, along with that derived from a regional study in the northeastern Yilgarn Craton (Hallberg, 1985), was reviewed and summarized by Hallberg & Giles (1986). Following the closure of the Teutonic Bore Mine in 1984 there has been little published detailed information directly pertaining to felsic volcanic rocks. However, on-going regional mapping carried out in the Eastern Goldfields Province by the Geological Survey of Western Australia (GSWA) and Hallberg Mapping Services Pty Ltd (HMS) has continued to document the distribution and nature of felsic volcanic rocks in the area (for example, Swager & others, 1992). This overview integrates previously published information (as reviewed by Hallberg & Giles, 1986) with subsequent work carried out by the GSWA and HMS.

Andesite-dominated calc–alkaline volcanic complexes

Calc-alkaline volcanic complexes dominated by andesite but containing minor dacite and rhyolite are widespread in the eastern portion of the Eastern Goldfields Province from White Flag Lake in the south to Spring Well and Duketon in the north (Fig. 1). Whereas subaqueous pillowed andesitic sequences with interflow shale and banded iron-formation (BIF) occur in the southeast of this area (Fig. 1), the majority of andesitic complexes form discrete, emergent centres surrounded by extensive deposits of feldspathic epiclastic sedimentary rocks. Emergent centres consist of interbedded andesite flows and immature chaotic mass flow deposits. The surrounding epiclastic sedimentary sequences show rapid transition from proximal fan deposits to more distal subaqueous turbiditic sequences interbedded with pillowed tholeiitic basalt. Evidence suggests that the andesitic centres were areas of relatively high relief which rapidly eroded, and that subaerial calc-alkaline volcanism was concomitant with subaqueous mafic volcanism.

Most andesite is porphyritic, containing zoned euhedral phenocrysts of plagioclase, clinopyroxene, and less commonly green hornblende in a pilotaxitic matrix of plagioclase and clinopyroxene; flow tops contain abundant amygdales filled with quartz, carbonate or chlorite. Secondary assemblages include quartz, chlorite, epidote, albite, prehnite, pumpellyite, sericite, titanite, leucoxene and calcite. Associated with andesite are porphyritic hornblende-phyric dacite and rhyolitic fragmental rocks containing quartz and plagioclase crystal fragments and locally well-preserved vitroclastic textures.

Details of andesite chemical composition are reviewed by Hallberg & Giles (1986); of note is the fact that even the most evolved members of andesite-dominated calc-alkaline volcanic complexes (rhyolite, dacite) are less enriched in LIL elements than the least evolved members of LIL element-enriched rhyolites to be described in the following section. As summarized by Hallberg & Giles (1986), petrochemical evidence suggests that parental melts for the calc-alkaline andesitic rocks (LIL element-enriched basalt to low-silica andesite) were derived by shallow, hydrous partial melting of

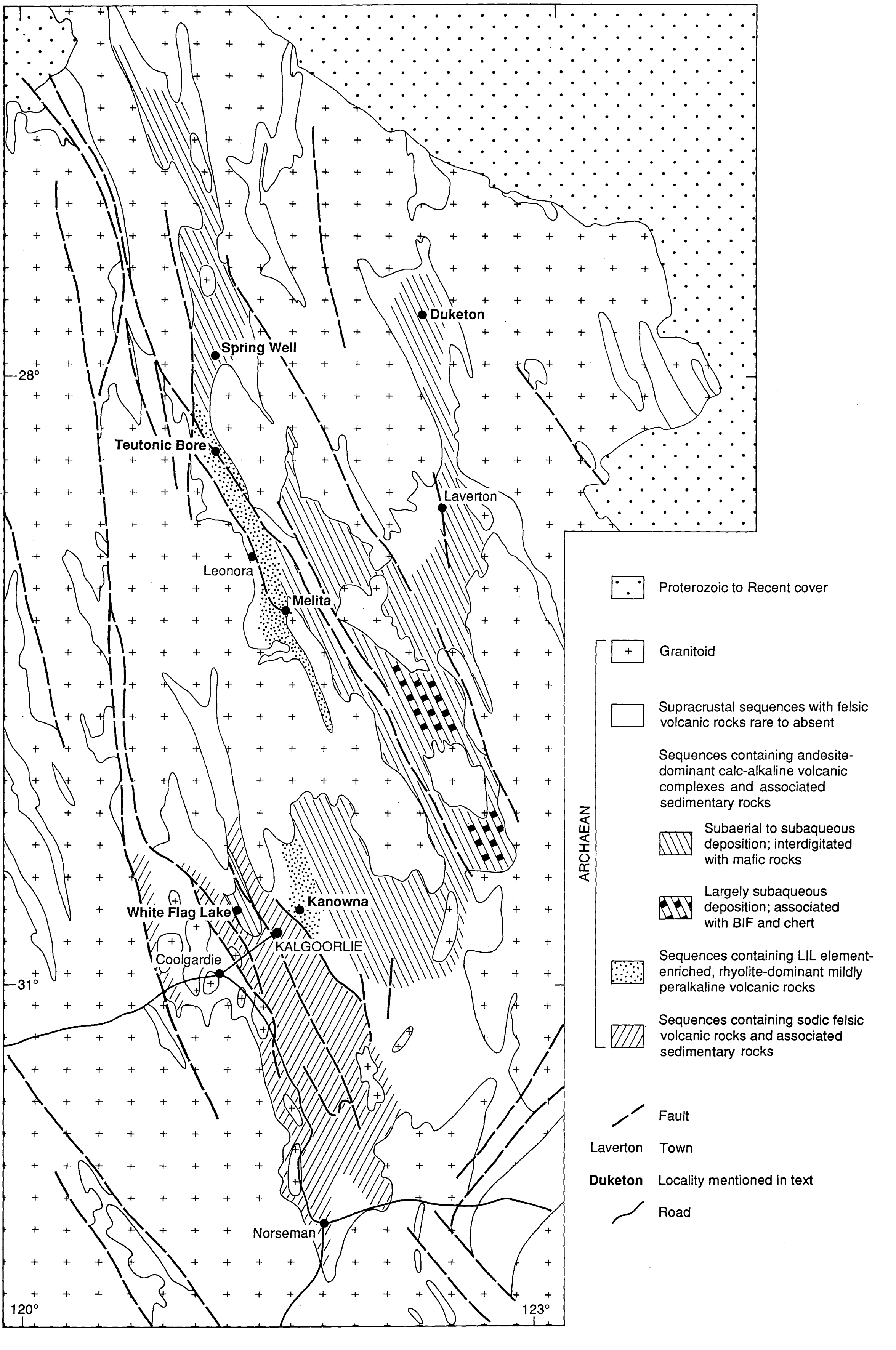

Fig. 1. Distribution of major felsic volcanic rock types within supracrustal sequences of the Eastern Goldfields Province.

LIL element-enriched mantle, and that voluminous andesite (and associated minor dacite and rhyolite) were derived by crystal fractionation of this melt (largely amphibole for andesite, variable proportions of amphibole, clinopyroxene, plagioclase, apatite and magnetite for associated dacite and rhyolite). The overall distribution of calc-alkaline volcanic rocks and the well-documented contemporaneity of calc-alkaline and tholeiitic volcanism does not support volcanic cyclicity involving major mantle or crustal differentiation schemes (Goodwin & Smith, 1980). Mechanisms invoked for andesite genesis include "hot spots" over mantle plumes (Hallberg & Giles, 1986) and subduction in magmatic arcs at convergent plate margins (Barley & Groves, 1990). Hammond & Nisbet (1992) favour an extensional regime for greenstone formation, but note problems in the genesis of calc-alkaline magmas through partial melting induced by underplating.

LIL element-enriched rhyolitic rocks

A regionally continuous "chain" of locally emergent rhyolite-dominated felsic volcanic centres separated by aquagene tuffs and fine-grained sedimentary rocks can be traced from Kanowna in the south to north of Teutonic Bore (Fig. 1). The disposition of these rocks suggests deposition in one or more linear repositories, possibly of tectonic origin. Felsic rocks are both overlain and underlain by mafic pillow lavas, and interdigitate with basalt, forming a distinct bimodal basalt-rhyolite association.

In outcropping areas rhyolite is the dominant lithology, although dacite is locally present and may form up to 20% of some sequences. A spectrum of textural types from shardy vitric tuffs to tuff breccias is present in emergent pyroclastic centres. Lithic fragments in the coarser varieties are similar in composition to the matrix although several textural variants with differing phenocryst ratios may occur. Quartz, albite and K-feldspar crystal fragments and phenocrysts are present in most coarser lithologies; plagioclase may be weakly zoned and partially replaced by K-feldspar. Primary glass is recrystallized and generally contains devitrification textures including quartz-albite and quartz-potash feldspar intergrowth, and quartz-albite spherulites. Hematite/goethite and magnetite dust, and minor amounts of sericite, brown pleochroic biotite, and epidote may be present in the matrix. Associated dacite is composed of quartz and plagioclase phenocrysts in a matrix of suboriented plagioclase microlites, chlorite, epidote, quartz and carbonate.

At a given Ti content rhyolite from rhyolite-dominant centres is enriched in Nb, Y, Zr, K, Rb and REE, and lower in Al and Ca with respect to rhyolite from andesite-dominated calc-alkaline complexes. REE patterns exhibit a distinct negative Eu anomaly. Although compositionally coherent as a group, recent data indicate that there may be subtle differences between individual volcanic centres. Trace element compositions suggest that mildly peralkaline rhyolite was formed by differentiation of a crustally-derived batch of felsic magma in a high-level magma chamber. Early crystallization of accessory phases and their extraction in felsic volcanic rocks and subvolcanic porphyries depleted the melt in Y, Zr, Nb and LREE; this depleted melt eventually rose to intrude its own volcanic pile as masses of syenogranite. The generation of mildly peralkaline melts is seen as related to increased rates of crustal extension at the margin of an ensialic basin to the west.

Felsic volcanic-sediment association of the Kalgoorlie terrane

Subaerial to subaqueous felsic volcanic rocks in the southern portion of the Eastern Goldfields Province (Fig. 1) lie largely within the Kalgoorlie Terrane of Swager & others (1992), and consist of soda-rich dacitic and rhyolitic fragmental rocks intimately associated with quartz-rich clastic sedimentary sequences containing oligomictic and polymictic conglomerates of local provenance (O'Beirne, 1968; Fehlberg & Giles, 1983; Keats, 1987). These felsic volcanic/sedimentary sequences, locally termed the Black Flag Beds (Keats, 1987), are extensively intruded by porphyries and granitoids of tonalitic to syenitic composition; the possibility of some shallow water environment is indicated by the occurrence of evaporite minerals in shales (Golding & Walter, 1979). Individual flows studied in detail contain autobreccias formed by contact with water and are intimately associated with poorly-bedded largely oligomictic breccias and volcanic sandstones formed by subsequent erosion of flow lobes.

Rhyolitic to dacitic volcanic rocks of the Kalgoorlie Terrane have a distinct and coherent chemical composition with Nb, Y and HREE lower, and Sr and Ti higher than LIL element-enriched rhyolite and dacite from volcanic centres at Kanowna, Melita and Teutonic Bore. REE patterns exhibit no Eu anomaly. Hammond & Nisbet (1992) suggest formation in an extensional environment, with parental felsic magmas generated by partial crustal melting during underplating.

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References

Barley, M. E & Groves, D. I. 1990, Deciphering the tectonic evolution of Archaean greenstone belts: the importance of contrasting histories to the distribution of mineralization in the Yilgarn Craton, Western Australia, *Precambrian Research*, 46, pp 3-20.

Fehlberg, B. & Giles, C. W. 1983, Archaean volcanic exhalative gold mineralization at Spargoville, Western Australia, in *Gold 82: the geology, geochemistry and genesis of gold deposits*, ed. R. P. Foster, Balkema, Rotterdam, pp 285-303.

Giles, C. W. 1982, The geology and geochemistry of the Archaean Spring Well felsic volcanic complex, Western Australia, *Journal of the Geological Society of Australia*, 29, pp 205-220.

Giles, C. W. & Hallberg, J. A. 1982, The genesis of the Archaean Welcome Well volcanic complex, Western Australia, *Contributions Mineralogy Petrology*, 80, pp 307-318.

Golding, L. Y. & Walter, M. R. 1979, Evidence of evaporite minerals in the Archaean Black Flag Beds, Kalgoorlie, Western Australia, *BMR Journal of Australian Geology & Geophysics*, 4, 67-71.

Goodwin, A. M. & Smith, I. E. M. 1980, Chemical discontinuities in Archean metavolcanic terains and the development of Archean crust, *Precambrian Research*, 10, pp 301-311.

Greig, D. D. 1984, Geology of the Teutonic Bore massive sulphide deposit, Western Australia, *Proceedings Australasian Institute of Mining and Metallurgy*, 289, pp 147-156.

Hallberg, J. A. 1985, *Geology and mineral deposits of the Leonora-Laverton area, northeastern Yilgarn Block, Western Australia*, Hesperian Press, Perth.

Hallberg, J. A. & Giles, C. W. 1986, Archaean felsic volcanism in the northeastern Yilgarn Block, Western Australia, *Precambrian Research*, 33,pp 413-427.

Hallberg, J. A. & Thompson, J. F. H. 1986, Geological setting of the Teutonic Bore massive sulfide deposit, Archean Yilgarn Block, Western Australia, *Economic Geology*, 80, pp 1953-1964.

Honman, C. S. 1916, The geology of the country to the south of Kalgoorlie (Coolgardie and East Coolgardie Goldfields), including the mining centres of Golden Ridge and Feysville, *Geological Survey of Western Australia Bulletin* 66.

Hammond, R. L. & Nisbet, B. W. 1992, Towards a structural and tectonic framework for the central Norseman-Wiluna Greenstone Belt, Western Australia, in *The Archaean: terrains, processes and metallogeny*, eds. J. E. Glover & S. E. Ho, Geology Department (Key Centre) & University Extension, University of Western Australia Publication 22, pp 39-49.

Keats, W. 1987, Regional geology of the Kalgoorlie-Boulder gold-mining district, *Geological Survey of Western Australia Report* 21.

O'Beirne, W. R. 1968, The acid porphyries and porphyroid rocks of the Kalgoorlie area, PhD Thesis, University of Western Australia (unpublished).

Swager, C. P., Witt, W. K., Griffin, T. J., Ahmat, A. L., Hunter, W. M., McGoldrick, P. J. & Wyche, S. 1992, Late Archaean granite-greenstones of the Kalgoorlie Terrane, Yilgarn Craton, Western Australia, in *The Archaean: terrains, processes and metallogeny*, eds. J. E. Glover & S. E. Ho, Geology Department (Key Centre) & University Extension, University of Western Australia Publication 22, pp 107-122.

Pre- and post-regional folding, I-type granitoid suites in the southwest Eastern Goldfields Province: an Archaean syn-collisional plutonic event?

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Approximately 40-50% of the southwest Eastern Goldfields Province (SWEGP) is underlain by granitoids. Three broad structural groupings of granitoids are recognised:

- granitoid gneiss,
- pre-regional folding granitoid (pre-RFG) complexes and
- post-regional folding granitoid (post-RFG) plutons.

Post-RFG plutons include syn-tectonic, late-tectonic and post-tectonic examples. The structural characteristics, form and emplacement mechanism of each structural group are described in Witt & Swager (1989) and Witt & Davy (in prep.). The distribution of each group, shown in Fig. 1, is based on field observations combined with evidence from commercially available aeromagnetic data. Limited precise U-Pb in zircon data from the SWEGP and adjacent areas (Hill & others, 1992) suggest emplacement ages of 2685-2690 Ma for pre-RFG complexes and 2660-2665 Ma for peak post-RFG magmatism. However, post-RFG calc-alkaline magmatism continued at least until approximately 2600 Ma. Small, alkaline intrusions are up to several hundred years younger than 2600Ma (Libby, 1989; Johnson & Cooper, 1989). Some granitoid gneiss was probably derived from protoliths with an age ≥2800 Ma (Hill & others, 1992).

Intrusive granitoids can be assigned to one of four pre-RFG, and four post-RFG suites, based on petrographic and chemical characteristics (Table 1). In addition, there are several unassigned post-RFG plutons (for example, the Liberty Granodiorite) which cannot be grouped into any suite. SWEGP granitoids are predominantly monzogranite and granodiorite. Primary mineral assemblages indicate that all granitoid suites were derived from relatively high f_{O_2} magmas (NNO $< f_{O_2} <$ HM) and are comparable to the "magnetite-series" granitoids of Ishihara (1977). Secondary minerals reflect a further increase in f_{O_2} during metamorphic (and deuteric?) recrystallisation. Rounded, relatively mafic microgranitoid xenoliths are a volumetrically minor feature of some pre-RFG suites and some unassigned post-RFG plutons. Structural and textural observations suggest that the xenoliths, and some dykes, crystallised from synplutonic magmas. Although these more mafic magmas mingled with the host granitoid magmas, there was only limited mixing between the two melts (terminology of Frost & Mahood, 1987).

Calc-alkaline granitoids of the SWEGP display I-type petrographic and chemical characteristics, whereas the alkaline plutons of the Gilgarna Suite show affinity to A-type granitoids (Chappell & White, 1992; Eby, 1990). Some examples of Harker variation diagrams for calc-alkaline granitoid suites and unassigned post-RFG plutons are shown in Fig. 2. Chondrite-normalised rare earth element (REE) plots for the Rainbow and Goongarrie Suites, and the Liberty Granodiorite, are steeply fractionated (La/Yb = 35-170) and lack a Eu anomaly. Woolgangie and Bali Suite granitoids have less fractionated curves (La/Yb = 25-110) with a variable negative Eu anomaly. Dairy Suite granitoids have a distinctive concave upward REE curve (La/Yb = 15-20) and a negative Eu anomaly.

Microgranitoid xenoliths and synplutonic dykes have a variable composition, ranging from diorite to quartz monzonite. SiO_2 contents extend from 50% to 68%. Although they contain greater amounts of mafic components (for example, TiO_2, MgO, CaO), the xenoliths are enriched in some incompatible (Ce, Li, Nb, Rb, Th, Y) and volatile (P_2O_5, F) elements, compared with most

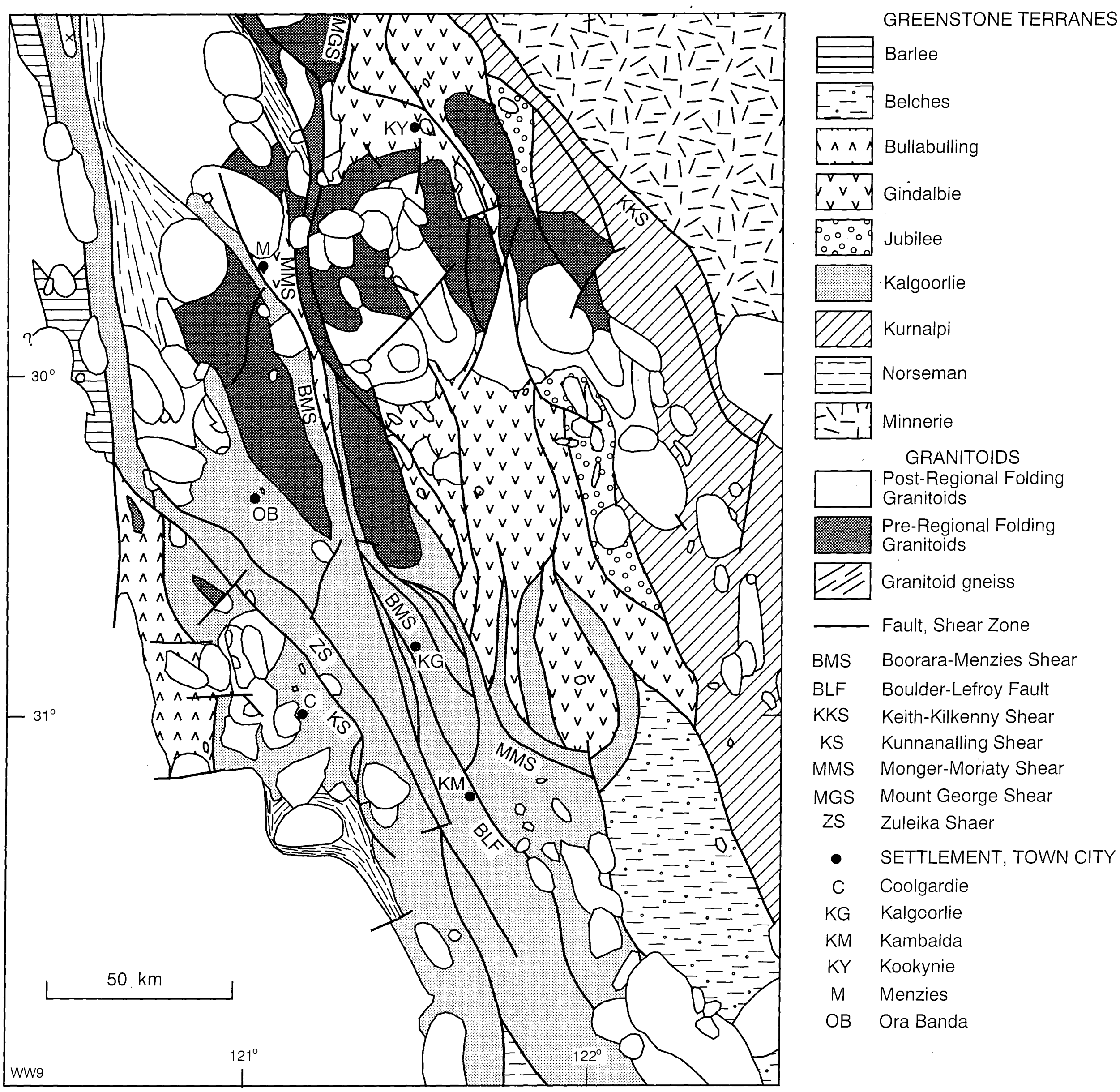

Figure 1 Pre-regional folding granitoids, post-regional folding granitoids and greenstone terranes, Southwest Eastern Goldfields Province

calc-alkaline granitoids in the SWEGP with similar %SiO_2. Chondrite-normalised REE plots for xenoliths are slightly more fractionated than those for the host granitoids (mainly Rainbow Suite and Liberty Granodiorite), and lack a Eu anomaly. The xenoliths have geochemical affinities with other small-volume, enriched, mantle-derived magmas such as appinites and lamprophyres.

Experimental studies (for example, Piwinskii, 1973; Skjerlie & Johnston, 1992) indicate that the granodiorite to monzogranite parent melts for calc-alkaline granitoid suites in the SWEGP were probably derived by partial melting of tonalitic to granodioritic source rocks in the lower crust. Hydrous melting is required to promote consumption of plagioclase, and stabilise residual hornblende (or garnet) in the source (see evidence of chondrite-normalised spidergrams, Table 1). Absence of an Y anomaly in the relatively SiO_2-rich Minyma and Dairy Suite spidergrams can be attributed to a relatively felsic source, lacking hornblende or garnet.

Subsequent fractionation within calc-alkaline suites, and some unassigned post-RFG plutons such as the Liberty Granodiorite was mainly by fractional crystallisation of biotite, plagioclase and apatite (± hornblende, K-feldspar, titanite, magnetite and zircon). Trace element modelling indicates that the Goongarrie Suite is the most fractionated pre-RFG suite (65-70% fractionation), and that the Woolgangie Suite is the most fractionated post-RFG suite (75-90% fractionation). Depletion of compatible trace elements, but only limited enrichment of

Table 1 Summary of main features of granitoid suites in the southwestern Eastern Goldfields Province

Suite	*est. vol. % of granitoids*	*% SiO_2*	*Non-quartzo-feldspathic mineralogy (a)*	*Microgranitoid xenoliths, synplutonic dykes*	*Negative anomalies on chondrite-normalized spidergrams*	*Probable source rock*	*Predominant fractionation mechanism*
Post-regional folding granitoid suites							
Gilgarna	<5	54.0–67.1	Clinopyroxene (Amphibole)	Present		Granulite	Uncertain
Dairy	<5	75.3–76.7	Biotite (Hornblende, muscovite)	Not observed	Nb, Sr?, P, Ti	Monzogranite	Fractional crystallization, contamination (?)
Bali	10	71.9–76.5	Biotite (Muscovite, garnet)	Not observed	Nb, P, Ti, Y	Granodiorite	Fractional crystallization, metasomatism (?)
Woolgangie	50	70.5–75.0	Biotite (Muscovite, garnet)	Not observed	Nb, P, Ti, Y	Granodiorite	Fractional crystallization
Liberty (b)	5	66.4–71.7	Biotite Hornblende	Present	Nb, P, Ti, Y	Tonalite	Fractional crystallization
Pre-regional folding granitoid suites							
Minyma	<5	76.4–77.3	Biotite Hornblende	Not observed	Nb, Sr?, P, Ti	Monzogranite	Fractional crystallization, contamination (?)
Goongarrie	10	71.0–76.5	Biotite	Locally only	Nb, P, Ti, Y	Granodiorite	Fractional crystallization
Twin Hills	10	71.3–75.1	Biotite	Present	Nb, P, Ti, Y	Granodiorite	Fractional crystallization
Rainbow	10	66.1–71.3	Biotite Hornblende (Clinopyroxene)	Relatively common	Nb, P, Ti, Y	Tonalite	Fractional crystallization

(a) Brackets indicate mineral is present (generally in minor amounts) in some samples only

(b) The Liberty Granodiorite is described as a representative of the unassigned post-RFG plutons

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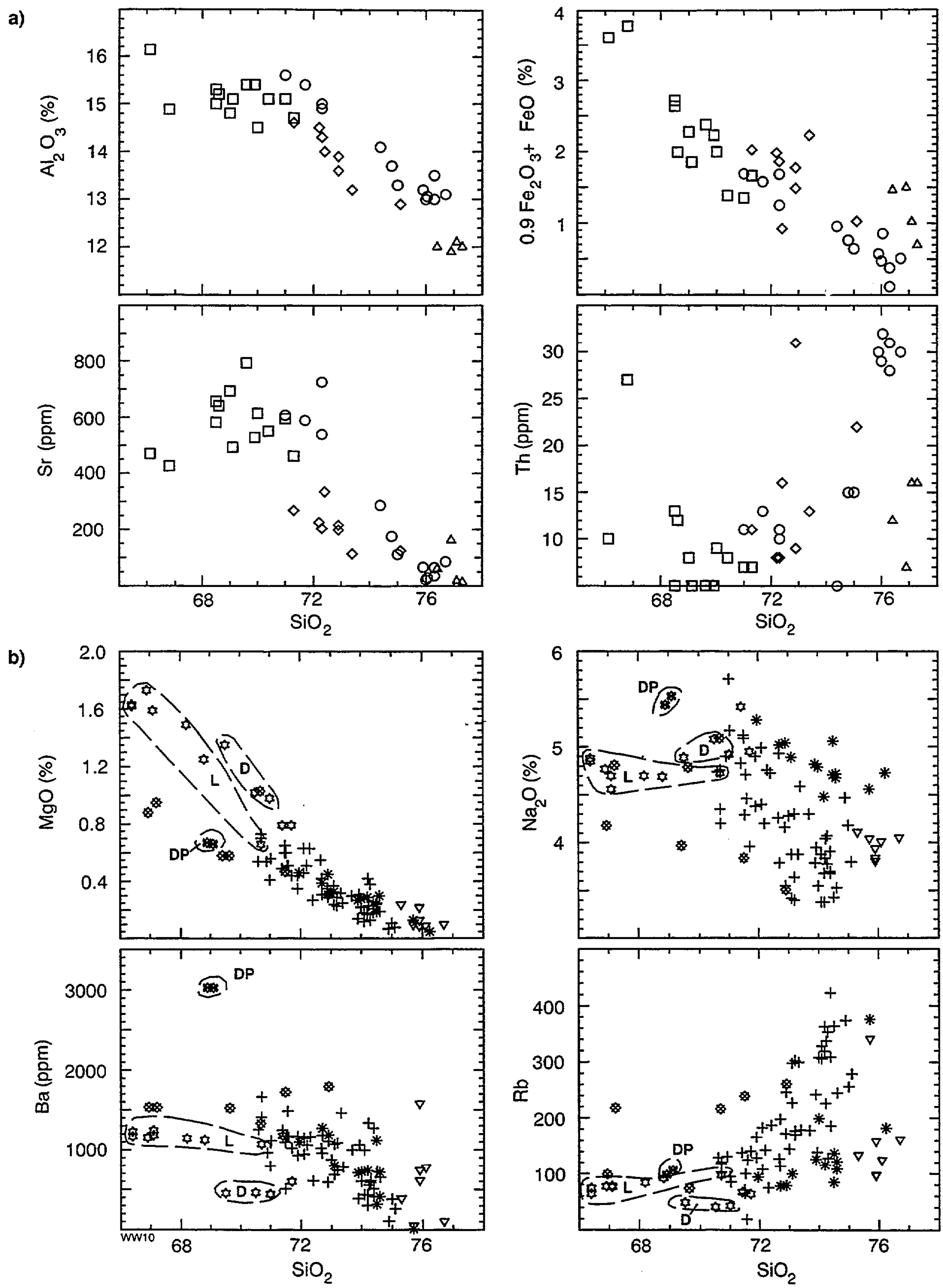

Figure 2a Harker variation diagrams, pre-RFG suites. □ Rainbow, ◇Twin Hills, ○Goongarrie, △Minyma.

Figure 2b Harker variation diagrams, post-RFG suites. +Woolgangie, ✱ Bali, ▽ Dairy.
Unassigned plutons are ✡Liberty Granodionite (L), Doyle Granodiorite (D), Bonnievale Tonalite and Kambalda Trondhemite, ✡Depot Granodiorite (DP),and ⊛ other unassigned post-RFG plutons.

incompatible trace elements, suggests (<40% fractional crystallisation for the Rainbow and Twin Hills Suites and Liberty Granodiorite.

Data for the Minyma and Dairy Suites cluster, or else define subvertical arrays, at high SiO_2 values on Harker variation diagrams. The subvertical arrays cannot be attributed to fractional crystallisation alone because there is a decoupling of elements (for example, Ni and Cr) which are normally considered compatible in high-SiO_2 melts). Although the origin of compositional variation within these suites is not clear, available data are consistent with a combination of fractional crystallisation and contamination by granitoid gneiss and greenstones. Supporting evidence for contamination includes the presence of abundant greenstone xenoliths in some Dairy Suite granitoids, the presence of coarse clots of ferromagnesian minerals which may represent incompletely digested mafic contaminants in the Minyma Suite, and relatively low f_{O2} for both suites (f_{O2} <TMQA). Although most suites appear to have preserved original igneous trends, some metasomatic modification of Bali Suite compositions may have occurred during regional metamorphism. These granitoids lie at the centre of a large-scale synmetamorphic hydrothermal system (Witt, 1991). They are petrographically similar to Woolgangie Suite granitoids but are relatively enriched in Na_2O and Sr, and relatively depleted in elements (K_2O, Rb, Th, U) which are concentrated in synmetamorphic gold deposits in the SWEGP.

Calc-alkaline granitoids in the SWEGP were emplaced during a period of regional shortening and crustal thickening, commonly as broadly conformable sheets and diapirs, are temporally associated with regional low pressure metamorphism, and contemporaneous felsic volcanic rocks are rare to absent. They therefore display regional similarities with the Hercyno-type granitoids of Pitcher (1987) which were formed during continental collision. Unlike Hercyno-type granitoid terranes, S-type granitoids are absent in the SWEGP. SWEGP granitoids are compositionally similar to Caledonian granitoids but have different regional and temporal relationships with respect to orogeny. The observations are interpreted to reflect a collision setting for SWEGP granitoids. The absence of S-type granitoids is attributed to an absence of large sedimentary accumulations in the lower crust at 2700-2600Ma, and compositional similarity with Caledonian granitoids probably reflects a similar igneous crustal source in both cases. A-type granitoids of the Gilgarna Suite may have been derived by anhydrous melting of depleted igneous source rocks during uplift related to cratonic stabilisation.

References

Chappell, B.W. & White, A.J.R. 1992, I- and S-type granites in the Lachlan Fold Belt, *Transactions of the Royal Society of Edinburgh*, 83, pp 1-26.

Eby, G.N. 1990, The A-type granitoids: a review of their occurrence and chemical characteristics and speculation on their petrogenesis, *Lithos*, 26, pp. 115-145.

Frost, T.P. & Mahood, G.A. 1987, Field, chemical and physical constraints on mafic-felsic magma interaction in the Lamarck Granodiorite, Sierra Nevada, California, *Geological Society of America Bulletin*, 99, pp 272-291.

Hill, R.I., Chappell, B.W. & Campbell, I.H. 1992, Late Archaean granites of the southeastern Yilgarn Block, Western Australia: age, geochemistry and origin, *Transactions of the Royal Society of Edinburgh*, 83, pp 211-226.

Ishihara, S. 1977, The magnetite-series and ilmenite-series granitic rocks, *Mining Geology*, 27, 293-305.

Johnson, G.I. & Cooper, J.A. 1989, Rb-Sr whole-rock and mineral dating of Gilgarna Rock syenite, Yilgarn Block, Western Australia, *Australian Journal of Earth Sciences*, 36, 472-474.

Libby, W.G. 1989, Chemistry of plutonic felsic rocks in the Eastern Goldfields, Western Australia, *Western Australia Geological Survey Report* 26, pp 83-104.

Pitcher, W.S. 1987, Granites and yet more granites forty years on, *Geologische Rundschau*, 76, pp 51-79.

Piwinskii, A.J. 1973, Experimental studies of igneous rock series, central Sierra Nevada batholith, California: Part II, *Neues Jahrbuch für Mineralogie*, 5, pp 193-215.

Skjerlie, K.P. & Johnston, A.D. 1992, Vapour-absent melting at 10 kbar of a biotite- and amphibole-bearing tonalitic gneiss: Implications for the generation of A-type granites, *Geology*, 20, pp 263-266.

Witt, W.K. 1991, Regional metamorphic controls on alteration assemblages associated with gold mineralisation in the Eastern Goldfields Province, Western Australia: Implications for the timing and origin of Archean lode-gold deposits, *Geology*, 19, pp 982-985.

Witt, W.K. & Swager, C.P. 1989, Structural setting and geochemistry of Archaean I-type granites in the Bardoc-Coolgardie area of the Norseman-Wiluna belt, Western Australia, *Precambrian Research*, 44, pp 323-351.

Witt, W.K. & Davy, R. in prep, Geology and geochemistry of granitoid rocks in the southwest Eastern Goldfields Province, *Western Australian Geological Survey of Western Australia Report*.

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Geochemistry of granitoids of the Leonora–Laverton region, Eastern Goldfields Province

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Although the granitoids[1] of the Archaean Yilgarn craton comprise two-thirds of the present exposure they remain relatively poorly studied geochemically, particularly in comparison to the more strongly mineralised greenstone belts. As part of the National Geoscience Mapping Accord, the Australian Geological Survey Organisation (AGSO) is currently remapping portions of the Eastern Goldfields Province (EGP). Concurrent with this work, studies of the granitoids have been undertaken to ascertain their distribution and composition, and to investigate their petrogenesis. This paper presents the initial results of that study, focussing on the Leonora–Laverton area, which extends from the eastern part of the Southern Cross Province to the northeastern EGP.

Granitoid Classification

Granitoid classification in the EGP has commonly been based on structural characteristics (Bettenay, 1977; Witt & Swager, 1989) and granitoid relationships to greenstone belts (Sofoulis, 1963; Perring & others, 1989). In this work, the granitoids and gneisses have been grouped into six groups using both structural and geochemical criteria. In possible order of intrusion these are:

- 1. Pre-folding
  - a – banded gneisses
  - b – pre-folding granitoids
- 2. Mafic granitoids
  - a – pre-folding
  - b – post-folding
- 3. HFSE-enriched granites
- 4. High-Ca post-folding granitoids
- 5. Low-Ca post-folding granitoids
- 6. Syenites (post-folding)

As the gneisses and the pre-folding granitoids are geochemically similar and appear to be of similar age (see below) they are treated here as one, pre-folding, group. With the possible exception of the syenites, all the granitoids studied appear to be I-types.

Field relations and petrography

Group 1 – Pre-folding granitoids

Pre-folding granitoids comprise an areally extensive part of the region. They are distinguished from other granitoids by the presence of gneissic layering and/or a strong foliation and commonly contain concordant zones of amphibolite and microgranitoid. The gneisses range from relatively homogeneous to strongly layered, and are locally migmatitic, with original igneous features largely absent. Original textures in the granitoids vary from porphyritic to equigranular, subhedral to anhedral granular. Deformational (and metamorphic) effects are evident in the development of lepidoblastic and granoblastic textures. The rocks range from biotite-rich trondhjemite[2] to biotite leucogranodiorite and granite. They contain locally abundant pegmatite and aplite veins which both parallel and cross-cut the foliation.

Group 2 – Mafic granitoids

This group includes the Lawlers Tonalite and other bodies that crop out adjacent to or within the greenstone belts. It is similar to Group 2 of Wyborn (1993), and to associations 1 and 2 of

[1] i.e. the granites, gneisses and migmatites. In this work the term granitoids, unless specifically stated otherwise, is used to denote igneous rocks of quartz diorite to granite composition.

[2] All igneous rock classifications are based on normative compositions (Barker, 1979) and on estimated modal compositions from thin sections.

Cassidy & others (1991). As noted by those authors, these granitoids are commonly more mafic (50-76% SiO_2) than those of the other groups (Fig. 1). They range in composition from hornblende-biotite quartz diorite to tonalite, granodiorite and granite, and appear to pre-date and post-date regional folding. These granitoids are discussed in detail by Foden & others (1984), Perring & others (1989), Witt & Swager (1989), and Cassidy & others (1991).

Group 3 – HFSE-enriched granites

This group is equivalent to the high-field strength elements (HFSE)-enriched syenogranites and rhyolitic volcanics described by Hallberg (1985) and Hallberg & Giles (1986) that crop out in the Keith–Kilkenny high strain zone. It has also been described by Perring & others (1989) and Cassidy & others (1991) as part of their Association 3. Granitoids of this group comprise grey and pink biotite granite and microgranite with porphyritic to seriate, subhedral to anhedral, granular to irregular granoblastic textures. Aplite, microgranite and rare pegmatite dykes are locally present.

Groups 4 & 5 – High-Ca and Low-Ca post-folding groups

These granitoids are characterised by their general lack of foliation, although a weak foliation is present locally. Both groups are petrographically similar, but the high-Ca group comprises sodic biotite granodiorite, trondhjemite and granite, whereas the low-Ca group is dominantly granite (syeno- and monzogranite). In particular the fluorite-bearing granites (e.g., Mt Boreas granite) commonly belong to the latter group. In addition, the low-Ca granites have high radiometric total counts (900-2800 counts per second), typically higher than the high-Ca granitoids (300-1400 counts per second). The post-folding granitoids appear to dominate in outcrops in the Leonora–Laverton region, finer grained varieties being particularly well represented. Textures vary from porphyritic to equigranular, and subhedral granular to irregular granoblastic. Microgranite, aplite and pegmatite dykes and patches are locally very abundant. The high-Ca and low-Ca groups are synonymous with the post-kinematic and fractionated leuco-adamellite groups, respectively, of Bettenay (1977). The low-Ca group is apparently not as common to the south as it is in the Leonora–Laverton region.

Group 6 – Syenites

These comprise a few typically small, late intrusions of pyroxene and/or amphibole syenite and quartz syenite that commonly appear to lie along lineaments (Libby, 1978). This group is equivalent to the alkali suite of Libby (1978), part of Association 3 of Cassidy & others (1991), and the Gilgarna suite of Witt & Davy (this volume).

Geochronological data

There are few reliable isotopic ages for granitoids in the EGP, although various dating techniques (Pb-Pb, Rb-Sr) have constrained ages to the period 2700 to 2600 Ma (see McNaughton & Dahl, 1987). Recent U-Pb zircon dating, largely in the Kalgoorlie–Norseman region (e.g., Hill & others, 1992), suggests that the majority of exposed granitoids in that area were emplaced in two periods (2690-2685 Ma and 2665-2660 Ma), with minor? magmatism continuing until 2600 Ma and younger. If this temporal framework applies to the northern EGP, then the pre-folding granitoids belong to the older age group, mafic granitoids probably include both ages, and the post-folding groups, including the HFSE-enriched granites, have ages of 2665 Ma and possibly younger. Recent U-Pb zircon dating of gneisses in the Leonora area (L.P. Black, pers. comm.) indicate ages of about 2685 Ma, identical to those of the older granites.

Geochemistry

Group 1 – Pre-folding group

The gneisses and granitoids of this group span a relatively narrow compositional range (68 to 76% SiO_2, Fig. 1), but exhibit significant heterogeneity with regard to most elements, especially the large-ion lithophile elements (LILE). They have high Al_2O_3 (greater than 15% at 70% SiO_2, see Barker, 1979), moderate to high Na_2O (5.2 to 4.0%), and moderate K_2O (commonly 1.5 to 4%), Rb, Pb, Th, and U (Table 1, Fig. 1). The Aluminium Saturation Index (ASI)[3] ranges from 0.98 to 1.07. The majority are Y (and, by analogy, heavy rare-earth element (HREE)) depleted, with Y typically less than 12 ppm (Fig. 1), the one main exception being a pluton in the Kookynie region which has higher Y (20 ppm, and marginally lower Sr). The granitoids show variable LREE enrichment (Ce 20-100 ppm, Fig. 1) and most have strongly fractionated REE patterns ($(Ce/Y)_N$[4] 10-60). Sr is relatively high (700-

[3] ASI = molecular $Al_2O_3/(CaO - 3.3P_2O_5 + Na_2O + K_2O)$

4 $(Ce/Y)_N$ = primordial mantle-normalised Ce divided by normalised Y

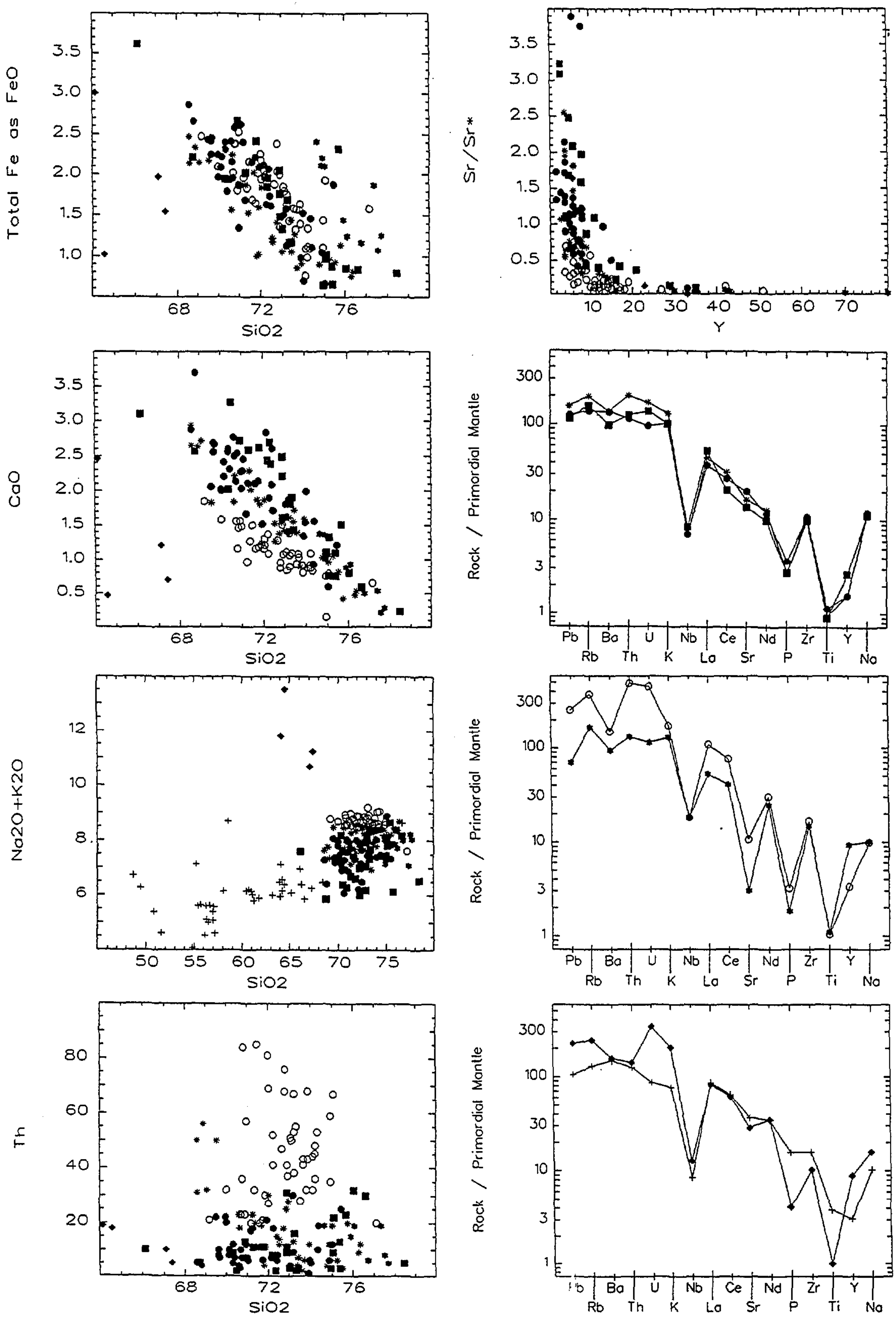

Fig. 1. Variation diagrams and multi-element primordial-mantle-normalised abundance diagrams for granitoids of the Leonora-Laverton region (normalizing values from Sun & McDonough, 1989, and Na = 2890 ppm). Multi-element abundance diagrams are for averages of granitoid groups (as listed in Table 1). Gneisses, Group 1 (pre-folding)–filled circles; Granitoids, Group 1–filled squares; Group 2 (mafic granitoids)–crosses; Group 3 (HFSE-enriched granitoids)–filled stars; Group 4 (high-Ca)–asterisks; Group 5 (low-Ca)–open circles; Group 6 (syenites)–filled diamonds. (Most geochemical data from AGSO, unpublished; additional data from Bettenay, 1977; Cassidy, 1992; Witt, unpublished.)

100 ppm) and overall the group is Sr undepleted, although Sr/Sr*[5] shows considerable variation (0.4 to 2.0, up to 4) (Fig. 1). Like most granitic rocks, all gneisses and granitoids are Nb depleted (Fig. 1). No obvious regional differences are evident, although local geochemical variations are apparent and several distinct suites have been recognised by Witt & Davy (this volume).

Group 3 – HFSE-enriched granites

The HFSE-enriched internal granites are very felsic (75-77% SiO_2), with low Al_2O_3 and high K_2O similar to the low-Ca group, but with CaO similar to the high-Ca group (Fig. 1). For a given SiO_2 content, they are significantly higher in TiO_2, total FeO and MgO than all other EGP granitoids and are characterised by high Y, Zr and Ce (Table 1, Fig. 1). However, Rb, Th and Pb tend to be low (Fig. 1). The granites of this group are Sr-depleted (Fig. 1) with Sr/Sr* ratios less than 0.3.

Group 4 – High-Ca post-folding granitoids

The high-Ca granitoids have a similar range of SiO_2 (68 to 76%, Fig. 1), and overlap geochemically with the more potassic members of the pre-folding group, namely moderate to high Al_2O_3, Na_2O (4-5%), K_2O (commonly between 2.5 to 5%) and LILE contents (Table 1, Fig. 1). ASI values, and most element trends are also similar to the pre-folding group (Fig. 1), although Ba, Sr, Zr, and Ce (LREE) show better defined negative correlations with SiO_2. $(Ce/Y)_N$ ranges from 5 to 70, typically decreasing with increasing SiO_2. The high-Ca granitoids have similar Y and Sr to the pre-folding group, and are Y-depleted and Sr-undepleted. Sr/Sr* ratios are highly variable (0.2 to 2.1), with the lower values probably resulting from some degree of plagioclase fractionation.

Group 5 – Low-Ca post-folding granites

The granites of this group (70-76% SiO_2, Fig. 1) are geochemically distinct from all other granitoids in the region. For a given SiO_2 content, they have lower Al_2O_3, CaO, and Na_2O (<4.0%) and higher total FeO and K_2O (<4.0%) (Table 1, Fig. 1). The most notable differences are in the trace elements, particularly the LILE and HFSE. Rb, Th, U, and Pb are distinctly higher (Table 1, Fig. 1), whilst Zr, La, Ce, Nd, Y are higher in the more mafic rocks. Systematic variations in Sr/Sr*, Rb/Sr and K/Rb, the latter decreasing to around 100-150, suggest that crystal fractionation was significantly more important than in the pre-folding and high-Ca post-folding granitoids. Moreover, Rb, Th, Nb, Pb, Ga/Al and Y increase with SiO_2, consistent with trends in fractionated I-type granites elsewhere (e.g. Champion & Chappell, 1992). Unlike most other EGP granitoids, many low-Ca granites contain moderate to high Y (10-40 ppm, Fig. 1) and Ce (up to 300 ppm); $(Ce/Y)_N$ ratios are, however, similar to those of the high-Ca granitoids. The low-Ca granitoids are also characterised by relatively low Sr (mostly <300 ppm) and low Sr/Sr* ratios (mostly <0.3).

Group 6 – Syenites

The syenites are relatively mafic (62-68% SiO_2) and are clearly distinguished from other EGP granitoids by their high total alkalis (11%, Fig. 1) (see Libby, 1978). Other geochemical differences include, for a given SiO_2 content, higher K_2O, Y, and lower TiO_2, total FeO, MgO, CaO, P_2O_5, and V. Notably, the syenites have variable Nb, Y, and Zr contents and Ga/Al ratios ranging from similar to much higher than other EGP granitoids and hence exhibit both I- and A-type features. They range from Sr undepleted to depleted and show marked Nb depletion (Fig. 1).

Petrogenesis

Groups 1 & 4 – Pre-folding granitoids, and high-Ca post-folding granitoids

The marked compositional similarities of these granitoid groups argues strongly for a similar origin. In particular, their Y (and HREE) depletion and overall lack of Sr depletion indicate an ultimate derivation from a plagioclase-poor (i.e., in effect a mafic) source. Experimental studies (Beard & Lofgren, 1991; Rapp & others, 1991) suggest that dehydration melting of mafic rocks at pressures high enough to stabilise residual garnet and pyroxene (i.e., eclogite facies) is most likely to produce slightly peraluminous or metaluminous tonalitic to trondhjemitic melts, i.e. granitoids essentially similar to those in the EGP. However, as discussed by Wyborn (1993), such granitoids can also be produced by inheriting these features through melting of pre-existing felsic crust. This process is favoured for many of the EGP granitoids as it can explain the presence of inherited zircons (Hill & others, 1992). However, melting of such a source would inevitably have led to marked Sr depletion due to residual plagioclase, unless near-complete remobilisation ("remagmatisation" of Chappell & Stephens, 1988)

[5] Sr/Sr* = primodial mantle-normalised Sr abundance divided by the interpolated value obtained by averaging the normalised Ce and Nd, i.e., equivalent to the Sr anomaly on the multi-element diagrams (Fig. 1).

Table 1. Averages of gneiss and granitoid groups in the Leonora–Laverton region

	A	B	C	D	E	F	G	H
SiO_2	72.25	71.64	73.20	72.52	72.80	75.03	65.80	60.98
TiO_2	0.22	0.24	0.19	0.20	0.22	0.23	0.21	0.81
Al_2O_3	14.59	14.90	14.10	14.50	13.87	12.56	17.08	15.44
Fe_2O_3	0.61	0.59	0.62	0.61	0.72	0.72	1.47	2.13
FeO	1.26	1.38	1.09	0.92	1.10	1.45	0.56	2.91
MnO	0.03	0.03	0.03	0.02	0.03	0.03	0.15	0.08
MgO	0.50	0.54	0.44	0.40	0.32	0.25	0.51	2.79
CaO	2.00	2.09	1.87	1.60	1.10	1.07	1.21	4.97
Na_2O	4.58	4.68	4.43	4.41	3.88	3.96	6.18	4.01
K_2O	2.81	2.83	2.80	3.59	4.79	3.54	5.64	2.13
P_2O_5	0.07	0.08	0.06	0.06	0.07	0.04	0.09	0.34
Ba	824	920	676	932	1028	648	1077	1018
Rb	90.5	85.5	98	123	234	105	153	81.5
Sr	367	419	287	343	223	63	595	767
Pb	24	25	23	31	51	14	45	21
Th	11	10.5	11.5	18.5	45	12	13	11.5
U	2.4	2.1	3	3.7	9.9	2.5	7.5	1.9
Zr	116	120	110	123	186	165	113	174
Nb	5.5	5	6	5	13	13	9	6
Y	9	7	12	7	15	42	40	14
La	24.3	26.7	19.4	31.7	76.6	37.2	57.8	60.9
Ce	45.8	49.6	37.6	58.1	138.9	74.1	111.5	117.4
Nd	15.1	15.9	13.4	17.4	40.6	33.3	46.7	46.3
Sc	4	4	4	3	3	5	5	13
V	19	21	16	14	12	10	22	101
Ni	6	6	6	6	5	5	5	32
Cu	7	6	9	10	5	4	6	25
Zn	37	40	32	37	44	32	51	81
Ga	19.4	20.2	18	19.7	20.8	15.9	21.5	20.3
K/Rb	258	275	237	242	170	280	306	217
Sr/Sr*	0.96	1.02	0.90	0.73	0.20	0.09	0.59	0.74
$(Ce/Y)_N$	12.7	17.7	7.8	20.8	23.2	4.1	7.0	21.0

A – average of Group 1 (pre-folding group), 69 samples
B – average of Group 1 gneisses, 42 samples
C – average of Group 1 granitoids, 27 samples
D – average of Group 4 (high-Ca post-folding granitoids), 34 samples
E – average of Group 5 (low-Ca post-folding granitoids), 45 samples
F – average of Group 3 (HFSE-enriched granitoids), 10 samples
G – average of Group 6 (syenites), 4 samples.
H – average of Group 2 (mafic granitoids), 41 samples.
K/Rb, Sr/Sr* and $(Ce/Y)_N$ ratios calculated from averages. (Most geochemical data from AGSO, unpublished; additional geochemical data from Bettenay, 1977; Cassidy, 1992; Witt, unpublished.)

occurred. It is difficult to reconcile the postulated andesitic primitive crust of Hill & others (1989) with this model, because melting of Q-normative andesite at lower crustal depths (even 40-50km or ~15kb) would still involve residual plagioclase (Laan & Wyllie, 1992). Remagmatisation of andesitic source rocks would clearly produce much less siliceous melts than was actually the case. Moreover, seismic data suggest a predominantly felsic crust with subordinate mafic layers rather than a uniform intermediate or mafic lower crust (Drummond & others, 1993).

The best candidate for the protolith of these granitoids would be one of tonalitic to granodioritic composition, i.e., similar to the typical Archaean TTG (tonalite-trondhjemite-granodiorite) granitoids elsewhere, as suggested by Bettenay (1977). It is likely that a limited degree of melt segregation occurred to explain the rather more potassic compositions of the granitoids compared to most Archaean TTG terranes, unless an unusually enriched source was involved, or the compositional differences reflect a vertical zonation of the crust (many TTG terranes are relatively high grade). The highly variable Sr/Sr^* of the EGP granitoids probably also reflects partial separation of melt from restite-rich material, which is supported by a positive correlation between Sr/Sr^* and K/Rb. There are small decreases in Sr/Sr^* and K/Rb and an increase in Rb/Sr from average gneiss, through pre-folding granitoid to high-Ca post-folding granitoid. The lack of correlation between Sr/Sr^* and SiO_2 implies that the source was not much less siliceous than the granitoids (see also Bettenay, 1977), although more mafic intrusives, like the Lawlers Tonalite, clearly require a more mafic source. The scope for at least some degree of melt segregation would be increased if the primary felsic crust had an overall positive Sr anomaly: model calculations show that melts in equilibrium with residual garnet + clinopyroxene (± a LREE-rich minor phase) would have Sr/Sr^* to 1.7, or more. Positive Sr anomalies are, in fact, quite common in Archaean TTG terranes, as well as Phanerozoic subduction-related and other granitiods (e.g., Silver & Chappell, 1988).

Groups 3 & 5 – Low-Ca and HFSE-enriched granitoids

These are more typical of I-type granitoids produced by intracrustal melting, which show marked Sr depletion. The trace element compositions of the average low-Ca granitoid can be quite accurately modelled by batch melting calculations assuming anatexis of the average felsic gneiss. The results are relatively insensitive to the types of residual mafic phases assumed, which are fairly minor (<7%), although significant hornblende or garnet would result in greater Y-depletion. The Low-Ca group shows evidence for more extensive fractional crystallisation than the other major granitoid groups: marked decreases in K/Rb, Ce/Y, and Sr/Sr^* and increases in Rb and Y with increasing SiO_2. Similar granitoids elsewhere are known to be associated with mineralisation. The HFSE-rich granitoids appear to have been derived from a different source to the low-Ca granitoids.

Tectonic setting

The tectonic setting under which new felsic crust was generated in the Archaean is still controversial. A mafic ("oceanic-crustal") source seems inescapable, but whether modern-type subduction or some other process was involved is uncertain. Subduction of oceanic crust would certainly seem to be the most efficient way of producing voluminous granitoids, such as those of the EGP, relatively quickly, and would be consistent with the observed Nb depletion in the granitoids, which is characteristic of subduction-related magmatism. If Archaean subduction involved dehydration melting, rather than simply dehydration, of the slab (Arculus & Ruff, 1990), then primary melts would be felsic and of similar composition to typical Archaean TTG granitoids (Martin, 1986; Drummond & Defant, 1990). The age of this earlier crust can be constrained by the inherited zircons and Sm-Nd isotope systematics of the granitoids, particularly given that the postulated TTG precursors would also have high La/Yb ratios. Sm-Nd depleted mantle model ages for granitoids are about 2.8 to 3.0 Ga (D. Champion, unpublished data), consistent with many, but not all, inherited zircon ages (Hill & others, 1992).

Generation of the original felsic crust in the EGP by a process as outlined above is consistent with later mantle plume activity as postulated by Archibald & others (1978) and Hill & others (1992). Subduction-related continental accretion over two-three hundred million years may have been followed between about 2700 and 2660 Ma by widespread crustal remobilisation related to plume activity. This involved emplacement of gneiss domes and younger granitoids in an extensional environment (Williams & Whitaker, 1993), as well as basaltic and komatiitic magmatism. Some addition of new felsic crust (e.g., the internal mafic granitoids?), perhaps derived by melting of a mafic crustal underplate, may also have occurred during this period, although there is no geophysical evidence for the existence of such an underplate at the present time. Crustal thickness at that time was almost certainly insufficient to allow partial melting of older felsic crust without significant residual plagioclase. Such melting resulted either in large-scale remobilisation or, with more extensive melt segregation, granitoids like the low-Ca group. Much more isotopic data will be required before the timing and mechanism of felsic crust generation in the EGP can be estimated with any precision.

References

Archibald, N.J, Bettenay, L.F, Binns, R.A., Groves, D.I. & Gunthorpe, R.J. 1978, The evolution of Archaean greenstone terrains, Eastern Goldfields Province, Western Australia, *Precambrian Research*, 6, 103-131.

Arculus, R.J. & Ruff, L.J. 1990, Genesis of continental crust: evidence from island arcs, granulites, and exospheric processes, in *Granulites and Crustal Evolution*, eds. D. Vielzeuf & Ph. Vidal, Kluwer Academic Publishers, pp 7-23.

Barker, F. 1979, Trondhjemite: definition, environment and hypotheses of origin, in *Trondhjemites, Dacites, and Related Rocks*, ed. F. Barker, Elsevier, Amsterdam, 1-12.

Beard, J.S. & Lofgren, G.E. 1991, Dehydration melting and water-saturated melting of basaltic and andesitic greenstones and amphibolites at 1, 3, and 6.9 kb, *Journal of Petrology*, 32, 365-401.

Bettenay, L.F. 1977, *Regional geology and petrogenesis of Archaean granitoids in the southeastern Yilgarn Block*, Ph.D. thesis, University of Western Australia.

Cassidy, K.F. 1992, *Archaean granitoid-hosted gold deposits in greenschist to amphibolite terrains: a high-PT depositional continuum equivalent to the greenstone-hosted deposits*, Ph.D. thesis, University of Western Australia.

Cassidy, K.F., Barley, M.E., Groves, D.I., Perring, C.S. & Hallberg, J.A. 1991, An overview of the nature, distribution and inferred tectonic setting of granitoids of the late-Archaean Norseman-Wiluna Belt, *Precambrian Research*, 51-83

Champion, D.C. & Chappell, B.W. 1992, Petrogenesis of felsic I-type granites: an example from northern Queensland, *Transactions of the Royal Socity of Edinburgh, Earth Sciences*, 83, 115-126.

Chappell, B.W. & Stephens, W.E. 1988, Origin of infracrustal (I-type) granite magmas, *Transactions of the Royal Socity of Edinburgh, Earth Sciences*, 79, 71-86.

Drummond, B.J., Goleby, B.R., Swager, C.P. & Williams, P.R. 1993, Constraints on Archaean crustal composition and structure provided by deep seismic sounding in the Yilgarn Block, *Ore Geology Reviews*, 8, 117-124.

Drummond, M.S. & Defant, M.J. 1990, A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons, *Journal of Geophysical Research*, 95, 21503-21521.

Foden, J.D., Nesbitt, R.W. & Rutland, R.W.R. 1984, The geochemistry and crustal origin of the Archaean acid intrusives of the Agnew Dome, Lawlers, Western Australia, *Precambrian Research*, 23, 247-271.

Hallberg, J.A. 1985, *Geology and mineral deposits of the Leonora - Laverton area, northeastern Yilgarn Block Western Austalia*, Hesperian Press, Perth.

Hallberg, J.A. & Giles, C.W. 1986, Archaean felsic volcanicsm in the northeastern Yilgarn Block, Western Australia, *Australian Journal of Earth Sciences, 33*, 413-427.

Hill, R.I., Campbell, I.H. & Compston, W. 1989, Age and origin of granitic rocks in the Kalgoorlie-Norseman region of Western Australia: Implications for the origin of Archaean crust. *Geochimica et Cosmochimica Acta*, 53, 1259-1275.

Hill, R.I., Chappell, B.W. & Campbell, I.H. 1992, Late Archaean granites of the southeastern Yilgarn Block, Western Australia: age, geochemistry, and origin, *Transactions of the Royal Socity of Edinburgh, Earth Sciences*, 83, 211-226.

Laan, S.R. van der & Wyllie, P.J. 1992, Constraints on Archaean trondhjemite genesis from hydrous crystallisation experiments on Nuk gneiss at 10-17 kbar, *Journal of Geology*, 100, 57-68.

Libby, W.G. 1978, The felsic alkaline rocks, *Geological Survey of Western Australia Report* 9, 111-137.

McNaughton, N.J. & Dahl, N. 1987, A geochronological framework for gold mineralization in the Yilgarn Block, Western Australia, in *Recent Advances in Understanding Precambrian Gold Deposits*, ed. S.E. Ho & D.I. Grove, Geology Department & University Extension, University of Western Australia, Publication 11, 29-50.

Perring, C.S., Barley, M.E., Cassidy, K.F., Groves, D.I., McNaughton, N.J., Rock, N.M.S., Bettenay, L.F., Golding, S.D. & Hallberg, J.A. 1989, The association of linear orogenic belts, mantle-crustal magmatism, and Archean gold mineralization in the Eastern Yilgarn Block of Western Australia, in *The Geology of Gold Deposits: The Perspective in 1988*, eds. R.R. Keays, W.R.H. Ramsay & Groves, D.I., Economic Geology Monograph 6, 571-584.

Rapp, P.R., Watson, E.B. & Miller, C.F. 1991, Partial melting of amphibolite/eclogite and the origin of Archaean trondhjemites and tonalites. *Precambrian Research*, 51, 1-25.

Silver, L.T. & Chappell, B.W. 1988, The Peninsular Ranges Batholith: an insight into the evolution of thé Cordilleran batholiths of southwestern North America, *Transactions of the Royal Socity of Edinburgh, Earth Sciences*, 79, 105-121.

Sofoulis, J. 1963, *Boorabin 1:250 000 geological se-*

ries. *Geological Survey of Western Australia, Explanatory Notes, SH/15-13*, Geological Survey of Western Austalia.

Sun, S.-S. & McDonough, W.F. 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes, in *Magmatism in the Ocean Basins*, eds. A.D. Saunders & M.J. Norry, Geological Society of London, Special Publication, 42, 313-345.

Williams, P.R. & Whitaker, A.J. 1993, Gneiss domes amd extensional deformation in the Archaean Eastern Goldfields Province, Western Australia, *Ore Geology Reviews*, 8, 141-162.

Witt, W.K. & Davy, R. 1993, Pre- and post-regional folding, I-type granitoid suites in the southwest Eastern Goldfields Province: An Archaean syn-collisional plutonic event?, this volume.

Witt, W.K. & Swager, C.P. 1989, Structural setting and geochemistry of Archaean I-type granites in the Bardoc-Coolgardie area of the Norseman-Wiluna Belt, Western Austaralia, *Precambrian Research*, 41, 323-351.

Wyborn, L.A.I. 1993, Constraints on interpretations of lower crustal structure, tectonic setting and metallogeny of the Eastern Goldfields and Southern Cross Provinces provided by granite geochemistry, *Ore Geology Reviews*, 8, 125-140.

Implications of zircon dates for the age of granite rocks in the Eastern Goldfields Province

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Granitoids, ranging in age between 2685 Ma and 2640 Ma are found throughout the Yilgarn Block and make up as much as 70% of the upper crust in this region (Bettenay, 1977; Archibald & others, 1981). The available evidence suggests that the age distribution is bimodal in the Eastern Goldfields with peaks at 2685 and 2665 Ma (Campbell & Hill, 1988; Hill & others, 1989). The older suite are generally granodiorites and they are synchronous with the felsic volcanics that dominate the upper stratigraphy of the greenstone successions. The younger suite are richer in K than the older suite and are generally granitic in character.

Both the granitoids and the felsic volcanics contain xenocrystic zircons that range in age between 2.8 Ga and 3.4 Ga (Campbell & Hill, 1988). These xenocrystic zircons are believed to date the proto-crust that melted to form the 2690 to 2685 Ma felsic magma. Xenocrystic zircons of these ages are also found in the hanging wall basalts at Kambalda and they provide clear evidence that the mafic magmas erupted through an older sialic (continental) crust (Compston & others, 1986).

The age of gold mineralisation can be constrained by dating lithologies cut by mineralisation and by dating rocks, usually pegmatite dykes, that are seen to cross-cut mineralisation. Gold mineralisation cuts rocks having a variety of ages (Table 1) ranging from a 2714 ± 5 Ma-old gabbro at Norseman to 2667 ± 4 and 2665 ± 4 Ma-old granites at Porphyry and Granny Smith, respectively. However, the only minimum age we have for gold mineralisation is from the Southern Cross Province, where mineralisation at Westonia predates intrusion of a 2637 ± 7 Ma granite.

The age of felsic plutons and dykes can also be used to constrain the age of movement on some of the major shears. For example, in the vicinity of Norseman, major activity on the Zuleika Shear postdated eruption of 2688 ± 8 Ma felsic volcanic rocks and predated emplacement of a 2686 ± 6 Ma granodiorite pluton. Similarly, major movement on the Lefroy Fault at the New Celebration mine is constrained to have taken place before 2686 ± 4 Ma. These data indicate that most of the movement on the major NNW-SSE trending faults predated or was synchronous with a regionally important 2690-2685 Ma felsic magmatic event. Certainly at New Celebration, and probably also at Mount Charlotte and the Golden Mile, mineralisation occurred after most of the activity on the major faults had ceased.

Granites from the Murchison show a wider range of ages than those from the Eastern Goldfields with ages varying between 2630 ± 6 and 2756 ± 6 Ma. The oldest granites are small to medium sized massive plutons that intrude the greenstone belts and the youngest are large massive external granite batholiths. Gneisses and other recrystallised granitoids that are also external to the greenstones give intermediate ages.

The old age of the massive internal granitoids, relative to the external gneisses and recrystallised granites was unexpected. Watkins and Hickman (Watkins & Hickman, 1990) and Watkins & others (1991) had previously interpreted the massive internal granitoids as post-deformational intrusions emplaced at a late stage in the event chronology, the main evidence being the absence of the penetrative regional deformation structures in these granitoid bodies. It is apparent that deformation is heterogeneous in the Murchison and that granitoids can not be placed in chronological order on the basis of their deformation history.

Detailed isotopic and geochemical studies of the granitoids of the Eastern Goldfields can be used to constrain the nature of the source region of the granitoids and the depth of melting. The incompatible trace element patterns are characterised by variable, but often pronounced negative Nb and Ti anomalies, suggesting that the source region contains a significant island arc component. Melting occurred within the deep to middle crust,

Rock type dated	Gold deposit	Age (Ma)
Granodiorite	Granny Smith	2665±4
Porphyritic biotite granodiorite	Porphyry	2667±4
Hornblende-biotite porphyry	Mt Charlotte	2673±5
Biotite tonalite	Bonnie Vale	2680±5
Porphyritic biotite granodiorite dyke	New Celebration	2686±4
Granophyric gabbro	Lady Bountiful	2687±5
Granophyric gabbro	Norseman	2714±5

TABLE 1. Age of rocks cut by gold mineralisation, Western Australia

over a depth range that is gradational between the garnet and plagioclase stability fields. The ratio of garnet to plagioclase has an important influence on the chemistry of the granites. The older granodiorites have a higher percentage of garnet in source regions and have formed at a deep crustal level whereas the younger granites have formed at a shallower level from a source region that was somewhat richer in K. The movement of the melting zone upwards through the crust is consistent with a model in which heat is conducted from the mantle (e.g., from a mantle plume) to successively higher levels in the crust (Hill & others, 1992). Modelling shows that the source rocks for all of the granitoids do not contain more than 20% garnet, precluding the possibility that they are eclogite.

References

Archibald, N.J., Bettenay, L.F., Bickle, M.J., & Groves, D.I. 1981, Evolution of Archaean crust in the Eastern Goldfields province of the Yilgarn Block, Western Australia. *Geological Society Australia Special Publication*

Bettenay, L.F. 1977, *Regional geology and petrogenesis of Archaean granitoids in the southeastern Yilgarn Block, Western Australia*. University of Western Australia.

Campbell, I.H., & Hill, R.I. 1988, A two-stage model for the formation of the granite-greenstone terrains of the Kalgoorlie-Norseman area, Western Australia. *Earth & Planetary Science Letters* 90, 11-25.

Compston, W., Williams, I.S., Campbell, I.H., & Gresham, J.J. 1986, Zircon xenocrysts from the Kambalda volcanics: age constraints and direct evidence for older continental crust below the Kambalda-Norseman greenstones. *Earth & Planetary Science Letters*, 76, 299-311.

Hill, R.I., Campbell, I.H., & Compston, W. 1989, Age and origin of granitic rocks in the Kalgoorlie-Norseman region of Western Australia: implications for the origin of Archaean crust. *Geochim. Cosmochim. Acta*, 53, 1259-1275.

Hill, R.I., Chappell, B.W., & Campbell, I.H. 1992, Late Archaean granites of the southeastern Yilgarn Block, Western Australia: age, geochemistry, and origin. *Royal Society Edinburgh: Earth Sciences*, 83, 211-226.

Watkins, K.P., Fletcher, I.R., & de Laeter, R.R. 1991, Crustal evolution of Archaean granitoids in the Murchison Province, Western Australia. *Precambrian Research*, 50, 311-336.

Watkins, K.P., & Hickman, A.H. 1990, Geological evolution and mineralization of the Murchison Province Western Australia. *Geological Survey of Western Australia Bulletin*, 137, 267 pp.

Granites of the Yilgarn Block and their relation to gold mineralisation

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Granites are implicated in many genetic models for gold mineralisation, including young circum-Pacific Au-Cu deposits which are clearly related to granites derived through subduction zone processes. The classic "mesothermal" lode-gold deposits which occur throughout the Archaean Yilgarn Block are not easily related to granites or subduction zones: they do not have a Au-Cu or Au-base metal association, and they seem to have a ubiquitous relationship to major shear or fault zones, rather than a particular series of granites. However, some models for the tectonic setting of Yilgarn lode-gold deposits highlight fundamental similarities between the Norseman–Wiluna Belt and young subduction-related terranes, and there is clearly strong support for Archaean subduction processes from Canadian researchers. Such tectonic-metallogenic models and a possible relationship between granites and lode-gold mineralisation should be more thoroughly tested for the Yilgarn Block.

Recent studies on Yilgarn lode-gold deposits have established a large depth range of mineralisation, from <5 km to >20 km, allowing models for a ubiquitous auriferous fluid source for this class of deposit to be derived from >20 km depth, a depth compatible with fluid derivation both from crustal anatexis and subduction zones. Much of the available data for a granite-gold relationship is based on the more prospective Norseman–Wiluna Belt, where it is possible that potential granites related to gold mineralisation are not exposed but occur at deeper crustal levels. Such granites, if they exist, may be represented in the more deeply eroded and higher metamorphic grade terranes of the central to western Yilgarn Block, and it is timely to consider the possiblity that granites possibly related to lode-gold mineralisation outcrop in the Yilgarn Block, but have not yet been recognised.

This contribution reviews current constraints on the role of granites in the genesis of Archaean lode-gold deposits of the Yilgarn Block, with particular emphasis on the more-intensely studied Norseman–Wiluna Belt.

Age constraints of Yilgarn lode-gold mineralisation

High-precision geochronology on lode-gold mineralisation has proved difficult to achieve due to the scarcity of suitable minerals formed at the time of mineralisation which are resistant to later geological events. The most success has been via the Pb-Pb isochron method based on:

- rutile or sphene (titanite) to yield the more radiogenic endmember of the isochrons, and
- ore sulphides or K-feldspar from proximal alteration as the less radiogenic endmember.

The only three reliable ages for mineralisation are from Pb-Pb isochrons: 2627 ± 14 Ma for the Victory-Defiance deposit, Kambalda, 2636 ± 3 Ma for the Griffin's Find deposit, Southern Cross Province, and 2639 ± 4 Ma for the Reedy's deposit, Murchison Province. These ages are coeval over the Yilgarn Block, and if confirmed by future work, suggest broadly synchronous, craton-wide mineralisation. The ca. 2.63-2.64 Ga mineralisation age is compatible with all known reliable geochronological constraints: i.e. overprinting relationships, host rocks to mineralisation are older and crosscutting dykes are younger. Model Pb-Pb ages for ore sulphides are demonstrably unreliable as formation ages, but modelling does not contradict the 2.63-2.64 Ga age of mineralisation.

Age constraints of Yilgarn granites

The greenstones and granites of the Norseman–Wiluna Belt show a consistent age pattern as follows:

- the greenstones formed on older sialic rocks at ca. 2.70 Ga;
- an early monzogranite-granodiorite suite, typi-

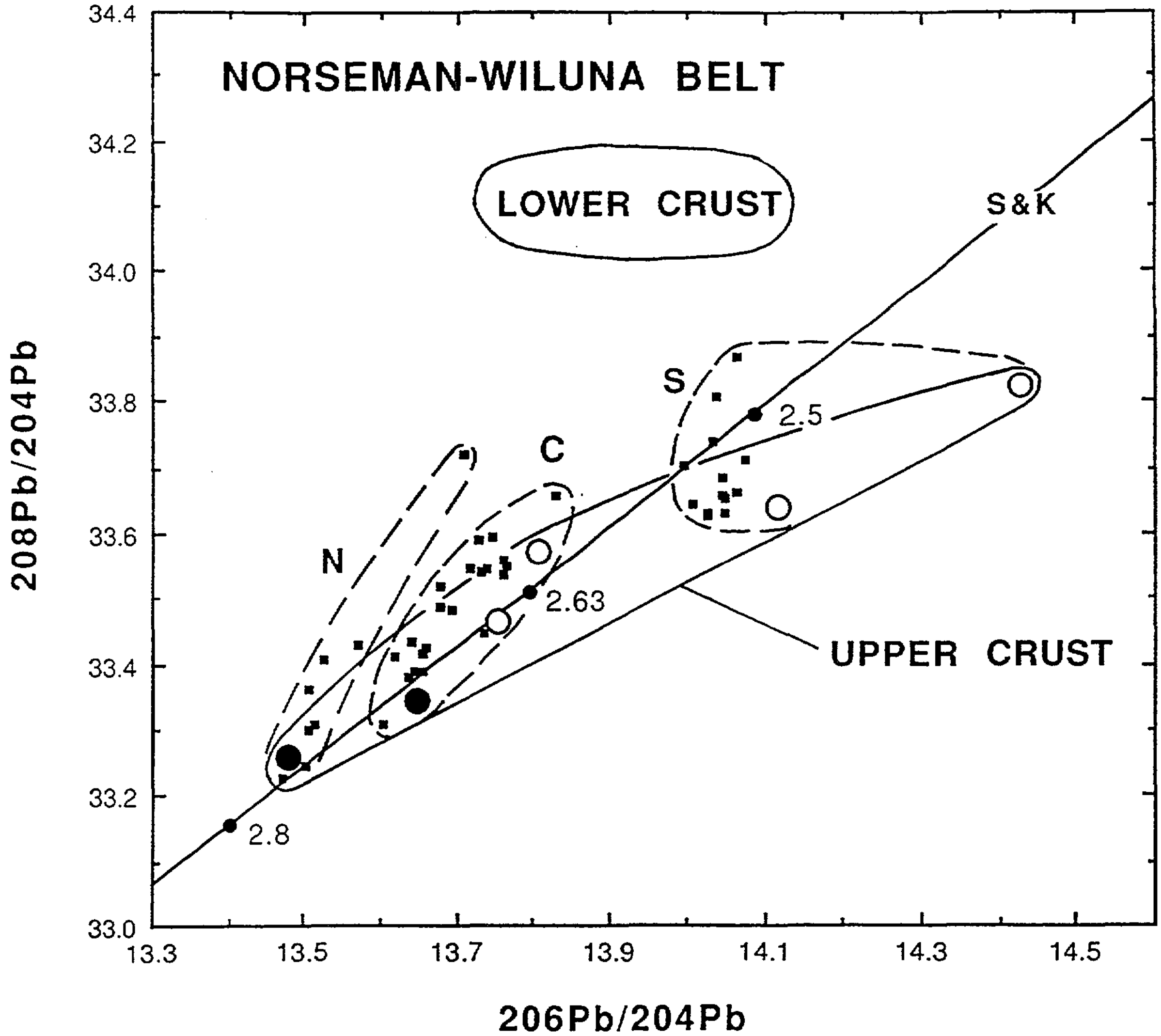

Fig. 1. Isotopic comparison of ore fluid Pb (small squares) and coeval crustal Pb (large circles) at 2.63-2.64 Ga in the northern (N), central (C) and southern (S) regions of the Norseman-Wiluna Belt. Upper crustal data are estimates from syngenetic massive sulphide mineralisation (closed circles) and granites (open circles). The lower crustal field is inferred as the required crustal Pb to explain the elongate trends for the ore fluid Pb data for each region. The Stacey & Kramers (1975) growth curve is shown for reference.

cally occuring as composite batholiths, formed shortly after initial greenstone development at ca. 2.69 to 2.66 Ga;

- a geologically younger tonalite-trondhjemite suite with spatially related felsic to intermediate porphyries and calc-alkaline lamprophyres emplaced at ca. 2.66 Ga, with less precise ages to 2.64 Ga suggesting these could be coeval with gold mineralisation; and
- minor post-tectonic peralkaline to alkali granites which are also potentially coeval with mineralisation.

Granites in the other provinces of the Yilgarn Block show a similar compositional-age trend, although a number of granites from the Western Gneiss Terrain and the Murchison Province have ages which overlap the 2.63-2.64 Ga period of gold mineralisation.

Ore fluid constraints

Ore fluids from all depths are saturated in potassium and quartz and require fluid buffering from their source or conduits by a K-mineral and quartz: i.e. granites to quartz-bearing amphibolites are allowable sources. Similarly, the elements added to proximal alteration haloes from the ore fluid (e.g. Si, S, As, K, Ba, Rb, Pb, Sb, CO_2) are granitophile. Fluid inclusions from gangue silicates indicate a ubiquitous H_2O-CO_2-NaCl ore fluid with restricted NaCl and CO_2 contents. The low salinity is considered to correlate with the low base metal contents of deposits because of the limitation of metal transport as chloride complexes. This indirectly biasses models against orthomagmatic ore fluids, which are typically highly saline. However, recent experimental studies suggest that fluid exsolution from CO_2-bearing granitic magmas at P-T conditions comparable to the granulite facies of metamorphism would produce fluids with the characteristics of the ubiquitous ore fluid for Yilgarn lode-gold deposits.

Lead isotopic constraints

Initial Pb isotopic compositions of granites and ore fluid Pb may be estimated from analyses of K-feldspars and Pb-rich ore sulphides, respectively. Detailed studies at the gold camp scale have so far failed to yield ore fluid initial Pb isotopic compositions which correspond to that for spatially associated porphyries, although derivation of Pb and ore fluids from hidden granites cannot be ruled out.

On a broader scale, there is a close correpondence between the Pb isotopic composition of the ore fluids in the Norseman–Wiluna Belt at 2.63-2.64 Ga, and the coeval Pb in the source regions of granitic magmas, presumably in the older felsic crust underlying each gold camp (Fig. 1). The variation in the crustal Pb compositions reflects pre-mineralisation events and the age structure of the older basement, and affords a means of relating the ore deposit Pb for each region to the older crust underlying that region. The granite initial Pb isotopic compositions are difficult to estimate precisely and are sometimes more radiogenic than expected due to the effects of in situ U-decay: the offset of the granite data to the right of the ore fluid Pb data in Fig. 1 may be due to this cause. Nonetheless, the ore fluid Pb data is compatible with derivation from mixed upper crustal and inferred lower crustal reservoirs with granites as a potential fluid source or transporting medium.

Discussion

Granites provide a possible source for lode-gold ore fluids and have the following properties which are inferred for auriferous ore fluids: they are quartz-bearing, contain K-mineral(s), have incompatible elements which correspond to those added to alteration haloes around lode-gold deposits, may produce fluids with compatible salinity and composition, and have an appropriate timing and Pb isotopic composition.

In the Norseman–Wiluna Belt, no granites coeval with mineralisation have yet been identified, possibly due to the outcrop restrictions and paucity of reliable high-precision data. It is also possible that such granites do not outcrop at the high crustal levels encountered, but may occur at depth. If lode-gold ore fluids are exsolved from CO_2-bearing granites at depth and are a ubiquitous component of Archaean metallogeny, the depth of granite emplacement is likely to exceed 20 km, the depth of the highest pressure lode-gold mineralisation. Recent geochronology has shown that 2.63-2.64 Ga granites occur in the higher metamorphic grade settings of the western Yilgarn Block, although these have not yet been studied for their potential relationship to lode-gold mineralisation.

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Archaean tectonics: convergence towards divergent models

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The history of our understanding of tectonic processes of Archaean terrains has always closely followed that of terrains of other ages. Just as McGregor in 1951 immediately recognised Archaean patterns of the mantled gneiss domes that Eskola in 1949 had just reported in the Proterozoic of Finland, so all the other major crustal building processes have been applied to the Archaean soon after recognition elsewhere: basement reactivation; fold interference; doming superposed on basement-cored nappes; plate tectonics; fold-thrust belts; low angle normal faulting and metamorphic core complexing; thrusting and piggy-back basin formation; microplate tectonics and terrane accretion, inversion tectonics and extensional collapse; indentor tectonics and terrane expulsion; plumes and continental break-up; meteorite impacts; etc. etc.; the list is endless.

In parallel with this applied "similarity" approach to constructing Archaean tectonic models is the "fine-tuning" of tectonic processes based on identifying differences. By recognizing that not all that looks similar is formed in the same way, focused field, geochemical, geophysical, experimental etc. analysis have contributed to major advances in understanding of Archaean processes. Over the period from the 1960s to the 1990s, we have witnessed the emergence of phrases such as "there are granites and granites"; "basins and basins"; "ophiolites and ophiolites". There is no question that, in a similar vein, the Archaean community today acknowledges that there are "greenstone belts and greenstone belts". No two greenstone belts are the same, and the idea of a "type" greenstone belt must now be abandoned. In fact, we are being forced to critically examine whether the term "greenstone belt" should be retained at all.

Archaean tectonics has moved a long way from the "static" models in which greenstone belts featured as regional synclines with simple layer cake stratigraphy. In the 1980s, in particular, detailed structural mapping coupled to geochemical investigations and precise U/Pb zircon age dating has revolutionised our thinking about Archaean tectonics and the origin of granite-greenstone terrains. Almost universally, the simple 1970s rift models of greenstone belts have given way to more complex models. At first the new models merely highlighted that certain greenstone belts had formed in tectonic environments which were different from simple rifts. Competing models focused selectively on the best preserved geological aspects of specific greenstone belts. For example, emphasis on features such as thrusting and syn-tectonic sedimentation; komatiites, stromatolites and shallow platform sedimentation; pillow lavas, turbidites and deepwater basins; shear zones, pull-apart basins and gold mineralization, gave us greenstone belts as foreland basins; oceanic plateaux; ophiolites; transpressional complexes, respectively. These models were built, to a great extent, on a mix of old and incomplete new data information. Investigations in different parts of the world during the latter part of the 1980s, however, have slowly caught up with these "hybrid" models; and for the moment at least, geologists agree to disagree about a single model for the origin of greenstone belts and granite-greenstone terrains. We are at the crossroads of realising, too, that indeed there are "granite-greenstone terrains and granite-greenstone terrains". There has been a final breakdown of all fixists models, and there is now a growing recognition that some of the classic terrains are composites of terranes.

For example, the Superior province of Canada, a classic granite-greenstone terrain, is now recognised to have formed by some sort of "uniformitarian" accretion process at a convergent plate margin, involving crustal components of diverse origin. These components have developed not only in situ, but are also of exotic nature (oceanic arcs, plateaux, continental arcs etc). The results of U/Pb age dating indicates, moreover, that this largest of all Archaean terrains, was formed within an amazingly short time span (less than 500 Ma, and with the majority of crustal formation and the major orogene-

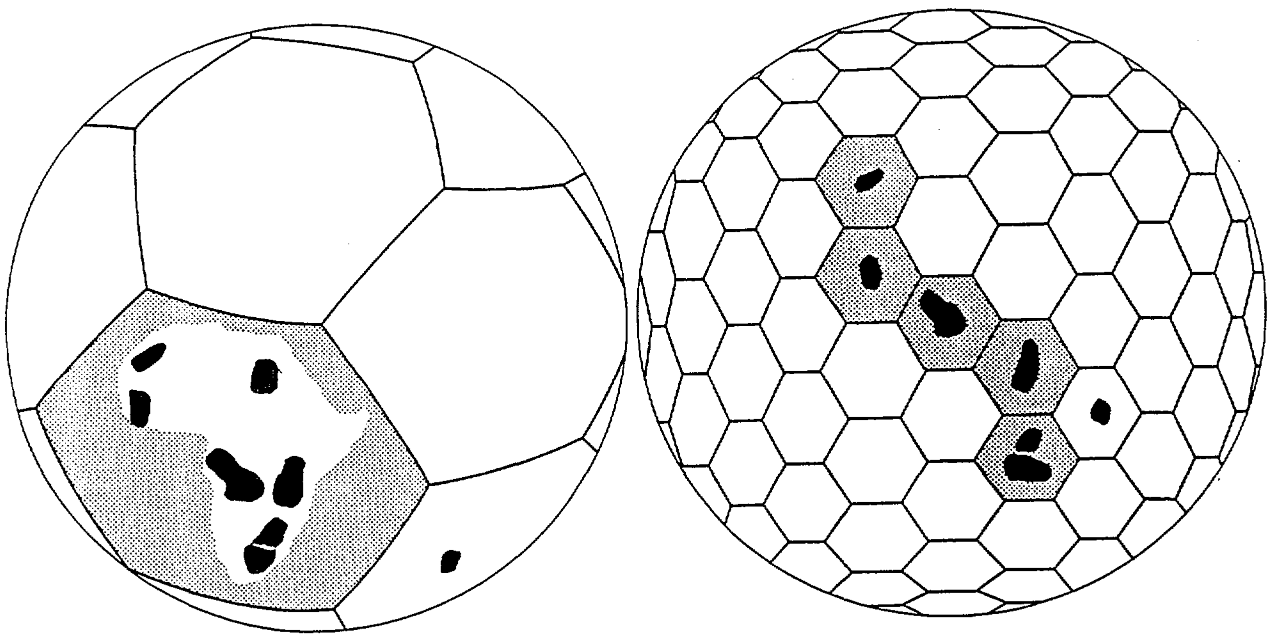

Fig. 1. Two possible plate tectonic models of the Archaean Earth constructed using simple heat equations, and knowledge that the Archaean Earth must have been losing heat at about 2-3 times the rate of the present Earth. It is assumed that heat loss through the formation of new oceanic lithosphere and hydrothermal cooling at spreading ridges is the most efficient way in which the Archaean Earth lost its excess heat. The model on the left has the same plate configuration as those of today; extra Archaean heat is lost by faster spreading rates at constructive plate boundaries. The model on the right has the same spreading rates as those of today; extra Archaean heat is lost through a much greater spreading ridge length. There is at present no geological or geochemical observation which allows for a confident choice between these two alternative models for an Archaean Earth. Stipples on the left model = total extent of the present Africa plate; black = extent of known Archaean continental crust presently preserved in Africa.

sis within circa 100 Ma). Individual greenstone belts have even smaller age ranges documenting their formation and progressive southward corporation into the larger granite-greenstone framework at rates no different from those seen in modern accretion environments of the Western Pacific.

In contrast, the Kaapvaal Craton, also a classic granite-greenstone terrain of substantial size, documents a much longer period of crustal formation, spanning almost 1000 million years. Although rapid accretion tectonics has also been recognised to have played a major role during the initial stages of granite-greenstone formation, the Craton has subsequently also been involved in episodic inversion tectonics with attenuated periods of crustal extension, shearing, rotation and break-up before final consolidation. Fragments of the Kaapvaal Craton may be recognised elsewhere in the world; in particular the Pilbara Craton shares a surprising range of similar Archaean geological events with that of the Kaapvaal Craton.

The extended history of the Kaapvaal granite-greenstone terrain is also reflected in the extended evolution of some of its individual greenstone belts. The classic Barberton greenstone belt is now recognised to have a polyphase tectonic history spanning more than 450 million years, and clearly comprises suspect terranes that differ in age by up to 200 million years; the age range recorded in the Pietersburg greenstone belt may be even greater. Fragments of the following tectonic environments are represented in the Barberton greenstone belt: spreading-ridge, intraoceanic suprasubduction, arc-trench, inter-arc, collisional (accretional processes including transpressional tectonics) and extensional collapse (including metamorphic core complex formation). Since the 450 million years of geological history recorded in the formation of the Barberton greenstone belt history equates to nearly the entire Phanerozoic (as well as to the formation of the whole of the Superior Province), there should, as yet, be no illusion that we fully understand all the details of the tectono-thermal evolution of this belt; nevertheless we have reached the crossroads of a crude polyphase framework. It is evident that similar models are emerging from the Yilgarn Craton and many other granite-greenstone terrains world-wide.

It appears, then, that we are confronted with a myriad of models, each different from one another, and yet all part of a greater puzzle, which we have yet to fully reconstruct. Greenstone belts contain a variety of geological information about a variety of Archaean tectonic settings: different greenstone belts have different polyphase tectonic histories, but which must be analysed in concert; and studied within an evolutionary framework. This is where I believe future Archaean tectonic studies will move: piecing together the spectrum of a great number of tectonic environments using the details obtained from a variety of different granite-greenstone terrains, as well as new ideas from studies of more recent tectonic environments. This will require much better global communication amongst those interested in interactive Earth processes than has hitherto been accomplished; and geoscientists studying Archaean rocks will have to learn to stop "hiding" behind their Precambrian "forcades". Only then will we be able to seriously address the question of how the Archaean Earth operated; how the first continental fragments formed; and what greenstone belts are really telling us.

To illustrate the immense gap in our present knowledge of Archaean tectonics, I would like to present one general and large scale example. Figure 1 is a graphic simulation of two possible states of the Archaean Earth, constructed from first order knowledge of the time-integrated heat flow from the planet: 4.5 billion years of decay of radioactive elements, means that the Archaean Earth must have been losing at least 2 to 3 times as much heat in the Archaean than today. On the left hand side of Fig. 1 is an Archaean plate tectonic Earth losing its extra heat through increased rates of spreading: this planet has the same number and sizes of plates as today. On the right, is an Archaean plate tectonic Earth losing its extra heat through greater spreading-ridge length (and associated extra length of subduction zones), but with the same spreading rates as today. Intuitively either planet should yield different rock signatures that we should be able to confidently analyse. It is sobering to know that, as yet, we have not learned to read the rock record of greenstone belts well enough to distinguish between these two very different possible Archaean Earth model. Of course, Fig. 1 represents only one possible set of Archaean models, based on the most efficiently known mode of heat loss from the contemporary planet. There is, therefore, much room for renewed effort in coordinated, integrated field and laboratory studies of Archaean terrains and in particular greenstone belts. The next 100 years in Kalgoorlie will, I believe, be as exciting, and as challenging as the last 100 years.

Follows p. 55

Resolving conflicting messages from granitoids and greenstones: the key to understanding Archaean tectonics

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Understanding the tectonic evolution of the Eastern Goldfields Province is a small but complex part of a larger problem, that of understanding Archaean tectonics in general. Advances in Phanerozoic tectonics and in high precision geochronology have recently lead to major breakthroughs in understanding Meso and Neoproterozoic tectonics. However, there is still much controversy regarding Archaean tectonics. Does this mean the Archaean tectonic regime was markedly different or just that we are having difficulty interpreting complex and often apparently conflicting messages from the rocks? In this extended abstract we examine some of the problems encountered in obtaining realistic tectonic histories from the Archaean rock record and in particular how apparently conflicting tectonic interpretations based on data from different components of granitoid-greenstone terranes may be resolved. We also attempt to place the geology of the Eastern Goldfields Province in its regional and global context.

Granitoid-greenstone relationships

Resolving the tectonic history of any area is a multidisciplinary problem. However, there is a tendency for earth scientists to become increasingly specialized. Abstracts in this volume address the stratigraphy, igneous petrology and geochemistry, metamorphic petrology, structural geology, mineralization, isotope geochemistry, geochronology and geophysics of rocks from the Eastern Goldfields and some draw very different conclusions from rocks which must be tectonically related. Any successful tectonic model must be able to explain all of this data. In the Phanerozoic this increased attention to detail has resulted in the simple end-member models of rift, transform and convergent margins, still found in undergraduate textbooks and many papers on Archaean geology, being replaced by a continuum of complex and evolving models which bring with them their own often difficult jargon. However, until all aspects of Archaean geology can be treated with a comparable level of sophistication it is unlikely that the major problems of Archaean tectonics will be resolved.

Before going any further we need to justify the use of plate tectonic models to interpret Late Archaean geology. Blake & Barley (1992) have argued that the Mt Bruce Megasequence in the Pilbara contains Late Archaean (ca 2.7 Ga) continental flood basalt provinces which record the rifting of a rigid Archaean continental plate. Also significant lateral viscosity differences between plates and plate boundaries are required for major strike-slip fault systems to exist. Consequently, strike-slip fault systems in the Superior Province which formed at ca 2.7 Ga, with lengths of more than 1000 km, are reasonable evidence that rigid plates existed at that time and that these plates were comparable in size to modern plates (Sleep, 1992).

If plate tectonics operated at about 2.7 Ga what do granite-greenstone terranes such as the Eastern Goldfields Province represent? Mesozoic to Tertiary greenstone complexes form at convergent plate margins, either in arc/back-arc basin complexes such as the Rocas Verdes complex in Chile (Tarney & others, 1976), or in accretionary complexes such as in Japan (Taira & others, 1992). However, a variety of other, mainly continental, environments have also been suggested for Archaean greenstone belts. Consequently determining whether greenstones were formed and preserved on continental crust, or are allocthonous is important. Unfortunately contacts between greenstone successions and granitoids in the Eastern Goldfields do not allow unambiguous interpretation of their original relationships. Where observed these contacts are either intrusive, or tectonic; being interpreted as thrusts (Spray, 1985), or extensional faults (Hammond & Nisbet, 1992, Williams & Whitaker, 1993). Basal unconformities and basin margin facies which would be the best evidence that supracrustal rocks are autochthonous and were deposited on silicic crust are absent.

Deposition of greenstones on silicic crust is inferred from zircon xenocrysts in komatiitic basalt at Kambalda and evidence that some komatiites and komatiitic basalts have been contaminated by silicic material (Compston & others, 1985; Barley, 1986). However, strong evidence of extensive thermal erosion of seafloor sediments by Kambalda komatiites raises the possibility that both the zircons and contaminant were derived from the seafloor rather than beneath it. In other words the contamination of komatiites by zircons and silicic material does not prove that they formed on continental crust.

Most studies of the greenstone successions in the Eastern Goldfields interpret them as forming in some sort of convergent plate margin setting (Barley & others, 1989; Swager & others, 1992). This is because the overall rock assemblages, their depositional and deformational histories, and mineralization closely resemble those of well documented younger greenstone complexes. However, modern convergent margins and their hinterlands are extremely variable and often have complex tectonic histories. How can we be sure what an Archaean magmatic arc would look like when modern ones are so variable? We can not know for certain, but we can make some predictions. On the modern Earth the flux from the mantle to the crust at subduction zones is mafic in composition. With higher mantle temperatures this was probably also the case in the Archaean. So it is most likely that Archaean arcs on ocean crust would be composed dominantly of basalt and gabbro, produced by hydrous mantle melting, with subordinate dacites (tonalites), produced by fractional crystallisation of basalt, or melting of the subducted slab. At Archaean convergent continental margins high thermal gradients would promote more extensive crustal melting above rising basalt magmas than occurs in most modern continental arcs, producing magmatic provinces with abundant dacite and rhyolite (granitoid), but subordinate andesite, such as in the North Island of New Zealand. If this was the case then it is unlikely that average continental crust formed at the convergent margins to Archaean plates. Archaean convergent plate margins were most likely sites of addition of dominantly mafic rocks by underplating and accretion and reworking of already existing continental crust.

Recent studies of the geochemistry of Eastern Goldfields granitoids appear at odds with the interpretation that convergent margin tectonic processes played an important role in the evolution of this terrane. This is because most of the granitoids probably formed by partial melting of an older crustal source. These granitoids have been interpreted by Hill & others (1992) as the result of crustal melting above the same deep-sourced mantle plume that produced tholeiitic and komatiitic volcanic rocks in the greenstone belts. It has been suggested that this occurred in a continental setting similar to that of Palaeozoic granitoids in the Lachlan Fold Belt. To evaluate this suggestion we need to examine the tectonic setting of granitic magmatism in the Lachlan Fold Belt. The Lachlan Fold Belt was the site of a convergent plate margin in the Ordovician and was inboard of a subduction zone again from the Late Devonian. Consequently voluminous silicic magmatism in the Silurian and Devonian is not likely to be a direct result of subduction. This magmatism occurred in continental crust comprising a thick turbidite wedge with accreted island arc and back-arc basin rocks inboard of a transform plate margin. A continental hinterland setting (to either a transform or convergent margin) during regional granitoid magmatism in the Eastern Goldfields at ca 2.68 to 2.66 Ga is consistent with emplacement of some granitoids as core complexes (e.g. Hammond & Nisbet, 1992; Williams & Whitaker, 1993) and was implied by the tectonic model proposed by Barley & others (1989).

However, calc-alkaline shoshonitic lamprophyres in the Norseman–Wiluna Belt (Perring, 1988) are difficult to explain as crust derived magmas and are most likely derived from mantle modified by active or recent subduction. These lamprophyres and related porphyries are coeval with regional granitoid magmatism between 2.69 to 2.66 Ga. Consequently, both the simple subduction model proposed by Cassidy & others (1990) and the mantle plume model as proposed by Hill & others (1992) are inadequate to explain the petrogenesis of the Eastern Goldfields granitoids. As stated above, the Taupo Volcanic Zone in the North Island of New Zealand is dominated by silicic volcanic rocks which are similar in composition to many Eastern Goldfields granitoids and may provide a better tectonic analogy for granitoid magmatism than the Lachlan Fold Belt. This magmatic province is inboard of an active subduction zone, accretionary complex and belt of strike-slip deformation, and comprises a magmatic arc (volumetrically subordinate andesite volcanoes) juxtaposed with a continental back-arc basin or magmatic belt (dominant rhyolite volcanoes). The silicic magmas are most likely generated by rising basaltic magma melting and interacting with continental crust composed of metamorphosed greywackes which are andesitic to tonalitic in composition. Extensive melting of andesitic or tonalitic crust is similar to the petrogenetic model for Eastern Goldfields granitoids proposed by most workers. Thus it appears that composition can not discriminate granitoid magmas generated by melting of silicic crust above a deep-sourced mantle plume from those generated by crustal melting induced by basaltic magmas related to an adjacent subduction zone. The best discriminant between competing tectonic models for Eastern Goldfields granitoids will be the total tectonic history of the Eastern Goldfields and how it fits into the evolution of the Yilgarn Craton as a whole.

The problems of scale and time

Two of the major problems encountered in Archaean tectonic interpretation are those of scale and time. Archaean cratons are small and often have long histories which are only now being subdivided into sufficiently short periods of time to allow meaningful correlation of rock units and events. Realistic tectonic interpretation also requires the ability to put a terrane in both its regional and global context. The major advances in Neoproterozoic tectonics in the last two or three years have involved reconstruction of Proterozoic continents. Comparable reconstructon of early Proterozoic and Archaean continents seems almost impossible at this stage. However, precise geochronology tied to detailed multi-disciplinary studies may allow correlation of events between Archaean cratons to establish which cratons were related at particular times. For example, on the modern Earth convergent and transform plate boundaries are all linked. This means that major changes in spreading-ridge geometry, or spreading rate, and changes from convergence to transform motion, or continental collisions may cause tectonic events in distant parts of the system. If this was also true in the Archaean we may be able to explain why Late Archaean granitoid-greenstone terranes such as the Yilgarn Craton and Superior Province evolved at the same time with broadly similar tectonic histories (which differ in detail).

Sequence stratigraphy combined with precise geochronology provides a way of unravelling the tectonic history of greenstone belts and attempting such chronostratigraphic correlations. Modern sequence stratigraphy is the study of genetically related facies within the framework of chronostratigraphically significant surfaces. It conceptualises the deposition of stratigraphic packages (sequences) as a response to tectonoeustatic cycles of relative sea level change (e.g. Vail & others, 1977; Haq, 1991). In relation to global tectonics, sets of first-order cycles are synonomous with Wilson Cycles and second-order cycles are related to changes in spreading-ridge geometry, ocean basin volume and continent collisions. A sequence is defined as a relatively conformable, genetically related succession of strata bounded by unconformities, or their correlative conformities, and is the lithostratigraphic response to third-order cyclicity. Sequences can be grouped into supersequences which are the stratigraphic response to second-order cycles. Supersequences are thus groups of sequences which were deposited either within a common composite depositional basin, or within superposed tectonically related depositional basins. The order of superposed tectonic environments represented by supersequences can be predicted from tectonic theory and mainly depends on whether the depositional basin faces a Pacific- or Atlantic-type ocean (see Krapez, 1993; Table 3). Supersequences can in turn be grouped into megasequences (representing first-order cycles).

The application of sequence stratigraphy to supracrustal rocks in Archaean granitoid-greenstone terranes is discussed in detail by Krapez (1993) who has applied it to greenstone successions in the Pilbara Craton. Blake & Barley (1992) have also applied sequence stratigraphy to the Late Archaean "Hamersley Basin" which formed at the same time as the Eastern Goldfields granitoid-greenstone terrane. The "Hamersley Basin" fill, the Mount Bruce Megasequence Set is interpreted as two megasequences formed during the opening and closure of an Atlantic-type ocean. The Mount Bruce Megasequence Set comprises two extensional supersequences at ca 2.77-2.76 Ga and ca 2.7 Ga, and a passive margin supersequence at 2.69 to 2.60 Ga. These supersequences comprise the Chichester Range Megasequence and represent the opening of the ocean. Open ocean is represented by a lacuna or condensed section from 2.6 Ga to 2.47 Ga, with a continental back-arc basin supersequence at 2.44 Ga, followed by a foreland basin supersequence. These supersequences comprise the Hamersley Range Megasequence and record the closure of the ocean. The Archaean/ Proterozoic boundary is at the end of the first megacycle, and the longevity of the megacycle set (~330 Ma) is approximately that estimated for the breakup of a Neoproterozoic supercontinent and its reaggregation as Pangea during the Palaeozoic, as is the order of superposition of tectonic environments. If the sequence stratigraphic approach is valid it should be possible to recognize correlative supersequences in other Late Archaean basins and indeed in greenstone belts such as those in the Eastern Goldfields.

Similarly the tectonic evolution of the Eastern Goldfields Province can not be deduced in isolation from that of the Yilgarn Craton as a whole. New data from the Western Yilgarn indicates continental andesitic to silicic arc magmatism from 2.76 to 2.72 Ga (Weidenbeck & Watkins, 1993; Wilde & Pidgeon, 1986) in the Murchison and Southern Cross Provinces, with andesites and porphyry-style Cu-Au mineralization at Boddington (at ca 2.7 Ga). This was followed by craton-wide granitoid magmatism and deformation at 2.66 to 2.63 Ga with maximum crustal thickening and granulite facies metamorphism in the gneiss terranes in the west. Neither the simple subduction from the east model, nor the mantle plume model can explain why the thickest Archaean crust and highest metamorphic grade rocks should be in the far west of the craton, nor why there should be episodic granitoid magmatism over more than 100 Ma in this part of the craton. This pattern of magmatism, deformation and metamorphism suggests that rather than being the continental hinterland to convergence from the east from 2.8 to 2.6 Ga (as interpreted by Barley & Groves, 1990), the Yilgarn was a Late Archaean continental micro-plate such as found the Indonesian archipelago, Borneo and the Philipines. In this environment, opposing subduction zones have affected a collage of continental, oceanic, arc and back-arc basin terranes and microplates since the Mesozoic. If we apply this tectonic scenario to the Yilgarn, long-lived subduction from the west culminated in collision with another plate or micro-plate by 2.66 Ga resulting in the present crustal structure and distribution of deformation and metamorphic facies by 2.63 Ga. The volcanic basin represented by the Kalgoorlie terrane had also closed by this time. Thus, at the time of gold mineralization, tectonics in the Eastern Goldfields may have been driven by collision to the west of the craton.

In terms of the Late Archaean sequence stratigraphy, the Yilgarn Craton contains the record of the first, or ocean-opening, megacycle. It has ca 2.76 Ga arc magmatism (in the Murchison), widespread 2.72 to 2.69 Ga arc and back-arc basin magmatism, 2.69 to 2.66 Ga back-arc basin closure (in the Eastern Goldfields) and micro-plate collision (to the west), followed by 2.66 to 2.60 Ga post-collisional magmatism and strike-slip deformation. This tectonic history is essentially that predicted for a continental micro-plate at a convergent margin to a Pacific-type ocean with rapid plate motion, subduction and collision accommodating the opening of an ocean elsewhere on the globe. Indeed world-wide cyclicity of greenstone belt volcanism at approximately 200 Ma intervals at ca 3.45 to 3.30 Ga, 3.10 to 2.95 Ga and 2.75 to 2.60 Ga supports the contention that Archaean tectonics operated via plate tectonic megacycles of ocean opening and closure. Deep-sourced mantle plumes have a role to play in this tectonic regime, but can not by them selves explain the complexity and longevity of granitoid-greenstone tectonic cycles.

References

Barley, M.E. 1986, Incompatible element enrichment in Archaean basalts: a consequence of contamination by older sialic crust rather than mantle heterogeneity, *Geology*, 14, pp 947-950.

Barley, M.E., & Groves, D.I. 1990, Deciphering the tectonic evolution of Archaean greenstone belts: the importance of contrasting histories to the distribution of mineral deposits in the Yilgarn Block, *Precambrian Research*, 46, pp 3-20.

Barley, M.E., Eisenlohr, B.N., Groves, D.I., Perring, C.S., & Vearncombe, J.R. 1989, Late Archaean convergent margin tectonics and gold mineralization: a new look at the Norseman-Wiluna Belt, *Geology*, 17, pp 826-829.

Blake, T.S., & Barley, M.E. 1992, Tectonic evolution of the Late Archaean to Early Proterozoic Mount Bruce Megasequence Set, Western Australia, *Tectonics*, 11, pp 1415-1425.

Cassidy, K.F., Barley, M.E., Perring, C.S., & Groves, D.I. 1991, The nature, distribution and inferred tectonic setting of granitoids in the Late Archaean Norseman-Wiluna Belt, *Precambrian Research*, 51, pp 51-84.

Compston, W., Williams, I.S., Campbell, I.H., & Gresham, J.J. 1985, Zircon xenocrysts from the Kambalda volcanics: age constraints and direct evidence for older crust below the Kambalda-Norseman greenstones, *Earth & Planetary Science Letters*, 76, pp 299-311.

Hammond, R.L., & Nisbet, B.W. 1992, Towards a structural and tectonic framework for the central Norseman-Wiluna greenstone belt, Western Australia, *Geology Deptartment & Univiversity Extension, University of Western Australia, Publication* 22, pp 39-50.

Haq, B.U. 1991, Sequence stratigraphy, sea-level change, and significance for the deep sea, *International Association of Sedimentologists, Special Publication* 12, pp 3-40.

Hill, R.I., Chappell, B.W., & Campbell, I.H. 1992, Late Archaean granites of the southeastern Yilgarn Block: age, geochemistry and origin, *Transactions of the Royal Society of Edinburgh: Earth Science*, 83, pp 211-226.

Krapez, B. 1993, Sequence stratigraphy of the Archaean supracrustal belts of the Pilbara Block, Western Australia, *Precambrian Research*, 60, pp 1-45.

Perring, C.S. 1988, Petrogenesis of the lamprophyre-porphyry suite from Kambalda, Western Australia, *Geology Deptartment & University Extension, University of Western Australia, Publication* 12, pp 277-294.

Taira, A., Pickering, K.T., Windley, B.F., & Soh, W. 1992, Accretion of Japanese island arcs and implications for the origin of Archean greenstone belts, *Tectonics*, 11, pp 1224-1244.

Tarney, J., Dalziel, I.W.D., & de Wit, M.J. 1976, Marginal basin Rocas Verdes Complex from southern Chile: a model for Archaean greenstone belt formation, in, *Early history of the Earth*, ed. B.F. Windley, John Wiley and Sons New York, pp 131-146.

Sleep, N.H. 1992, Archean plate tectonics: what can be learned fron continental geology? *Canadian Journal of Earth Science*, 29, pp 2066-2071.

Spray, J.G. 1985, Dynamothermal transition zone between Archaean greenstone and granitoid gneiss at Lake Dundas, Western Australia, *Journal of Structural Geology*, 7, pp 187-203.

Swager, C.P., & others 1992, Late Archaean granite-greenstone terranes of the Kalgoorlie Terrane, Yilgarn Craton, Western Australia, *Geology Deptartment & University Extension, University of Western Australia, Publication* 22, pp 107-122.

Vail, P.R., & others 1977, Seismic stratigraphy and global changes of sea level, parts 1-6, *American Association of Petroleum Geologists, Memoir* 26, pp 49-133.

Wiedenbeck, M., & Watkins K.P. 1993, A time scale for granitoid emplacement in the Archaean Murchison Province, Western Australia, by single zircon geochronology, *Precambrian Research*, 61, pp 1-26.

Wilde, S.A., & Pidgeon, R.T. 1986, Geology and geochronology of the Saddleback greenstone belt in the Archaean Yilgarn Block, southwestern Australia, *Australian Journal of Earth Science*, 33, pp 491-501.

Williams, P.R., & Whitaker, A.J. 1993, Gneiss domes and extensional deformation in the highly mineralized Archaean Eastern Goldfields Province, Western Australia, *Ore Geology Reviews*, 8, pp. 141-162.

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Regional geophysical constraints on tectonic models for the Eastern Goldfields Province

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The Eastern Goldfields Province (Gee, 1979) occupies the eastern third of the Yilgarn Block. Greenstone accounts for approximately 25% of the Province with the remainder composed of gneiss, migmatite and granite. The difficulty in developing satisfactory tectonic models for the Province has been due in part to the poor and unrepresentative outcrop throughout the region. A further constraint to the development of a full tectonic model has been the concentration of geological effort on economically important greenstone belts. The combination of these factors has resulted in the development of a wide variety of tectonic models which represent differing portions of the evolutionary history and include: accretion of primitive oceanic crust (Glikson, 1972); accretion of island arc material in a subduction setting (Barley & others, 1989); intracratonic rifting and basement uplift (Archibald & others, 1981; Blake & Groves, 1987); mantle plume tectonics (Archibald & others, 1978; Campbell & Hill, 1988); and extension tectonics (Williams & Whitaker, 1993). The aeromagnetic and gravity data are not effected by the widespread regolith and transported cover and thus reflect bedrock geology throughout the whole area. Through models inferred from the geophysical data, information in scattered outcrops can be related, and extrapolated into areas of no outcrop. This paper describes the geophysical model of the Eastern Goldfields Province in the western Kalgoorlie and Esperance 1:1M sheets and relates key aspects to tectonic models. The region described in detail lies between 28° and 33° south and 120° and 124°30' east (Fig. 1) and includes most of the area of the Eastern Goldfields National Geoscience Mapping Accord project.

Geophysical model

The geophysical model draws heavily on the AGSO regional aeromagnetic data (1.5 km line spacing), which provides both regional extent and moderate detail. Regional gravity data (11 km station spacing; AGSO), and more detailed aeromagnetic (400 m line spacing; AGSO/Aerodata) and gravity data (4 km station spacing; AGSO/ GSWA) were used in combination with existing geological mapping to provide complementary information, local detail and geological understanding. The Yilgarn Block is dominated by north-northwest to north trends due to lithological layering. In the south, these trends show a gradational drop in magnetisation on approaching the boundary of the Block and are modified to roughly parallel the adjacent boundary. This deformation and demagnetisation is attributed to the thrusting of the Albany–Fraser Province during the Proterozoic. The deformed margin of the Block is not discussed further. The geophysical model is described in terms of informally named domains (Whitaker, 1992; Williams & Whitaker, 1993). The area in which north-northwest trends dominate is readily subdivided on the basis of the aeromagnetic data into nine domains. Five of these correspond with gneiss, migmatite and granite outcrop, two with greenstone terrane, and two in which granite dominates.

Gneiss-granite domains (basement to the greenstones?)

Gneiss, migmatite and granite are the main rock types in the five domains inferred to be basement to greenstone. The Laverton and Eastern Gneiss domains (Fig. 1) are located to the east of the large greenstone domains, together with which they approximate the extent of the Eastern Goldfields Province (Gee, 1979). The Southern Cross, Lake Johnston and Forrestania domains (Fig. 1) are located to the west and southwest of the large greenstone domains and correlate with the Southern Cross Province (Gee, 1979). The gneiss-granite domains have many features in common. They are poor to moderately magnetised and contain sparse nebulous anomalies of slightly higher magnetisation. Cross-cutting lineaments are abundant. The gneiss-granite

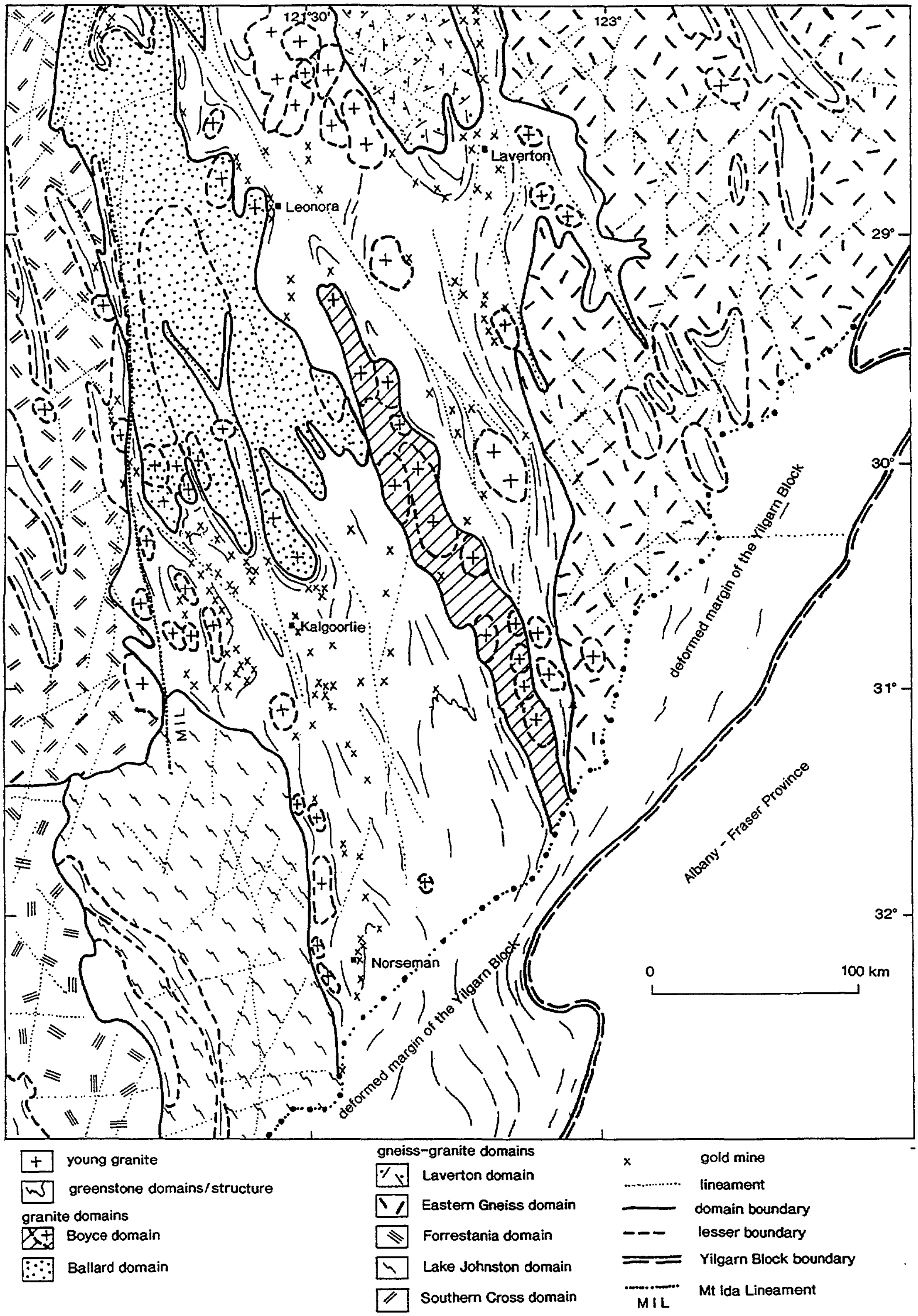

Fig. 1. The domains of the Eastern Goldfields Province as determined from regional aeromagnetic data. Lithological layering in the greenstone domains is dominantly oriented north-northwest to north though layering generally parallels local boundaries with the gneiss-granite and domed granite domains. Gold deposits correlate with some lineaments, structural complexities and equivalent stratigraphy.

domains coincide with Bouguer anomalies of intermediate value (-650 um.sec^{-2}). Bouguer anomaly variation over the domains is low and is interpreted as indicating the upper crust is of relatively constant density. Few discrete bodies of granite are resolved in the domains by either the aeromagnetic (regional and detailed) or gravity data, so either their density and apparent susceptibility are similar to accompanying migmatite and gneiss or they are uncommon. Each of the gneiss-granite domains enclose small remnants of greenstone recognised by outcrop, corresponding small zones of abnormally low and high magnetisation, and high Bouguer anomalies. Remnants in the Southern Cross domain commonly contain highly magnetised banded iron formation (BIF), and are similar in both average and variability of magnetisation to greenstone belts further west. Magnetisation and orientation of lithological trends of remnants in the other domains most closely resemble those of the two large greenstone domains of the Eastern Goldfields Province.

Greenstone domains

The two large greenstone domains of the Eastern Goldfields Province (Fig. 1) are poorly magnetised relative to adjacent gneiss and granite domains. Most rocks in these domains are similarly magnetised and are not resolved in regional aeromagnetic surveys. Sparse highly magnetised, elongate bodies are distributed throughout both domains and correlate with ultramafic rocks and BIF. Very highly magnetised BIF is more common in the east of both domains. Where these units are laterally extensive, associated anomaly patterns provide structural information on the domains. Compositional layering in the domains is dominantly oriented north-northwest to north, grossly aligned with the orientation of the major lineaments (320-330° and 345-350°). However, the layering shows considerable variation from these trends, being generally sub-parallel to the boundaries with adjacent gneiss and granite domains. The greenstone domains correlate with areas of dominantly high gravity. Bouguer anomalies of -350 um.sec^{-2} occur above basalt, dolerite, ultramafic rocks and BIF. Less abundant anomalies of -750 um.sec^{-2} occur above granite.

The greenstone domains have similar gross magnetisation, lithological composition and distribution, and deformation, and are considered to be part of a once more continuous basin. The regional geophysical data indicate that the two domains constitute the largest extent of greenstone in the Yilgarn Block. Together they represent a basin that currently stretches 800 km north-south across the Block and is at least 200 km wide (400 km wide if as inferred, remnants further east are part of the same basin).

Mineralisation in the Eastern Goldfields Province is dominated by gold and nickel and is almost entirely confined to the greenstone domains. Gold mineralisation shows a close association with some lineaments, equivalent stratigraphy and structural complexities. Mineralisation is particularly common in structures developed adjacent to the boundaries of the greenstone with the gneiss-granite basement and domed granite (Fig. 1). No gross regional zonation of gold or nickel deposits is evident between or across the two large greenstone domains.

Granite domains, isolated granite and dykes

The Ballard and Boyce domains are dominated by granite and together separate the two greenstone domains. The Ballard domain abuts the Southern Cross domain in the west and the Boyce domain in the east. It coincides with Bouguer anomalies of -800 um.sec^{-2} which are comparable with anomalies over large bodies of granite in the region and are lower than anomalies associated with gneiss (-650 um.sec^{-2}). The domain consists of several moderately magnetised ovoid features inferred to be domes. The domes are commonly surrounded by concordant sub-parallel anomalies which correspond to banded gneiss or highly metamorphosed greenstone. Greenstone occurs within the domain both as isolated enclaves and as narrow belts between domes. Long axes of the domes are oriented north-northwest to north, parallel to the gross lithological trends of the adjacent greenstone domains.

The Boyce domain is a long linear belt of similarly magnetised granite plutons which is aligned north-northwest (335°) from near the south-eastern boundary of the Yilgarn Block, to the eastern boundary of the Ballard domain. The axes of individual plutons are oriented 345° and are parallel to the regional cleavage. Intrusion along a long-lived tectonic structure is postulated (Williams & Whitaker, 1993).

Granite is also relatively common in the greenstone domains. Plutons range from high to low magnetisation and several are zoned. Their shape in plan view is highly variable and includes nearly circular, ovoid, dumbell and deformed tear drop shapes. Both concordant and discordant contacts are observed with enclosing greenstone. Much granite has similar magnetisation to the surrounding greenstone and is not resolved by aeromagnetic data. Larger granite plutons coincide with Bouguer anomalies of -750 to -800 um.sec^{-2}.

All domains are cut by long east-west and north-northwest trending dyke suites. Detailed aeromagnetic data resolve some of the east west dykes into en echelon dykes that step between subparallel fractures. The dykes are generally continuous across lithological boundaries and major lineaments and are considered post cratonic.

Discussion

Greenstone belts show the greatest variation in geophysical properties of the upper crust in the Eastern Goldfields Province. Gneiss-granite domains to the east and west of the major greenstone domains show similar gravity anomalies and magnetisation. Structural deformation of the greenstones has caused a dominance of north-northwest oriented lithological trends. The strong directional control of these trends contrasts with the relatively random compositional layering trends of the gneiss-granite domains. The age relationship of the gneiss-granite domains with greenstones are uncertain. Field evidence indicates that contacts are tectonic (Williams & Whitaker, 1993) with greenstone of high metamorphic grade (high pressure and temperature) in sheared or faulted contact with the gneiss-granite domains. In the larger greenstone domains, metamorphic grade decreases with distance from the contacts (Binns & others, 1976). There is little doubt that the gneiss-granite domains have been at deeper crustal levels than much of the greenstone. The lateral extent of the gneiss-granite domains, the occurrence in these domains of greenstone remnants and the metamorphic relationships are used to infer these domains are basement to greenstone.

There is no geophysical evidence to support the presence of a major accretionary tectonic boundary within the greenstones of the Eastern Goldfields Province. Close similarities of magnetisation, distribution of highly magnetised ultramafic and BIF, and gravity anomalies between the proposed marginal basin and arc associations (Barley & others, 1989) are evidence against gross changes in depositional environment. An accretionary model should bring together crust with different compositions and structural history; however, both the crust and deformation represented by the gneiss-granite domains on either side of the large greenstone domains appear to be similar. Furthermore, mineralisation within the greenstones shows no strong regional zonation as might be expected from the asymmetry of geological environment provided by accretion and subduction. Arguments against the accretion of oceanic crust (Gilkson, 1972) include evidence that basalt in the southern greenstone domain contains xenocrystic zircons from underlying continental crust (Compston & others, 1986).

The gross similarity of magnetisation, magnetisation contrasts, deformation and component lithologies of greenstone throughout the Eastern Goldfields provide some support for a model involving a laterally extensive greenstone basin development. The magnetic characteristics of these greenstones differ from those of the Southern Cross Province which contain a higher proportion of highly magnetised BIF. The change in greenstone types as defined by aeromagnetic data approximates the position and orientation of the north-northwest trending Mount Ida Lineament, although minor greenstones, similar to those of the Eastern Goldfields occur immediately west of this lineament. No other tectonic feature has been recognised between these contrasting greenstone types. Deformation of the greenstones of both the Eastern Goldfields and the Southern Cross Province seem closely associated with the major lineament directions, though these are dominantly north-northwest in the Eastern Goldfields, but show a greater range of north-northwest to north-northeast in the Southern Cross Province. Thus, greenstone basin development may have resulted from intra-cratonic rifting (Blake & Groves, 1987) with long lived lineaments influencing subsequent deformation. Variations in the extent of rifting may account for differences in lithological abundance between the basins.

The application of an extension tectonic model to the late evolutionary history of the greenstones of the Eastern Goldfields Province is described by Williams & Whitaker (1993). The geophysical data define a domain dominated by domed granite (the Ballard domain) between the main greenstone domains. The domes are surrounded by high-grade gneiss and greenstone. Shears that host several gold deposits separate the high grade rocks from low grade greenstone. These features are well accomodated by a model of extension and metamorphic core complex formation.

The geophysical data provide few obvious constraints on the mantle plume tectonic model of Campbell & Hill (1988). High density, basalt rich greenstone occurs over a linear extent of at least 800 km in the Eastern Goldfields Province. Komatiite, though considerably less abundant, occurs over approximately the same area. Older greenstones of the Southern Cross Province (Pidgeon & Wilde, 1990) also contain abundant basalt and minor komatiite. However, if mantle plumes are initiators of greenstone basin development, as well as required to explain the abundance of mafic and ultramafic material in the basins, then the model must also accommodate the apparent north-south elongation and eastward younging of the basins.

A model encompassing basin development in intra-cratonic rifts (Blake & Groves, 1987), followed by extension and gneiss-granite domain (greenstone basement?) uplift (Williams & Whitaker, 1993) is thought to best explain the distribution and deformation of greenstones in the Eastern Goldfields. The geophysical data do little to constrain possible models for the formation of the pre-greenstone continental crust. Widespread geochemical and isotopic studies (including zircon dating) are required to determine if the gneiss-granite domains are distinct terranes, and also whether they represent basement to the greenstones.

References

Archibald, N.J., Bettenay, L.F., Binns, R.A., Groves, D.I. & Gunthorpe, R.J. 1978, The evolution of Archaean greenstone terrains, Eastern Goldfields Province, Western Australia, *Precambrian Research*, 6, pp 103-131.

Archibald, N.J., Bettenay, L.F., Bickle, M.J. & Groves, D.I. 1981, Evolution of Archaean crust in the Eastern Goldfields Province of the Yilgarn Block, Western Australia, in *Archaean Geology*, eds. J.E. Glover & D.I. Groves, Special Publication No. 7, Geological Society of Australia, pp 491-504.

Barley , M.E., Eisenlohr, B.N.,Groves, D.I., Perring C.S., & Vearncombe, J.R, 1989, Late Archaean convergent margin tectonics and gold mineralisation: A new look at the Norseman-Wiluna Belt, Western Australia, *Geology*, 17, pp 826-829.

Binns, R.A., Gunthorpe, R.J., & Groves, D.I., 1976, Metamorphic patterns and development of greenstone belts in the eastern Yilgarn Block, Western Australia, in Early history of the Earthed. B. Windley, Wiley London, pp 303-313.

Blake, T.S., & Groves, D.I. 1987, Continental rifting and the Archaean - Proterozoic transition, *Geology*, 15, pp 229-232.

Campbell, I.H., & Hill, R.I. 1988, A two stage model for the formation of the granite-greenstone terrains of the Kalgoorlie-Norseman area, Western Australia, *Earth and Planetary Science Letters*, 90 pp 11-25.

Compston, W, Williams, I.S., Campbell, I.H., & Gresham, J.J. 1986, Zircon xenocrysts from the Kambalda volcanics: age constraints and direct evidence for older continental crust below the Kambalda-Norseman greenstones, *Earth and Planetary Science Letters*,76, pp 299-311.

Gee, D.R. 1979, Structure and tectonic style of the Western Australian Shield, *Tectonophysics*, 58, pp 327-369.

Glikson, A.Y. 1972, Early Precambrian evidence of a primitive ocean crust and island nuclei of sodic granite, *Geological Society of America Bulletin* 83, pp 3323-3344.

Pidgeon, R.T. & Wilde, S.A. 1990, The distribution of 3.0 Ga and 2.7 Ga volcanic episodes in the Yilgarn Craton of Western Australia, *Precambrian Research*, 48, pp 309-325.

Whitaker, A.J. 1992, Kalgoorlie magnetic and gravity interpretation, 1:1M scale map, Australian Geological Survey Organisation, Canberra.

Williams, P.R., & Whitaker, A.J. 1993, Gneiss domes and extensional deformation in the highly mineralised Archaean Eastern Goldfields Province, Western Australia, *Ore Geology Reviews*, 8, pp 141-162.

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Stratigraphy and structure in the southeastern Goldfields Province

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The Kalgoorlie Terrane in the Eastern Goldfields Province was proposed several years ago as a regional fault-bounded greenstone belt characterized by a distinctive lithostratigraphy (Swager & others, 1990). Adjacent terranes contain different rock types, have different successions of rock types, and may have different ages, but appear to have undergone the same regional deformation history. The Barlee Terrane (Myers, 1990) lies west of the Kalgoorlie Terrane and is separated from it by the Ida Fault. This boundary fault is a major crustal structure that dips shallowly east to a depth of at least 25 km and has an inferred normal displacement (Drummond & others, 1993). The greenstones in the Barlee Terrane include rock types not seen in the Kalgoorlie Terrane, such as locally preserved basal quartzite and quartz pebble conglomerate, and widespread oxide facies banded iron-formation within mafic volcanic sequences. U-Pb zircon geochronology, though at best sketchy, suggests that the youngest volcanic rocks in the Barlee Terrane (2.735 Ga) predate the Kalgoorlie greenstones by approximately 20 Ma (2.71-2.68 Ga; Claoue-Long & others, 1988; Pidgeon & Wilde, 1990; Hill & others, 1992).

East of the Kalgoorlie Terrane, recent mapping has revealed several fault-bounded domains, which, despite many similarities, have distinctive tectono-stratigraphic features (Fig. 1). The stratigraphy, internal structure and bounding faults of these domains, and possible correlations across the faults, should determine their tectono-stratigraphic status. Detailed U-Pb zircon age dating of the greenstone sequences—a prerequisite for regional correlations—is planned for the near future.

Boundary faults between the domains are largely inferred from regional discontinuities (such as stratigraphic truncations), and are only locally exposed as shear zones of variable width. Displacements inferred from structural fabrics may only reflect late stages of movement, whereas the boundary faults are probably long-lived with multiple stages of substantial movement (Swager & others, 1990; Williams & others, in prep.).

The Emu Fault separates a west-dipping homoclinal sequence in the Jubilee domain from an anticlinal or domal structure in the Gindalbie domain. The fault is buried under a coarse polymictic conglomerate that unconformably overlies greenstones in both domains. The conglomerate appears transitional to a greywacke + BIF sequence to the south. Seismic reflection profiling (Goleby & others, 1993) indicates a 30° westerly dip for the Emu Fault and underlying Jubilee greenstones, and a hanging wall anticline in the Gindalbie greenstones. This geometry may indicate west-to-east thrusting of the Gindalbie domain onto the Jubilee domain, possibly following an earlier extensional event. Deposition of the clastic rocks attests to the substantial movements along the Emu fault, and probably predates late stage shortening/thrusting because the rocks are metamorphosed and contain the regional upright foliation.

The Yilgangi Fault, like the Emu Fault, appears to lie along a synformal axial trace for a large part of its strike length, and is partly overlain by a coarse polymictic conglomerate. On a regional scale substantial stratigraphic sequences are cut at a low angle by the fault. The Yilgangi Fault is the southern continuation of the Keith–Kilkenny Fault, a major regional discontinuity.

The Claypan Fault is exposed locally and shows subhorizontal mineral lineations with left-lateral movement indicators. By way of contrast, the Pinjin Shear contains steeply west-dipping (down-dip) lineations with west-side-down displacement. This shear separates domains at substantially different metamorphic grades.

Most domains contain similar rock types to those in the Kalgoorlie Terrane, but in different proportions or different tectono-stratigraphic sequences. In general, lateral facies (and tectonic?) variations are more apparent in contrast to

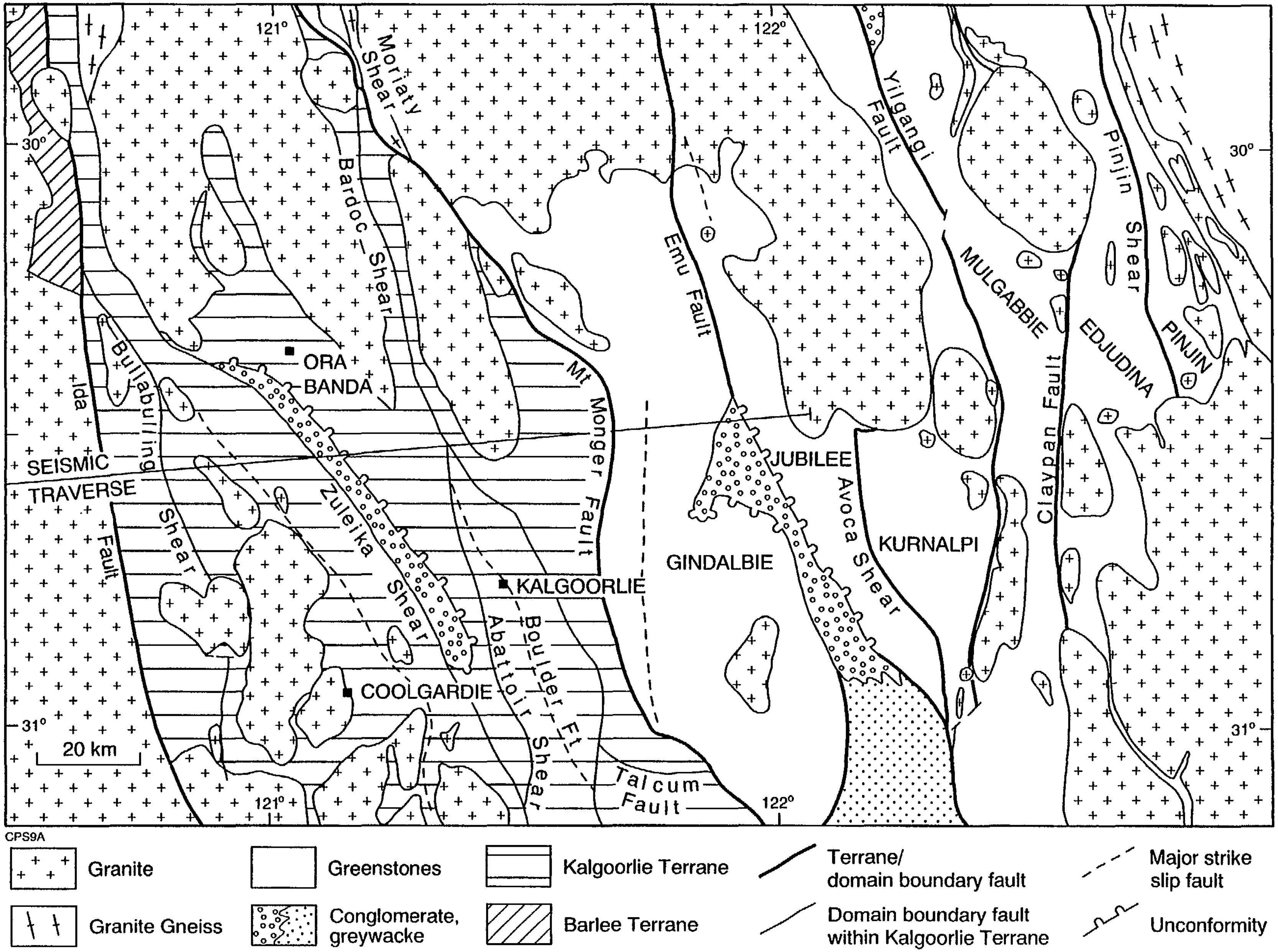

Fig. 1. Regional overview of greenstone terranes and domains, and their bounding faults in the southern Eastern Goldfields Province. Approximate position of the AGSO 1991 seismic traverse is shown.

the almost layer-cake stratigraphy in the Kalgoorlie Terrane. They also contain oxide facies BIF.

The Gindalbie domain is best exposed in the south as a doubly-plunging north-northwest trending anticline. Felsic volcanic rocks in the core of the anticline are in low angle fault contact with overlying komatiite (dominated by olivine cumulate; Ahmat, this volume) and basalt. This mafic-ultramafic sequence is deformed by early layer-parallel faults and recumbent folds which are refolded around the upright anticline or dome, and which are crosscut by later strike-slip faults. The felsic volcanics have been provisionally dated at 2.71 Ga (Compston & others, 1986), and are older than or as old as the lowest mafic unit in the Kalgoorlie Terrane. One possible interpretation is that the felsic volcanics are equivalent to strongly deformed felsic rock duplexes inferred below the Kalgoorlie Terrane stratigraphy from seismic and gravity data (Goleby & others, 1993), and that the mafic-ultramafic rocks correlate with those in the Kalgoorlie Terrane. This would suggest that the Gindalbie domain is part of the Kalgoorlie Terrane.

The Jubilee greenstones contain komatiite layers at up to four levels within a west-dipping sequence with apparent lateral variations from basalt-dominated to felsic volcaniclastic dominated. There are suggestions of, but no definite evidence for, stratigraphic repetition by early thrusting.

The Kurnalpi and Mulgabbie domains have several structural-stratigraphic features in common, but are separated by the Yilgangi–Kilkenny fault system which can be traced throughout the Eastern Goldfields Province. Both domains contain apparently thick successions with several mafic-ultramafic volcanic sequences interleaved with felsic volcanic-volcaniclastic rocks. Komatiite forms relatively thin and laterally discontinuous units in this southern part. Lateral (facies?) variations and wedged-out sequences of andesitic rocks are present within the Mulgabbie domain. Both stacking of mafic-to-felsic volcanic piles during early thrusting and/or (partly overlapping) cycles of mafic-to-felsic volcanism could explain the regional successions in these domains. The successions in both domains show truncation against the Yilgangi Fault.

The Edjudina domain is characterized by persistent BIF and several distinct felsic (acid - intermediate) volcanic complexes in addition to basalt, some komatiite, and intermediate volcaniclastic rocks. Little is known about the internal structure although large recumbent folds in BIF indicate structural thickening.

The Pinjin domain contains a basalt (+ andesite)-dominated sequence with interleaved komatiite, felsic volcanic rocks and BIF. This well-foliated sequence, which is similar to that in the Barlee Terrane, is metamorphosed at low to upper amphibolite facies. Metamorphic grade increases eastwards to the contact with migmatitic banded granite-gneiss, with increasing amounts of variably foliated granite interleaved with the greenstones. The western boundary fault of the domain, the Pinjin Shear, records west-side-down movement, which is compatible with the juxtaposition of the higher grade rocks in this domain against the lower grade Edjudina domain.

The Pinjin domain may represent a crustal section, with progressively deeper levels exposed to the east; the banded granite-gneiss may represent remnants of the 'basement' to the greenstones. The overall structure developed during east-west extension, probably relatively late in the tectonic history.

In early regional interpretations, the Kalgoorlie Terrane and all domains to the east lie within the Norseman–Wiluna Belt as defined by Gee & others (1981). Williams (1976) emphasized similarities in the greenstone sequences, and proposed three cycles of mafic-to-felsic volcanism, each cycle overlain by clastic units. Groves & Batt (1984) drew attention to an apparent asymmetry within the belt; they distinguished a western rift sequence with komatiite and an eastern zone with abundant felsic volcanic rocks. More recently, Barley & others (1989) redefined this asymmetry within the belt in terms of marginal basin (tholeiite-komatiite) and volcanic arc (tholeiite-calc-alkalic volcanics) associations. Recent mapping indicates, however, that the western sequence contains equally large volumes of felsic volcanic rocks.

Interpretation of the tectonic development of the domains should take into account, among other factors, the probable presence of felsic basement throughout the tectonic history (for example, Archibald & others, 1981; Hill & others, 1992; Drummond & others, 1993), the 'variations on a theme' character of the greenstone sequences, possibly slightly different ages of the greenstones, the possible stacking of sequences during several deformation stages, and a proposed phase of regional east-west extension after early thrust stacking but before east-west regional shortening (Williams & others, in prep.). The preferred model involves adjacent ensialic basins with different volcanic sequences (early versus late stages, deep versus shallow basins), separated by domes and/or syn-volcanic faults. A late-stage overlap succession linking adjacent basins may have consisted of felsic volcanic-volcaniclastic piles which signalled the end of the main depositional history, and which may be related to the earliest intrusive granites (circa 2.685 Ga; Hill & others, 1992). Coarse clastic sequences in isolated basins have locally developed on top of early (south-to-north) thrust faults, and contain the regional upright foliation. These basins may have formed during regional extension, and were caught up in subsequent east-west regional shortening and stacking.

References

Archibald, N.J., Bettenay, L.F., Bickle, M.J. & Groves, D.I. 1981, Evolution of Archaean crust in the Eastern Goldfields Province of the Yilgarn Block, Western Australia, in *Archaean Geology*, eds. J.E. Glover & D.I. Groves, Second International Symposium, Perth, 1980. Special Publication Geological Society Australia 7, pp 491-504.

Barley, M.E., Eisenlohr. B., Groves, D.I., Perring, C.S. & Vearncombe, J.R. 1989, Late Archaean convergent margin tectonics and gold mineralization: a new look at the Norseman-Wiluna Belt, Western Australia. *Geology*, 17, pp 826-829.

Claoue-Long, J.C., Compston, W. & Cowden, A. 1988. The age of the Kambalda greenstones resolved by ion-microprobe: implications for Archaean dating methods. *Earth and Planetary Science Letters*, 89, pp 239-259.

Compston, W., Williams, I.S., McNaughton, N.J., Martyn, J.E., Groves, D.I. & deLaeter, J.R. 1986, Unpublished manuscript.

Drummond, B.J., Goleby, B.R., Swager, C.P. & Williams, P.R. 1993, Constraints on Archaean crustal composition and structure provided by deep seismic sounding in the Yilgarn Block, *Ore Geology Reviews*, 9, pp 117-124.

Gee, R.D., Baxter, J.L., Wilde, S.A. & Williams, I.R. 1981, Crustal development in the Yilgarn Block, Western Australia, in *Archaean Geology*, eds. J.E. Glover & D.I. Groves, Second International Symposium, Perth, 1980. Special Publication Geological Society Australia 7, pp 43-56.

Goleby, B.R., Rattenbury, M.S., Swager, C.P., Drummond, B.J., Williams, P.R., Sheraton, J.W. & Heinrich, C.A. 1993, Archaean crustal structure from seismic reflection profiling, Eastern Goldfields, Western Australia, *Australian Geological Survey Organisation Record* 1993/15.

Groves, D.I. & Batt, W.D. 1984, Spatial and temporal variations of Archaean metallogenic associations in terms of evolution of granitoid-greenstone terrains with particular emphasis on Western Australia, in *Archaean Geochemistry*, eds. A. Kroner, G.N. Hanson & A.M. Goodwin, Springer-Verlag, Berlin, pp 73-98.

Hill, R.I., Chappell, B.W. & Campbell, I.H. 1992, Late Archaean granites of the southeastern Yilgarn Block, Western Australia: age, geochemistry, and origin, *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 83, pp 211-226.

Myers, J.S., 1990, Precambrian tectonic evolution of part of Gondwana, southwestern Australia. *Geology*, 18, pp 537-540.

Pidgeon, R.T. & Wilde, S.A. 1990, The distribution of 3.0 and 2.7 Ga volcanic episodes in the Yilgarn Craton of Western Australia, *Precambrian Research*, 48, pp 309-325.

Swager, C.P., Griffin, T.J., Witt, W.K., Wyche, S., Ahmat, A.L., Hunter, W.M., & McGoldrick, P.J. 1990, Geology of the Archaean Kalgoorlie Terrane - an explanatory note, *Western Australia Geological Survey Record* 1990/12.

Williams, I.R. 1976, Regional interpretation map of the Archaean geology in the southeast part of the Yilgarn Block. 1:1 000 000 Map Series, Geological Survey Western Australia.

Williams, P.R. & Whitaker, A.J. 1993, Gneiss domes and extensional deformation in the highly mineralised Archaean Eastern Goldfields Province, Western Australia, *Ore Geology Reviews*, 8, pp 141-162.Williams, P.R., Rattenbury, M.S., Swager, C.P., Goleby, B.R. & Drummond, B.J. in preparation, Archaean greenstone architecture from seismic reflection profiling, Eastern Goldfields, Western Australia.

Tectonostratigraphic terranes in the northern Eastern Goldfields

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The structural and stratigraphic contexts of greenstone belts have been re-examined in light of new mapping, and the introduction of the terrane concept to the Eastern Goldfields. The NGMA Eastern Goldfields Project has recently mapped parts of the Menzies, Leonora, Laverton and Edjudina 1:250 000 sheets and offered the opportunity to reassess regional correlations of local stratigraphic sequences by previous studies such as Williams et al. (1976), Gower (1976), Hallberg (1985), and Swager & Griffin (1990). Utilising new mapping techniques such as detailed aeromagnetic imagery and new concepts arising from, for example, the recent crustal seismic reflection study, he significance of structures between greenstone belts can be more confidently assessed. The recently mapped area has been divided into a number of domains, and the Murrin and Margaret domains essentially correspond to "sectors" defined by Gower (1976) and Hallberg (1985). The broad stratigraphic scheme of Hallberg (1985) in these domains has been confirmed (Fig. 1), although some areas have been reassigned to different parts of the scheme. Furthermore, this stratigraphy can be correlated across apparent major structures, such as the Keith–Kilkenny Tectonic Zone, to local stratigraphic sections in the Leonora, Lawlers, and Mt Ida domains as well as linking with the scheme erected for the Kalgoorlie–Kambalda region (Fig. 1).

Most ultramafic rocks in the Eastern Goldfields, including the komatiites and the olivine-rich cumulates, are considered to be extrusive flow rocks (Hill & others, 1988). Komatiitic lavas have very low viscosities so that the lateral distribution of flows is largely controlled by topography existing at the time of eruption, and single unimpeded komatiite flows may travel more than 150 km. Ultramafic layers, therefore, have the potential to be important stratigraphic markers units. The problem is, however, to determine how many resolvable ultramafic flow horizons occur within the regional Eastern Goldfields greenstone stratigraphic framework. The number of stratigraphically resolvable ultramafic layers within individual greenstone belts can be assessed in relatively continuous, well understood stratigraphic sections (Fig. 1). The established Kalgoorlie Terrane stratigraphic scheme (Swager & Griffin 1990) has only one ultramafic horizon (commonly repeated by D1 thrusting), and most stratigraphic sections through individual greenstone belts in the northern Eastern Goldfields have only one ultramafic horizon. Exceptions include the Benalla Anticline within the Murrin domain which shows an unusually thick stratigraphic section bracketed by ultramafic horizons. Sections from Lawlers and Margaret domains indicate multiple levels of ultramafic rock.

Correlation of ultramafic layers between greenstone belts has been achieved by matching associations of mafic, felsic and intermediate volcanic and sedimentary sequences above and below each ultramafic occurrence throughout the study area (Fig. 1). On this basis, a regional ultramafic marker horizon is apparent, comprising the upper ultramafic layer in the Murrin domain and most other single ultramafic layers in adjacent greenstones belts at a level equivalent to the komatiite horizon in the existing Kalgoorlie Terrane stratigraphic scheme. Single zircon U-Pb geochronology (Claoué-Long, pers. comm.) confirms the upper Murrin domain ultramafic layer is the same age (within analytical error) as the komatiite from the Kambalda region in the Kalgoorlie Terrane. The Mt Ida domain mafic-ultramafic greenstone sequence correlates (Fig. 1) with the stratigraphy north of Leonora towards Clifford Bore, the upper part of the Murrin domain stratigraphy, and the Lawlers domain. The Keith–Kilkenny Tectonic Zone appears to contain a younger section of the stratigraphy. The Margaret domain stratigraphy is complicated by multiple levels of ultramafic rocks, and the stratigraphic position of the proposed regional ultramafic marker horizon

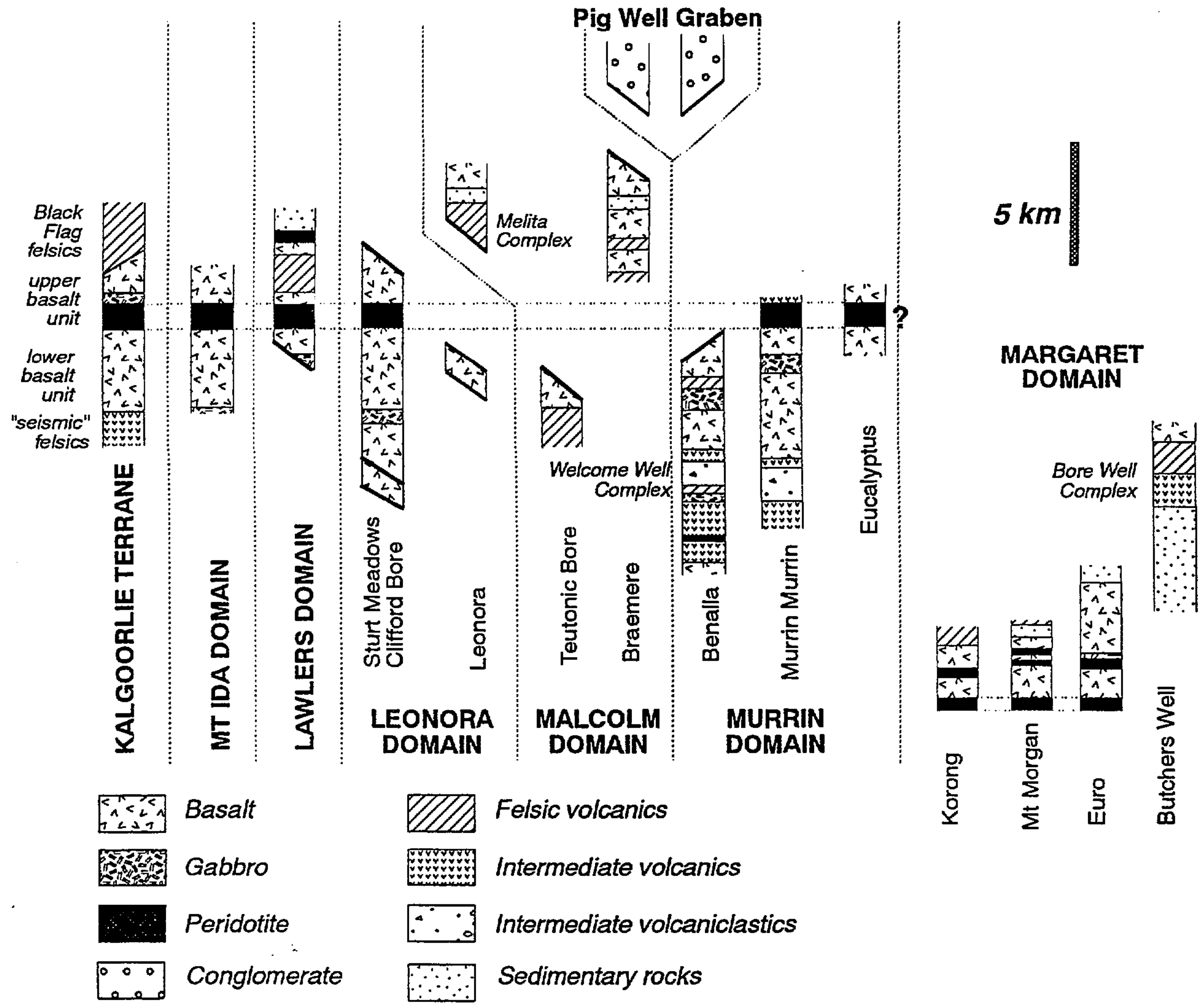

Fig. 1. Schematic stratigraphic columns from greenstone belts in the Eastern Goldfields. Vertical scale very approximate and assumes no structural repetition or excision except where shown by fault breaks.

in the Margaret domain is uncertain (Fig. 1). The boundary between the Murrin and Margaret domains west of Korong may be a fault which has juxtaposed different levels of the stratigraphy. Aeromagnetic imagery suggests this fault continues south between the Eucalyptus mafic-ultramafic volcanics and the Bore Well felsic-intermediate volcanics to the east, and probably continues as the boundary between the Edjudina and Mulgabbie domains (of Swager, this volume).

Felsic and intermediate volcanic centres occur at at least two stratigraphic levels, above and below the ultramafic marker horizon (Fig. 1). The Welcome Well volcanic centre lies stratigraphically below the ultramafic marker whereas the Melita and Black Flag volcanic centres are younger than the ultramafic marker. The Bore Well felsic-intermediate volcanic centres cannot yet be confidently placed into a regional stratigraphic context. The recognition of intermediate and felsic volcanic rocks older than the lowest known mafic-ultramafic sections of the Kalgoorlie Terrane stratigraphy supports the recent crustal seismic reflection/gravity traverse interpretation of basal felsic (volcanic?) rocks below the lowermost basalt (Goleby & others, 1993).

The application of terrane terminology to the Eastern Goldfields should be reassessed in the light of regional stratigraphic correlations. Terrane nomenclature was introduced by Swager & others, (1992) to identify fault-bounded blocks defined by the presence (or absence) of particular rock types, by a distinctive stratigraphy, by characteristic structures or structural history and/or differences in age, based on the limited geochronology available. Distinctive rock types such as komatiite, and the Kalgoorlie Terrane stratigraphic sequence appear to extend well outside the presently defined Kalgoorlie Terrane boundary, and new precision U-Pb dating is suggesting there are no significant differences in age. The crustal seismic reflection study also traversed the Mt Monger Fault, which is the Kalgoorlie Terrane eastern boundary in that area, and did not reveal any sufficiently major structures indicative of a terrane boundary. The stratigraphic relationship of the Laverton region to areas west is ambiguous but the differences in stratigraphy and rock type may not be significant enough to warrant separate terrane status. High-precision single zircon U-Pb dating of the Laverton stratigraphy is viewed as a priority target which could aid understanding of the greenstone belt sequences east of Kalgoorlie.

References

Goleby, B.R., Rattenbury, M.S., Swager, C.P., Drummond, B.J., Williams, P.R., Sheraton, J.W., Heinrich, C.A. 1993, Archaean crustal structure from seismic reflection profiling, Eastern Goldfields, Western Australia. *AGSO Record* 1993/15.

Gower, C.F. 1976, Laverton, W.A. Geological Survey of Western Australia 1:250,000 Geological Series Explanatory Notes, Sheet SH/51-1.

Hallberg, J.A. 1985, *Geology and mineral deposits of the Leonora-Laverton area, northeastern Yilgarn Block, Western Australia.* Hesperian Press, Perth.

Hill, R.E.T., Gole, M.J., Barnes, S.J. 1988, Physical volcanology of komatiites. *Geological Society of Australia (W.A. Division) Excursion Guidebook* no. 1.

Swager, C.P., Griffin, T.J. 1990, Geology of the Archaean Kalgoorlie Terrane (Northern and Southern Sheets) 1:250 000 Geological Map, Geological Survey of Western Australia.

Swager, C.P., Witt, W.K., Griffin, T.J., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J., Wyche, S. 1992, Late Archaean granite-greenstones of the Kalgoorlie Terrane, Yilgarn Craton, Western Australia. Geology Dept (Key Centre) & University Extension, *The University of Western Australia publ.* 22: 107-122.

Williams, I.R., Gower, C.F., Thom, R. 1976, Edjudina, W.A. Geological Survey of Western Australia 1:250,000 Geological Series Explanatory Notes, SH/51-6.

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A new hypothesis for the evolution of the Eastern Goldfields Province

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Over the past few years, there has been a resurgence of research activity aimed at determining the structural evolution of the greenstone belts of the Eastern Goldfields Province (EGP) from widely spaced areas, and from that to develop a regional structural and tectonic synthesis. This has involved research into the geometry of granite/greenstone margins, the metamorphic features of the gneiss/granite regions immediately adjacent to those margins, definition of geophysical domains in areas dominated by granitoids (Williams & Whitaker, 1993), and geochemical studies of the felsic igneous rocks (eg Wyborn, 1992; Witt & Davy, 1993; Champion & Sheraton, 1993). Results from the recent seismic deep crustal reflection profile (Goleby & others, 1993; Williams & others, in press) have added considerably to understanding of the structural evolution, and placed additional constraints on the timing and geometry of movement episodes. Models for the emplacement of the gneissic rocks as metamorphic core complexes formed in an extensional environment (Williams & others, 1990; Hammond & Nisbet, 1992; Williams & Currie, 1993) appear reasonable to explain many of the features observed, and there is now better evidence that the extension was of regional significance and took place in two episodes; basin formation and following a thrusting event. Thus despite some outstanding problems with regard to the structural history, it is now possible to construct structural models for the evolution of the greenstones, and use this as a basis to postulate a tectonic synthesis.

Stratigraphic setting

Although no definite basement to the greenstone sequences has been established, a regional stratigraphy has been identified in several regions, but particularly around Kalgoorlie and Kambalda. The lowest exposed unit is a thick basaltic succession, overlain by extensive komatiite flows. In places the komatiite is overlain by an upper basaltic succession. The upper part of the succession comprises felsic volcanic rocks and volcaniclastic sediments, in places unconformably overlain by conglomeratic sedimentary sequences. Age determinations on a variety of rock types within the Kalgoorlie region suggest that deposition of the sequence commenced just prior to 2700 Ma and continued until at least 2690 Ma (Claoué-Long, 1988; Campbell & Hill, 1988; Hill & others, 1989). There is speculation that felsic volcanic sequences underlie lower basalt unit, based largely on interpretation of gravity data in conjunction with the regional seismic traverse (Goleby & others, 1993, Williams & others, in press). In addition, Hallberg (1985) and Williams & others (1993) have mapped a significant section of intermediate volcanic and volcaniclastic rocks stratigraphically below the Kalgoorlie "lower basalt" equivalent in the area east of Leonora (Rattenbury & others, 1993). It seems unlikely, however, that greenstones in the northeastern Eastern Goldfields Province are older than 2735Ma, the oldest date so far obtained from within the greenstone stratigraphy (Pidgeon & Wilde, 1990).

Granitic gneiss and the nature of the margins

There is mounting evidence that the geological domains of the EGP and surrounding granitoids (Fig. 1) are derived from a range of crustal levels, and that the greenstones form a flat sheet which is separated by a detachment zone from the underlying felsic crust (Archibald, 1990; Goleby & others, 1993; Williams & others, in press). Felsic gneiss (from middle crustal levels) domains are commonly intruded by voluminous later granitic plutons and abundant minor granitic intrusions. Prior to the acquisition of the regional geophysical data, the nature and extent of the gneissic domains was poorly known, and their significance underestimated in most geological models for the EGP.

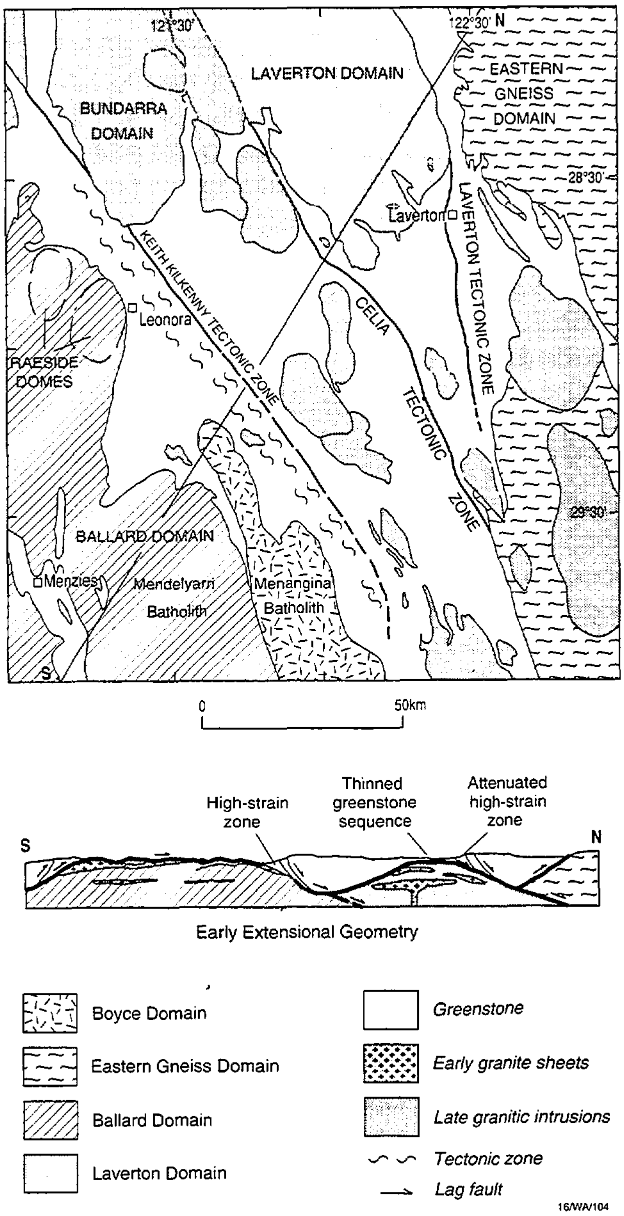

Fig. 1. A possible schematic deep cross section through the Eastern Goldfields along the Leonora-Laverton transect. The section does not attempt to portray details of the surface structures (modified from Williams & Whitaker, 1993).

Two samples of the gneiss have been analysed using SHRIMP 1 at the ANU Research School of Earth Sciences (L.P. Black; personal communication). Both samples are from the Riverina Gneiss, on the western margin of the EGP, which has a well-defined, complexely deformed gneissic banding and a distinctive lineated aeromagnetic pattern . The rocks are migmatitic in places, and of upper amphibolite metamorphic grade (based on thermobarometric calculations of mineral compositions in associated amphibolite bodies). Both samples have a relatively simple zircon population, with ages of 2684 ± 9 Ma (Bluey's Well) and 2680 ± 5 Ma (Peter's Bore). A small number (6) of grains from the Peter's Bore sample yielded older ages, and are presumed to be xenocrysts. A mutifaceted, probably metamorphic, zircon grain from the Peter's Bore sample yielded an age of 2677 ± 10 Ma. From these data, the gneiss is interpreted to be a metamorphosed equivalent of a granitic unit that was intruded at about 2680 Ma and metamorphed shortly afterwards. The absolute ages of other gneissic domains is still uncertain, and whether these domains either represent or contain basement, or are deformed, high-grade equivalents of some of the intrusive granites has yet to be determined.

Metamorphism

The metamorphic grade of the greenstone belt varies from very low in some areas to middle-upper amphibolite facies in narrow zones close to gneissic granites (eg Binns & others, 1976; Archibald & others, 1981). In addition, granite intrusions lying wholely within the greenstone belt have relatively narrow thermal aureoles in which post-kinematic andalusite porphyroblasts are common in appropriate rock types. The regional metamorphic pattern was mapped by Binns & others, (1976), and the timing of metamorphism in relation to the structural history discussed by Archibald & others, (1981). In the Kambalda area, peak metamorphism coincided with upright folding, and grade was controlled by proximity to nearby granite intrusions. However, at Leonora, several lines of evidence, principally andalusite, chloritoid and hornblende porphyroblast relationships (Williams & others, 1990; Passchier, 1990; Vanderhor, 1991) indicate that peak metamorphism was associated with extensional deformation and largely predated the upright folding. The grade of metamorphism drops rapidly away from the high-grade zones, and Williams & Currie (1993) suggest that peak metamorphism in the lower-grade areas was later than that in the amphibolite facies domains.

Results of interpretation and restoration of the seismic section

The seismic section provides constraints on the shape of the greenstone belt and its relationship to the underlying rocks, and defines the geometry of a major extensional event which probably occurred between two shortening events (Williams & others, in press). The geological cross-section interpreted from the seismic data is shown in Fig. 2a. The base of the greenstones is interpreted to be a major décollement surface. Thrust repetitions of the ultramafic units in the Kurrawang Syncline and on the eastern limb of the Scotia-Kanowna Anticline

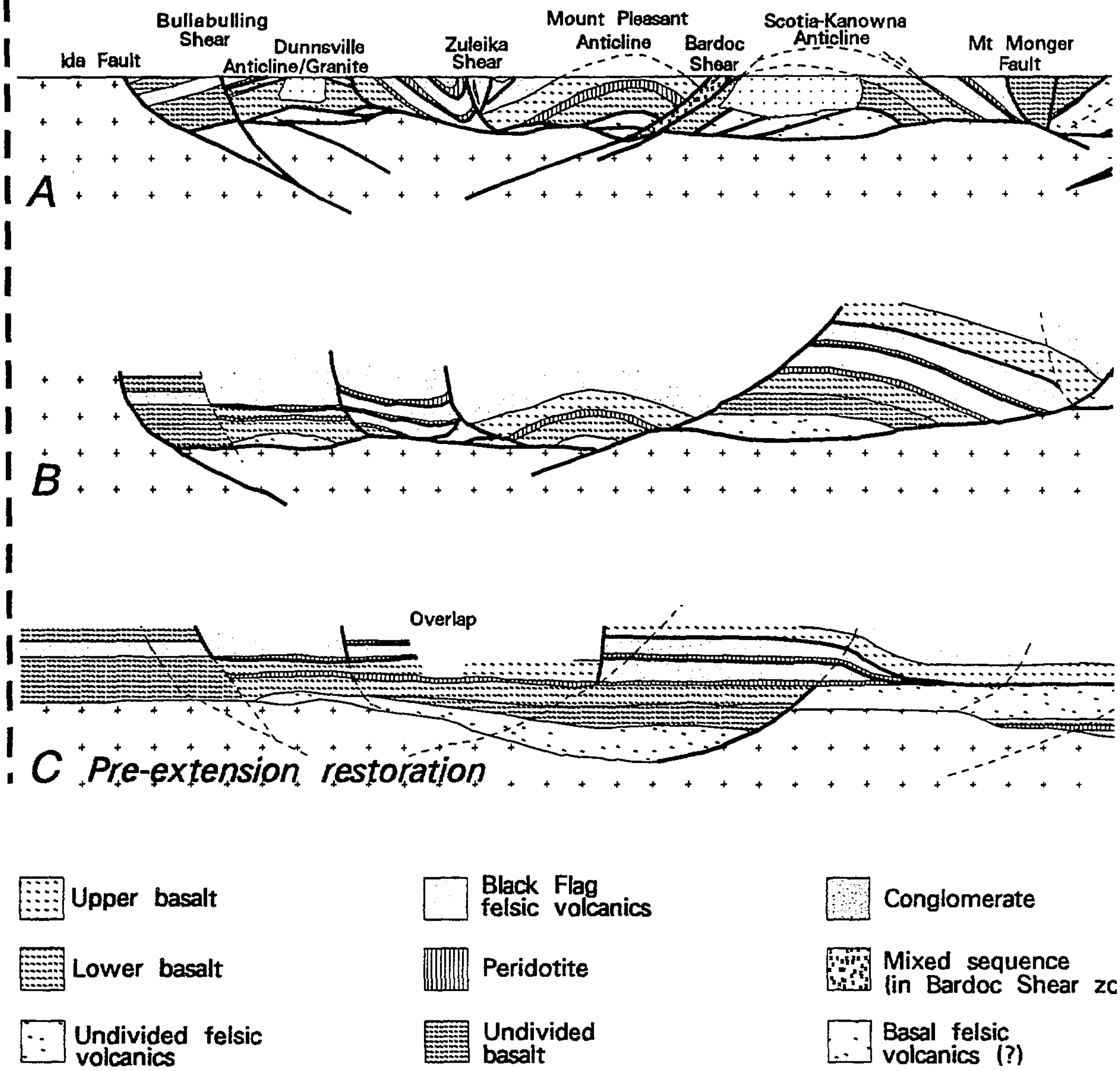

Fig. 2. Interpretation and restoration of the AGSO Seismic section—Kalgoorlie and adjacent Terranes. Restoration implies extension at two stages in the structural history (from Williams & others, submitted ms).

are inferred from both map and seismic data. Williams & others, (ms, submitted) suggest that because the repeated komatiite horizons are folded and cut by the Bardoc Shear, which is one of the major internal structures of the belt, the thrust faults pre-dated both upright folding and extension. Restoration of the section by removal of both upright folding and deformation associated with granite intrusion (line balanced at the komatiite horizon) is shown in Fig. 2b. The restoration assumes correlation of the komatiite unit above the lower basalt across domain and terrane faults, and clearly shows that the stratigraphy cannot be restored by removal of these deformations alone. The restored section reveals the extensional nature of several faults and the basal décollement, prior to the upright folding. The stratigraphic succession which is truncated by the basal décollement beneath the Scotia–Kanowna Anticline has the form of a major rotational fault block bounded to the west by the Bardoc Shear. Both the Zuleika and Bardoc Shears show normal displacement of the komatiite and lower basalt units. Restoration of the stratigraphy to its position prior to the extensional faulting is shown in Fig. 2c. Lateral changes in stratigraphy across the Mount Monger Fault have been interpreted as due to a syn-depositional growth fault, which accounts for the thickening of the greenstone sequence to the east. Although less definitive, the greenstones to the east of the Mount Monger Fault also appear to thicken to the east, implying they were deposited in an adjacent half-graben. The actual basin margin may have been further west than the Ida Fault, although the basal stratigraphy clearly thins towards the fault and the thickest part of the succession is against an internal growth fault. A total extension of 44% is inferred by the cross-section restoration.

The structural profile across the Basin

and Range–Colorado Plateau transects (Allmendinger & others, 1983; 1986) shows many similarities in style with that across the EGP. Similar stratigraphic cutouts occur on the basal décollements, and the upper plate fold and fault structures occur at similar positions in relation to the lower plate basement. This similarity reinforces the interpretation that the basal décollement to the greenstones was a significant extensional detachment fault during part of its history. The evidence from the seismic data in conjunction with limited geochronology indicates that substantial extensional displacement must be younger than early thrust deformation and hence basin formation.

Deformation history

The structural history of the EGP has been discussed by several authors (eg Archibald & others, 1978; Swager & others, 1990; Swager & Griffin, 1990; Williams & others, 1987; Hammond & Nisbet, 1992; Williams & others, in press). Table 1 shows a summary of the structural history of the Province established in different areas. All recognise an early phase of low-angle bedding-parallel deformation, a later phase of upright folding, and still later strike-slip faulting.

However, there are significant differences in the details of the structural history from different regions. In the northeast Goldfields, Hammond & Nisbet (1990; 1992; 1993) suggest that the early deformation was extensional, and that the later upright folding was accompanied by significant high-angle reverse faults which splay off a major décollement at depth. Archibald (1992) recognised two phases of early thrust deformation. Williams & Currie (1993) suggest that the earliest phase of low-angle deformation in the Leonora district is extensional rather than compressional.

Reconstruction and restoration of the seismic section provides support for a structural history commencing with:

- (1) deposition of greenstones in extensional half-graben with local internal growth faulting, followed by
- (2) thrusting,
- (3) regional extensional detachment and emplacement of granite as tabular "surf-board shaped" bodies, and emplacement of gneiss domes as core complexes, followed by,
- (4) east-west shortening with associated high-angle thrusts, and finally
- (5) strike-slip faulting, probably decoupled at a shallow level in the crust.

Clearly, more work is needed to resolve the issue of timing of regional deformation events, and the links between deformation sequences in different areas.

A regional tectonic model

In an attempt to explain the structural relationships, metamorphic history and the boundary relationships between gneiss, granite and greenstones, Williams & Currie (1993) and Williams & Whitaker (1993) have suggested that the emplacement of gneiss and granite domes may be related to regional extensional deformation. The emplacement model is based on rapid crustal uplift by mechanisms similar to those associated with metamorphic core complex formation in the Cordilleran tectonic setting. A cross section similar to that shown in Fig. 1 is likely in this type of model.

Juxtaposition of high-grade metamorphic rocks arising from mid-crustal levels against low-grade rocks requires substantial uplift of the mid-crustal rocks. This can be achieved through either multi-stage thick-skinned thrusting such as documented by Shaw & others (1992), or thermal uplift as metamorphic core complexes, commonly in an extensional tectonic setting. In the former process, the higher grade rocks normally occur structurally above the lower grade rocks, and the two sequences are bounded by either thrust or high-angle reverse faults. In the second environment, the reverse is true, and the lower grade rocks lie above the higher grade rocks on (originally) shallowly-dipping mylonitic faults. In the EGP, many authors have noted that gneiss and deformed (gneissic) granite usually underlie the greenstones, and that the boundaries between the two are marked by mylonitic shear zones with an extensional sense of shear. Williams & Currie (1993) have shown that the lower grade rocks are juxtaposed against higher grade rocks over a narrow interval in the Leonora area. Consequently, the major boundary fault in that area is one of structural excision of section, and not merely an intrusive boundary.

Crustal extension causes rapid uplift of material beneath the main detachment fault (lower plate), at the same time as the lower plate undergoes deformation by ductile non-coaxial laminar flow (Lister & others, 1986). Once extension has commenced, uplift is driven by thermal effects in the crust and isostatic compensation (Sonder & England, 1989; Buck, 1991). The thermal regime of the crust prior to extension has a major effect on the yield strength of the crust, with higher heat flow reducing initial yield strength. Thus a thermal input (such as

EVENT	STUDY			
	Swager & Griffin 1990 (Kalgoorlie)	Williams & others 1993 (seismic line)	Hammond & Nisbet 1992 (northern)	Williams & Currie 1993 (Leonora)
De 1		Basin formation, possible growth faults and half-graben development	Shear zones on gneiss/ granite-greenstone margins	Shear zones on gneiss/ granite-greenstone margins
D1	Thrust faults and sequence repeats	Basal shears on greenstone, high level thrust faults	NNW directed thrusts, sequence repeats	Thrust faults and sequence repeats
De 2		Extensional faulting, affecting whole of upper and middle crust, core complex emplacement		
D2	ENE-WSW shortening, upright folds, NNW steep cleavage	ENE-WSW shortening, upright folds, regional cleavage	ENE-WSW shortening, fault imbricatiotion over a deep detachment	ENE-WSW shortening, upright folds, cleavage, reactivation of earlier shears
D3	Sinistral wrench fault during regional shortening, later faults	NW-NNW sinistral faults and shears NE faults	NS dextral faults and shears, related to D2	NS dextral shears, NNW sinistral reactivation

TABLE 1. Deformation sequence in the Eastern Goldfields

a mantle plume) will enhance crustal flow under extension and physical properties will favour core complex formation as the main response to extension (Buck, 1991).

There is, however, considerable debate over the actual driving force of extensional processes. For example, in the Basin and Range Province two main processes have been proposed: plate interactions (Coney, 1980) and crustal flow due to overthickening during the Laramide Orogeny (Wernicke & others, 1987). In the EGP, the same difficulties are apparent (Table 1).

However, the tectonic evolution suggested below goes some way to explaining the observation from the numerous data sets:

1: Mantle activity to provide initial impetus for basin formation. This may be a mantle plume (Campbell & Hill, 1988), just prior to 2700 Ma.

2: Asymmetrical rifting and uplift of rocks to the west of the EGP above an initial shallowly dipping detachment (see Hammmond & Nisbet, 1992; 1993). Voluminous mafic volcanism was deposited as the rift succession in large scale half-grabens. Major structures developed at this stage later acted as terrane boundaries (eg Mt Monger Fault). This model allows the accumulation of the several km of greenstone stratigraphy, not normally possible in a basin formed solely by crustal downwarping. Deposition of the bulk of the greenstone succession was completed by 2690 Ma (age of the Upper Basalt).

3: Active rifting ceased, and was rapidly followed by thrust faulting and stacking of the stratigraphy. Emplacement of voluminous granite magma took place at this stage (ca 2680 Ma), and represents massive re-cycling of the lower crust, probably in response to the thermal input from the mantle some 20 Ma earlier (see Campbell & Hill, 1988). Age constraints on gneiss in the Leonora area (L.P. Black, personal communication) suggest that emplacement took place at a range of levels in the crust, from as deep as 20 km (upper amphibolite) to the lower parts of the newly deposited greenstone stratigraphy. These early granites were probably emplaced as sheets and small elongate flattened plugs (Goleby & others, 1993). .

4: The renewed instability of the crust as a result of thickening, granite intrusion and thermal weakening of the lower crust resulted in renewed extensional deformation. This event largely re-activated the earlier extensional faults and half-graben margins, and caused normal faulting in the overlying greenstone stratigraphy. This faulting in the upper plate was largely of a brittle nature, and caused roll-over structures and hence stratigraphic cut-outs on the basal décollement surface (Fig. 2a). The extension caused uplift of the basin margins, which were largely composed of granite gneiss of the immediately preceding igneous event, and also caused the compressed metamorphic gradients observed on the greenstone margins. Several of the early granite sheets were uplifted in a similar way, as metamorphic core complexes within the greenstone belt. These core complexes commonly contain internal blocks or separate regions of banded gneiss.

5: Initiation of this second extensional phase probably resulted in a second rapid heat input from mantle asthenosphere, and eventual remelting of the lower crust. This occurred at about 2660 Ma (a further ~20 Ma after extension) and also probably caused flow in the lower crust to compensate for extensional thinning, explaining the lack of deflection on the reflection Moho during this later extension event. Geochemical evidence (Champion & Sheraton, 1993) suggests that granitoids emplaced in this event arose from a variety of crustal sources, including the earlier intrusives. Some of these phases are located within distinct structural zones.

6: Compressional orogeny followed the second extensional event, and caused significant reactivation of the extensional faults as reverse-slip structures, steepening of the structures, and tightening of the extensional anticlines. Strain was markedly partitioned into zones between the anticlines, which were largely areas of earlier extensional and thrust faulting. Structural evidence suggests that the main compressional phase belongs to this penultimate stage and largely pre-dated the second phase of granite emplacement.

7: Continued compression after granite emplacement resulted in the formation of strike-slip movement on suitable oriented earlier fault structures.

Clearly, models such as these must remain working hypotheses until they are thoroughly tested in the field and by more geochemical and geochronological data. The age of uplift of the gneiss domes and belts, relative to the compressional deformation phases, needs to be determined, and the tectonic processes leading to formation of the greenstone basins needs better integration into the regional deformation history, as has been attempted by Hammond & Nisbet (1992). The timing of mineralisation late in the structural history, begs the question as to the fluid transport mechanism and the extent of reactivation of major structures which acted as fluid conduits. If ore fluid formation was related to the later phase of granite magmatism, then understanding the reasons for the location of certain intrusions in the structural zones and the dynamics of the faulting could lead to useful predictive models. As the overall geometry of the EGP was established before the gold mineralisation event, understanding that geometry has a major bearing on exploration strategies.

References

Allmendinger, R.W., Sharp, J., Von Tish, D., Serpa, L., Brown, S., Kaufman, S., Oliver, J. & Smith, R.B. 1983, Cenozoic and Mesozoic structure of the eastern Basin and Range Province, Utah, from COCORP seismic reflection data. *Geology*, 11, 532-536.

Allmendinger, R.W., Farmer, H., Hauser, E., Sharp, J., Von Tish, D., Oliver, J. & Kaufman, S. 1986, Phanerozoic tectonics of the Basin and Range - Colorado Plateau transition from COCORP data and geologic data: a review. In Barazangi, M. & Brown, L. eds. *Reflection Seismology: The Continental Crust.* American Geophysical Union, Geodynamics Series 14, 257-267.

Archibald, N.J., Bettenay, L.F., Binns, R.A., Groves, D.I., & Gunthorpe, R.J. 1978, The evolution of Archaean greenstone terrains, Eastern Goldfields Province, Western Australia. *Precambrian Research*, 6, 103-131.

Archibald, N.J., Bettenay, L.F., Bickle, M.J. & Groves, D.I. 1978, Evolution of the crust in the Eastern Goldfields Province of the Yilgarn Block, Western Australia, in Glover, J.E. & Groves, D.I. eds. *Archaean Geology.* Special Publication Geologival Society of Australia, 7, 491-504.

Archibald, N.J. 1990, Tectonic-metamorphic history of the Lake Lefroy area: implications for greenstone-belt evolution in the Kambalda - Norseman region, Western Australia, in Glover, J.E. & Ho, S.E. eds. *Third International Archaean Symposium, extended abstracts.* Geoconferences (W.A.) Inc, Perth. pp. 457-458.

Binns, R.A., Gunthorpe, R.J. & Groves, D.I. 1976, Metamorphic patterns and development of greenstone belts in the Eastern Yilgarn Block, Western Australia, in Windley, B. ed. *Early History of the Earth.* Wiley, London, 303-313.

Buck, W.R. 1991, Modes of continental extension. *Journal of Geophysical Research*, 96, 20161-20178.

Campbell, I.H. & Hill, R.I. 1988, A two stage model for the formation of the granite-greenstone terrains of the Kalgoorlie-Norseman area, Western Australia. *Earth and Planetary Science Letters*, 90, 11-25.

Champion, D.C. & Sheraton, J.W. 1993, Geochemistry of granitoids of the Leonora-Laverton region, eastern Goldfields Province, in Williams, P.R. & Haldane, J.A. eds. *Crustal Evolution, Metallogeny and Exploration of the Eastern Goldfields.* AGSO Record 1993/54, 39-46.

Claoué-Long, J.C., Compston, W. & Cowden, A. 1988, The age of the Kambalda greenstones resolved by ion-microprobe: implications for Archaean dating methods. *Earth and Planetary Science Letters*, 89, 239-259.

Coney, P.J. 1980, Cordilleran metamorphic core complexes: An overview, in Crittenden, M.L., Coney, P.J. & Davis, G.H. eds. *Cordilleran Core Complexes.* Memoir of the Geological Society of America, 153, 7-34.

Goleby, B.R., Rattenbury, M.S., Swager, C.P., Drummond, B.J. Williams, P.R., Sheraton, J.W. & Heinrich, C.A. 1993, Archaean crustal structure from seismic reflection profiling, eastern Goldfields, Western Australia. *AGSO Record* 1993/15, 54pp.

Hallberg, J.A. 1985, *Geology and mineral deposits of the Leonora-Laverton area, northeast Yilgarn Block, Western Australia.* Hesperian Press, Perth. 140pp.

Hammond, R.L. & Nisbet, B.W. 1992, Towards a structural and tectonic framework for the central Norseman-wiluna greenstone belt, Western Australia, in Glover, J.E. & Ho, S.E. eds. *The Archaean: Terrains, Processes and Metallogeny.* Geology Department (Key Centre) & University Extension, the University of Western Australia, Publication 22,39-49.

Hammond, R.L. & Nisbet, B.W. 1993, Archaean Crustal Processes As Indicated By The Structural Geology, Eastern Goldfields Province Of Western Australia, in Williams, P.R. & Haldane, J.A. eds. *Crustal Evolution, Metallogeny and Exploration of the Eastern Goldfields.* AGSO Record 1993/54, 105-114.

Hill, R.I, Campbell, I.H. & Compston, W. 1989, Age and origin of granitic rocks in the Kalgoorlie-Norseman refion of Western Australia: Implications for the origin of Archaean crust. *Geochimica et Cosmochimica Acta*, 5 3,1 259-1275.

Lister, G.S., Etheridge, M.A. & Symonds, P.A. 1986, Detachment faulting and the evolution of passive continental margins. *Geology,* 14, 246-250.

Passchier, C.W. 1990, Report on the geology of the Leonora Area, Western Australia. *BMR Record* 1990/59, 29pp.

Pidgeon, R.T. & Wilde, S.A. 1990, The distribution of 3.0 Ga and 2.7 Ga volcanic episodes in the Yilgarn Craton of Western Australia. *Precambrian Research,* 48, pp 309-325.

Rattenbury, M.S. 1993. Tectonostratigraphic terranes in the northern Eastern Goldfields, in Williams, P.R. & Haldane, J.A. eds. *Crustal Evolution, Metallogeny and Exploration of the Eastern Goldfields.* AGSO Record 1993/54,73-76.

Shaw, R.D., Goleby, B.R., Korsch, R.J. & Wright, C.W. 1992, Basement and cover thrust tectonics in Central Australia based on the Arunta-Amadeus seismic reflection profile, in Rickard, M.J., Harrington, H.J. & Williams, P.R. eds. *Basement Tectonics 9 Australia and Other Regions.* Kluwer Academic Publishers, Dordrecht. 55-84.

Sonder, L.J. and England. P.C. 1989, Effect of temperature dependent rheology on large-scale continental extension. *Journal of Geophysical Research,* 94, 7603-7619.

Swager, C.P. & Griffin. T.J. 1990, An early thrust duplex in the Kalgoorlie-Kambalda greenstone belt, Eastern Goldfields Province, Western Australia. *Precambrian Research,* 48, 63-73.

Swager, C.P., Griffin, T.J., Witt, W.K., Wyche, S., Ahmat, A.L. & Hunter, W.M. 1990, Geology of the Archean Kalgoorlie Terrane: An explanatory note. *Geological Survey of Western Australia Record* 1990/12.

Vanderhor, F. 1992, Strain partitioning near the Keith-Kilkenny Fault Zone in the central Norseman-Wiluna Belt, Western Australia. *BMR Record* 1992/68.

Wernicke, B.P., Christiansen, R.L., England, P.C. and Sonder, L.C. 1987, Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera, in Coward, M.P, Dewey, J.F. & Hancock, P.L. eds. *Continental Extension Tectonics.* Special Publication of the Geological Society of London, 28, 203-221.

Williams, P.R., Currie, K.L. & Duggan, M.B. 1990, Sons of Gwalia and Harbour Lights gold deposits–localisation in an Archaean extensional ductile shear zone, in Glover, J.E. & Ho, S.E. *Third International Archaean Symposium, extended abstracts.* Geoconferences (W.A.) Inc, Perth. pp. 469-471.

Williams, P.R. & Currie, K.L. 1993, Character and regional implications of the sheared Archaean granite-greenstone contact near Leonora, western Australia. *Precambrian Research,* 62, 343-365.

Williams, P.R., Nisbet, B.W. & Etheridge, M.A. 1989, *Australian Journal of Earth Sciences*

Williams, P.R. & Whitaker, A.J. 1993, Gneiss domes and extensional deformation in the highly mineralised Archaean Eastern Goldfields Province, Western Australia. *Ore Geology Reviews,* 8, 141-162.

Williams, P.R., Rattenbury, M.S., Swager, C.P., Goleby, B.R. & Drummond, B.J. submitted. Archaean greenstone architecture from seismic reflection profiling, Eastern Goldfields, western Australia. *Nature.*

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Constraints from seismic data on the regional and district scale structure of the Eastern Goldfields Province

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In 1991, the Australian Geological Survey Organisation (AGSO) (then the Bureau of Mineral Resources, Geology & Geophysics) recorded a 213 km long deep seismic reflection profile oriented approximately east-west and centred some 30 km to the north of Kalgoorlie (Fig. 1). The seismic traverse was positioned to intersect many of the key features of the greenstone belts within the Eastern Goldfields Province, as well as the boundary with the adjacent Southern Cross Province to the west (Fig. 1; Goleby & others, 1992).

The main aims of the seismic traverse were to constrain the geometry of the greenstone belts at depth, determine the nature of the basement and its structural relationship to the greenstones rocks. The study also aimed to examine the differences in structure, form and crustal thickness in the Eastern Goldfields and Southern Cross Provinces in order to understand their respective tectonic evolution.

Drummond & others, (1993) described the preliminary results from the survey, focussing mainly on the regional crustal structure and composition. Figure 2 shows the seismic data used in this analysis, a summary of the key features imaged within the crust and schematic depth section showing the positions of key reflectors and crustal boundaries.

The crust within the Southern Cross Province is about 33 km thick (11 s TWT; Fig. 2b). The crust is two layered, with an upper crust about 10 km thick (3.0-3.5 s TWT), which is largely non-reflective and interpreted to be mainly felsic. The lower crust is more reflective, and probably more mafic than the upper crust. Refraction data farther west in the Southern Cross Province indicate a 35 km thick crust. The crust must be predominantly felsic in composition (Drummond, 1988). The seismic signature of the crust beneath the greenstones of the Eastern Goldfields Province is similar to the Southern Cross Province, except that the crust is slightly thicker; about 37-38 km (12-13 s TWT; Fig. 2b). The thickening of the crust, from the Southern Cross Province to the Eastern Goldfields Province, commences below the surface location of the Ida Fault (Fig. 1) and extends to the down-dip extrapolation of the Ida Fault where it intersects the Moho.

In this paper, we describe some of the key features within the greenstone belts that are apparent from the seismic data and the relationship of the greenstone belts to other, major crustal structures. Williams (1993) provides a tectonic reconstruction of the region based on a detailed geological interpretation coupled with the depth constraints provided by the seismic data.

Internal structures of the greenstones

The seismic data have successfully imaged regional folds, major shear zones and faults, granitic intrusions and the base of the greenstones (Goleby & others, 1993; Williams & others, 1993).

The seismic data from the Mt Pleasant Anticline region (Fig. 3) clearly show moderate dips to both limbs. The greenstones in this area are particularly well imaged because of the high impedance contrasts between the interlayered mafic, ultramafic and sedimentary rocks and the relatively shallow-dipping and simple structure. The reflections have varying amplitudes, and no single layer can be correlated laterally for more than a few kilometres. However, bundles of reflections can be correlated over longer distances. For example, a bundle of stronger than average reflections in the crest of the anticline just below 1 s TWT (Fig. 3) can be traced down both limbs of the anticlines. Both the individual reflections and the bundles of reflections show

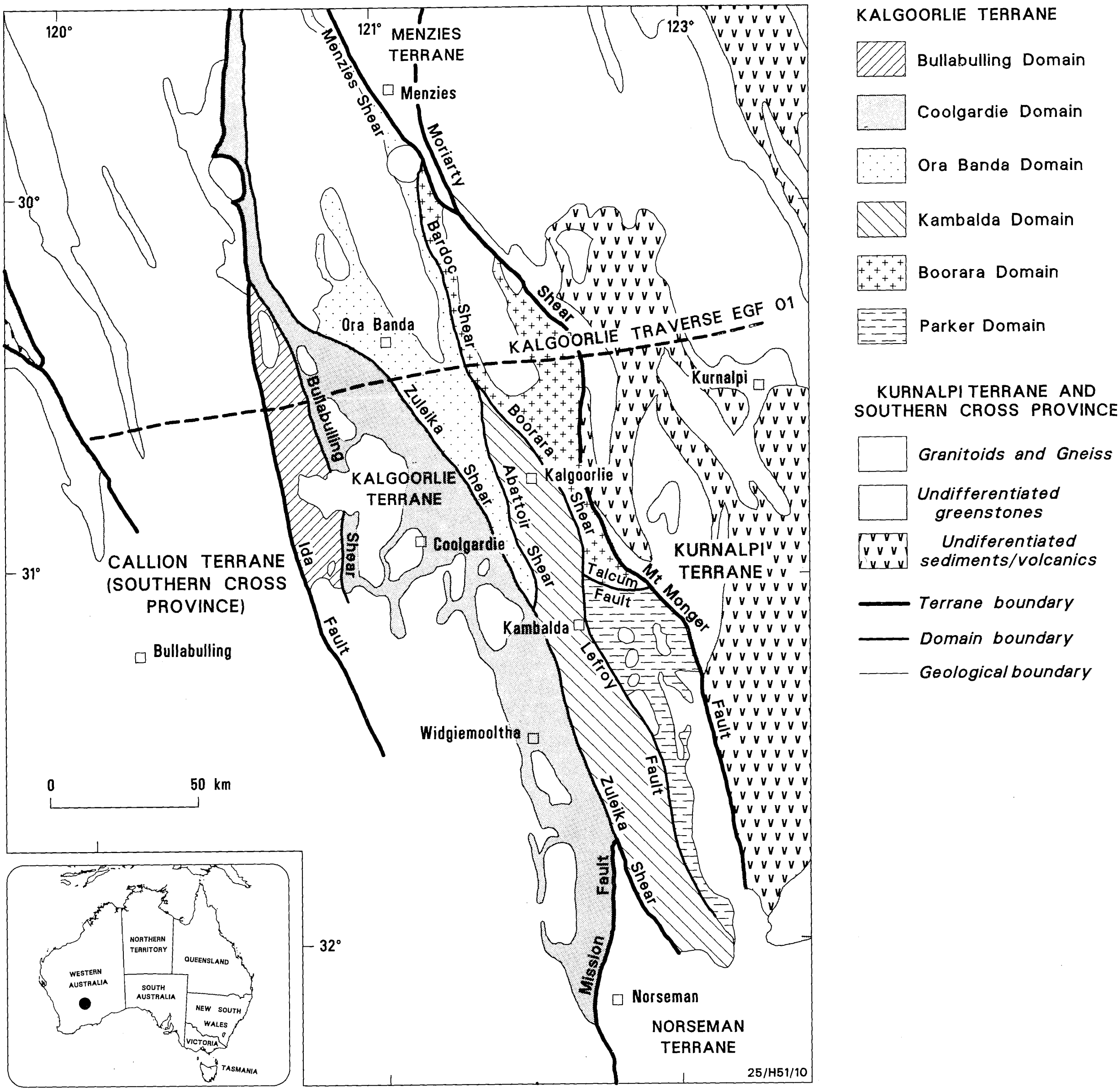

Fig. 1. Geological map of the Eastern Goldfields region showing the major structural sub-divisions. The position of the 1991 Eastern Goldfields Seismic Traverse is shown as a dashed line (Base map modified from Swager & Griffin, 1990).

the anticlinal form of the strata, although in this section the continuity of any specific rock unit is difficult to map.

Faults have a number of different seismic signatures. Faults and shear zones which have an associated broad foliated zone at the surface are commonly strongly reflective at depth (e.g. Bardoc Shear, Fig. 3). The reflectivity results from several causes. Firstly, the foliation has an associated seismic anisotropy, such that the seismic impedance at right angles to the foliation is considerably higher than that parallel to the foliation. Secondly, the foliation produces constructive interferences to produce what can be extremely strong reflections. Extremely strong sub-horizontal reflections occur at the base of the greenstones and these reflections are interpreted as a major decollement (Fig. 3).

Other faults, such the Mt Monger Fault farther east, are not reflective because of their steep dips but can be interpreted because the faults truncate reflections in the seismic section. In other cases, where reflections within the greenstone section are weak or absent, such as in some of the felsic volcanosedimentary units, faults are not resolvable in the seismic sections, and often can only be mapped by extrapolating the fault trace from its surface outcrop position to a conformable reflector in the underlying detachment surface.

The locations of granites along the transect are well constrained from surface outcrop. At depth, granites are imaged as small, rootless, tabular bodies, defined in the seismic section by an absence of clear reflections compared to the surrounding greenstones. None of these granites are as large as

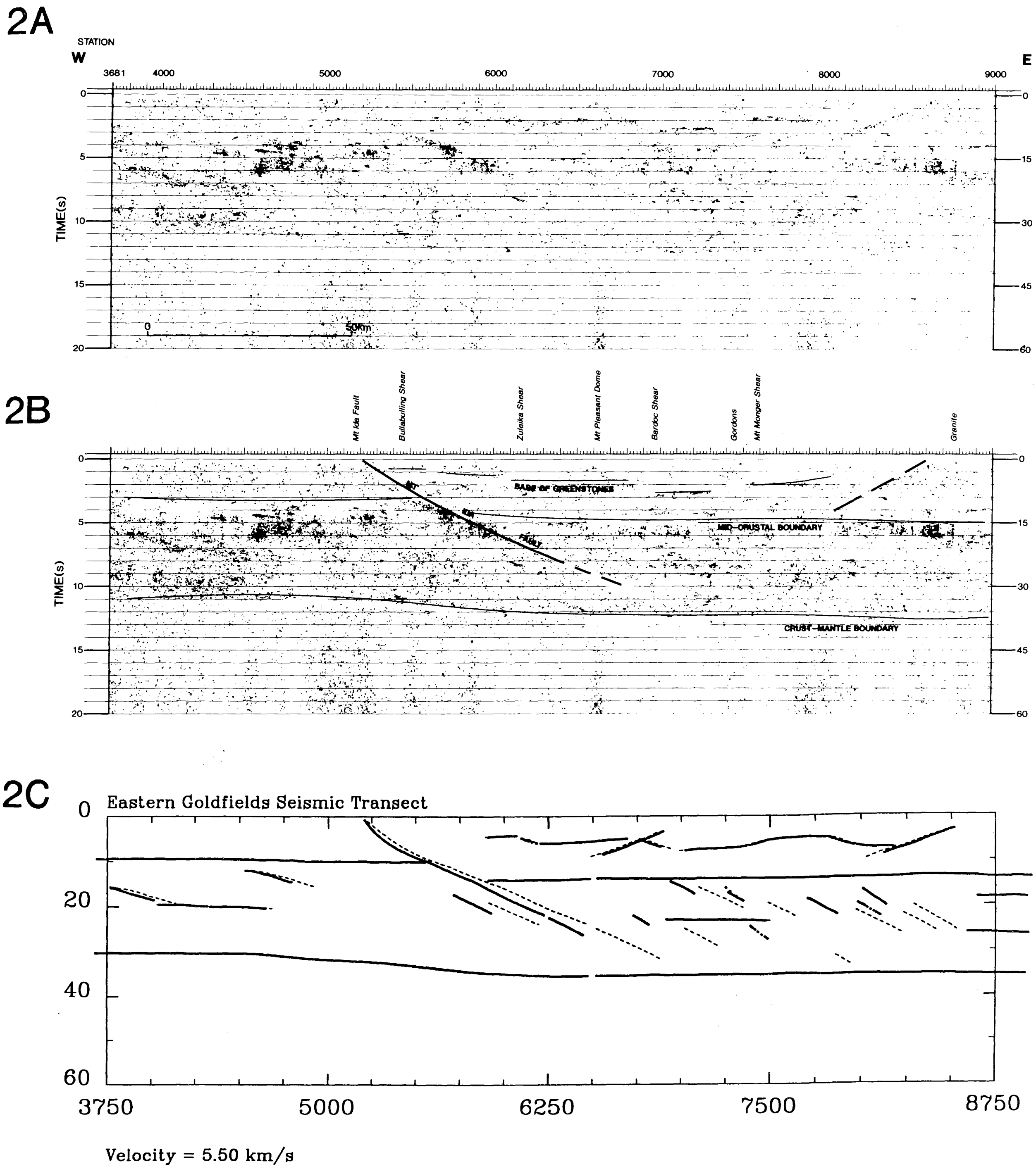

Fig. 2. Deep seismic reflection data from the Eastern Goldfields region of Western Australia, showing the uninterpreted seismic data (A), the key features imaged within the crust (B), and a line diagram illustrating the effect of mapping the reflections from a time section into their proper position in a depth section by the process of migration (C). The dotted lines mark the positions of the key reflectors and crustal boundaries in a time section. The solid lines mark their true positions in a depth section. In all sections, the vertical scale is approximately equal to the horizontal scale.

previously supposed (eg Swager & Griffin, 1990). Their geometry is probably more like a flat-lying oblate ellipsoid, or surf-board shape, with a limited depth extent. The granites truncate seismic reflectors to the east and west and have a maximum depth extent that is defined by the lowest continuous reflector beneath the granite (Fig. 4). Some granites have evidence of internal reflectors. These may be due to either shear zones or foliation within the granite.

The greenstone belts within a regional perspective

The basal contact of the greenstones is imaged as a sub-horizontal to gently undulating surface that reaches a maximum depth of 7 km.

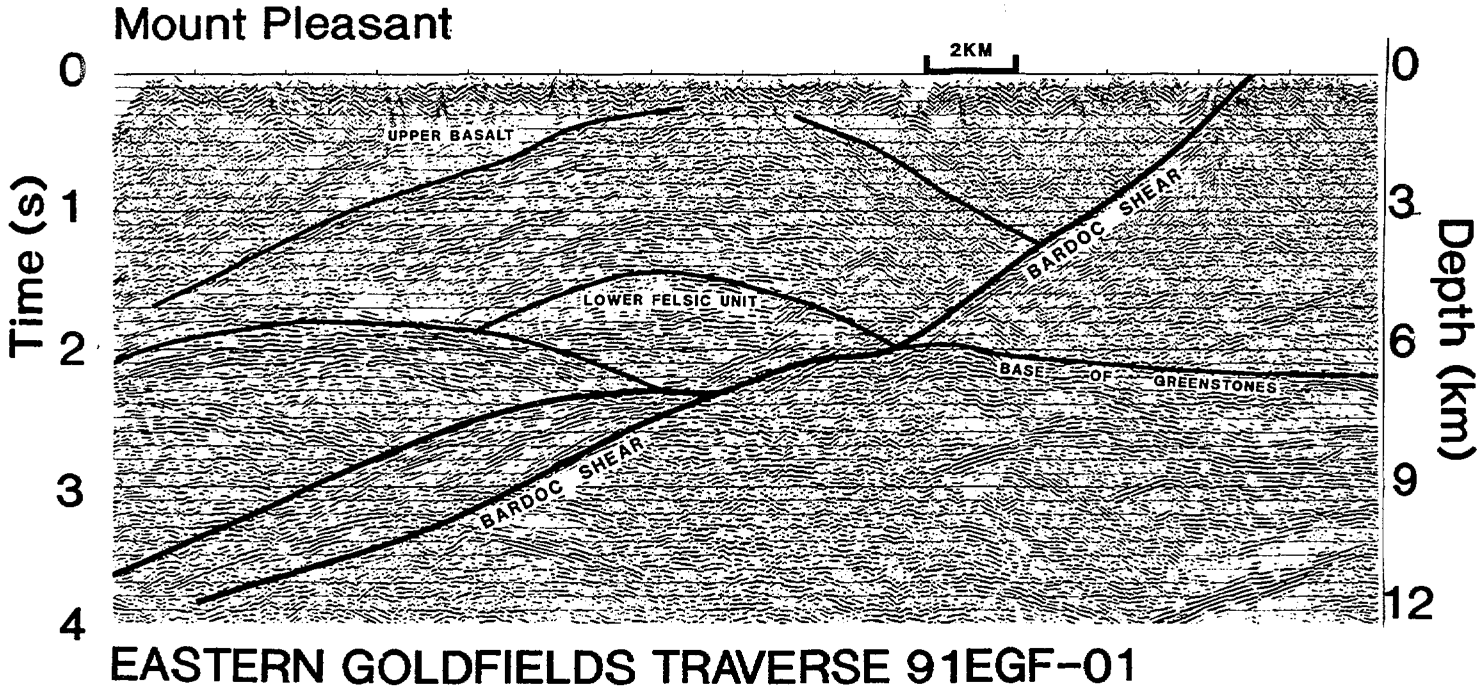

Fig. 3. A portion of the seismic data from the Mt Pleasant Anticline region of the Eastern Goldfields with geological interpretation overlayed. The basal greenstone-gneiss contact and Bardoc Shear are marked. Vertical exaggeration is one.

The Mt Monger Fault is the eastern boundary of the Kalgoorlie Terrane, juxtaposing the Kalgoorlie Terrane against the basalts within the Kurnalpi Terrane (Swager & Griffin, 1990). At depth, the Mt Monger Fault is interpreted as soling out on the greenstone-gneiss basement contact at about 2 to 2.5 seconds (6-7.5 km depth) as part of a shallow-dipping (10°) ramp.

The Ida Fault forms the present day boundary between the Eastern Goldfields Province and the Southern Cross Province to the west (Fig 2). The seismic data show the Ida Fault as mostly planar, dipping at approximately 30° to the east, to 25-30 km depth. The Ida Fault zone offsets upper and mid-crustal reflectors by approximately 5 km normal displacement (Figs. 2b,c). The fault does not offset the crust-mantle boundary; rather, the crust-mantle boundary deepens over a broad zone underneath the Ida Fault. Within 9 km of the surface, the fault has not been directly imaged but the fault trace is delineated by truncated reflectors. The Ida Fault is therefore a major crustal boundary separating two pieces of crust which, on the basis of their seismic signatures, are very similar at depth, and whose main differences is the presence of greenstone supra-crustals in the east.

The Bardoc Shear (Fig. 2b) cuts and offsets the detachment at the base of the greenstones by about 3 km. At the surface, the fault is a zone of complex deformation 2 km wide. At depth, strong reflectors dipping about 20-30° west have been imaged from about 1 to 5 seconds (3-15 km depth) terminating against the Ida Fault (Goleby & others, 1993).

Several other zones of reflectors, paralleling the Ida Fault, cut the lower crust. When migrated to their proper place in the depth section, they generally fall above, and some intersect, a moderately strong horizontal reflector which is seen at several places in the section between 20 and 25 km depth under both the Southern Cross and Eastern Goldfields Provinces (Fig. 2c). This boundary could be a detachment surface. Most of the dipping, crust-penetrating reflections occur in the crust under the greenstone belts. On the basis of their seismic character, they are interpreted as shear zones, similar to the Mt Ida Fault. Several lie within the Southern Cross Province; one of these projects to the surface near Southern Cross, and may correlate with the Koolyanobbing Shear Zone.

Williams & others (1993) provided a model for the migration of fluids from the lower crust into the Bardoc Shear and its splays. The lower crustal reflectors parallel to the Ida Fault possibly represent swarms of shear zones which can also act as conduits for fluids from the lower crust into high levels. The Bardoc Shear dips west, compared to the main crust-penetrating shears, which dip east. The Bardoc Shear has therefore been able to scavenge fluids from a number of the lower crustal east-dipping shear zones. Fluids from the lower crust would also have migrated into the basal detachment of the

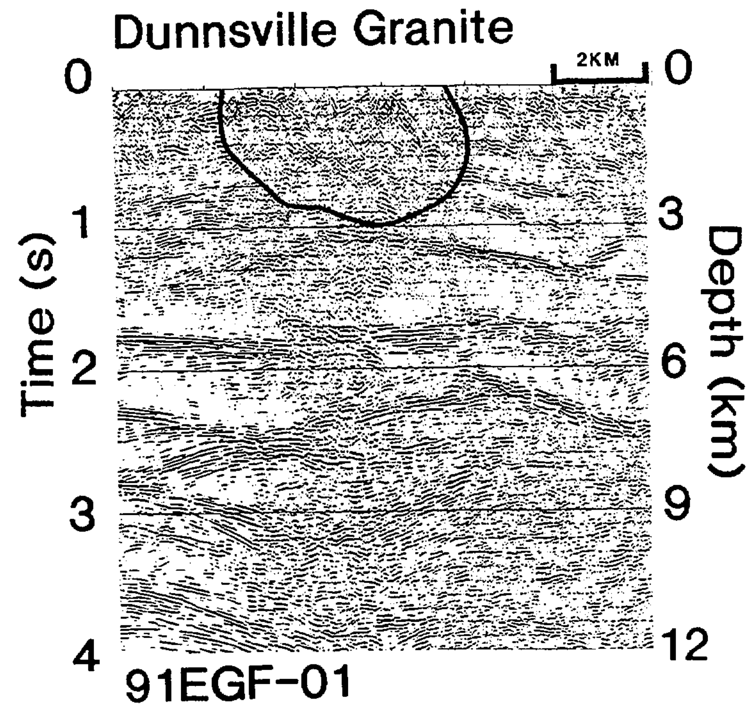

Fig. 4. A portion of the seismic data from the Dunnsville Granite region of the Eastern Goldfields with geological interpretation overlayed. The sides of the granite are defined by the termination of reflections. VE is one.

greenstones, especially to the east of the Bardoc Shear, and then into other faults within the greenstones. However, the Bardoc Shear appears in the seismic data to be younger than the basal detachment, and provides a more direct fluid path to the surface.

Relevance to the rest of the Yilgarn Block

- The seismic transect was limited to the immediate vicinity of the greenstone belts, although major east-dipping reflectors in the lower crust in the western part project to the surface at the position of the Koolyanobbing Shear which outcrops west of the transect. This shear is therefore inferred to be another major, east dipping, crust penetrating feature. An unpublished interpretation of Magsat data shows that the Koolyanobbing Shear also coincides with a major change in crustal magnetisation (F. Arnott, pers comm.). Drummond & Esa Mohamed (1986) interpreted yet another major crustal boundary farther west between the Western Gneiss Belt and the Southern Cross Province.

The Yilgarn Block therefore appears to be a series of blocks separated by (mostly) east dipping shear zones. Although the Magsat data indicate a difference in crustal magnetisation data across the Yilgarn Block, all available seismic data suggest a crust of uniform composition. However, no suitable seismic data presently exist that can point to the juxtaposition of the parameters needed for localising large orebodies: crust penetrating shears, a fault system suitable for localising the fluids, and suitable host rocks.

Acknowledgments

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References

Drummond B.J. 1988, A review of crust/mantle structure in the Precambrian areas of Australia and implications for Precambrian crustal evolution. *Precambrian Research*, 40/41, 101-116.

Drummond B.J. & Esa Mohamed, Rokiah. 1986, Crustal structure in the Southwest Seismic Zone, Western Australia. *Geological Society of Australia, Abstracts*, 15, 59-60.

Drummond B.J., Goleby B.R., Swager C.P., & Williams, P.R., 1993. Constraints on Archaean crustal composition and structure provided by deep seismic sounding in the Yilgarn Block. *Ore Geology Reviews*, 8, 117-124.

Goleby B.R., Drummond B.J., Williams, P.R., & Swager, C.P. 1992, The 1991 Eastern Goldfields seismic reflection survey, *Bureau of Mineral Resources, Research Newsletter*, 16, 9-10.

Goleby B.R., Rattenbury, M.S., Swager C.P., Drummond B.J., Williams, P.R., Sheraton, J.W. & Heinrich, C.A. 1993, Archaean Crustal Structure from Seismic Reflection Profiling, Eastern Goldfields, Western Australia. *Australian Geological Survey Organisation*, 1993/15, 54pp.

Swager C.P., & Griffin, T.J. 1990, *Geology of the Archaean Kalgoorlie Terrane (Northern and Southern Sheets), 1:250,000 Geological Map.* Geological Survey of Western Australia, Perth.

Williams P.R. 1993, A new hypothesis for the evolution of the Eastern Goldfields. *This Volume.*

Williams, P.R., Rattenbury, M.S., Swager C.P., Goleby B.R. & Drummond B.J. 1993, Constraints on Archaean greenstone architecture from crustal seismic reflection profiling, Eastern Goldfields, Western Australia. *Nature*, (in press).

Three-dimensional structure of greenstone belts in Western Australia

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Despite the fact that the greenstone belts of Western Australia host huge reserves of gold and nickel, their three-dimensional structure, i.e their structure in cross-section, is poorly known. Consequently, models for their tectonic evolution and metallogenesis are inherently incomplete.

The three-dimensional structure of greenstone belts elsewhere in the world is reasonably well known and is described in numerous publications. The main constraint on their structure has been provided by geophysical data, particularly gravity, and to a lesser extent, resistivity and seismic reflection data. Most work of this type has been undertaken in southern and central Africa (De Beer & others, 1984, 1988, Kleywegt & others, 1987) and to a lesser extent Canada (Jackson & others, 1990, Jebrak & others, 1991). Work from Indian (Subrahmanyam & Verma, 1982) and Scandanavian (Olesen & Solli, 1985) has also be published.

Figure 1 shows a schematic cross-section through a greenstone belt based on published cross-sections. The belts are typically about 5 km thick but may be reach a thickness in excess of 10 km. Their margins may be steep or shallowly dipping and may dip either into or away from the belt. The base of the greenstones is usually fairly flat, however there may be deep keels and basement ridges. There is evidence that such ridges may have influenced the distribution of mineralisation within the belts. Granitoid intrusions into the greenstone belts may be in the form of sheets, or steep-sided bodies forming the basement ridges referred to above.

Very little work has been done to determine the three-dimensional structure of greenstone belts in Western Australia (Dentith & others 1992). The distribution of greenstone belts in the Yilgarn Craton of Western Australia is shown in Fig.2. Fig-

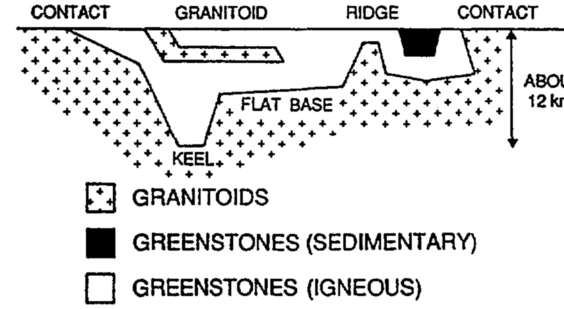

Fig.1. Schematic cross-section through a greenstone belt derived from geophysical studies. Specific features common to many belts are labelled (Dentith & others 1992).

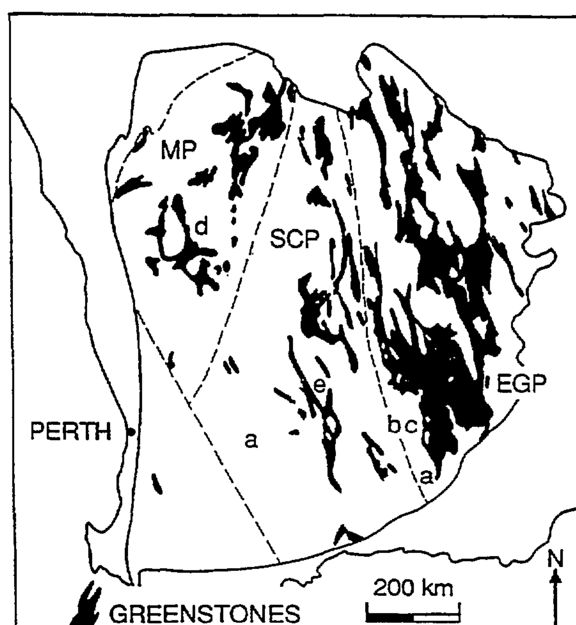

Fig. 2. Map of the Yilgarn granitoid-greenstone terrain. The locations of the profiles in Fig. 3 are indicated; the letters correspond to the individual cross-sections in this figure. EGP–Eastern Goldfield Province, MP–Murchison Province, SCP–Southern Cross Province (Dentith & others 1992).

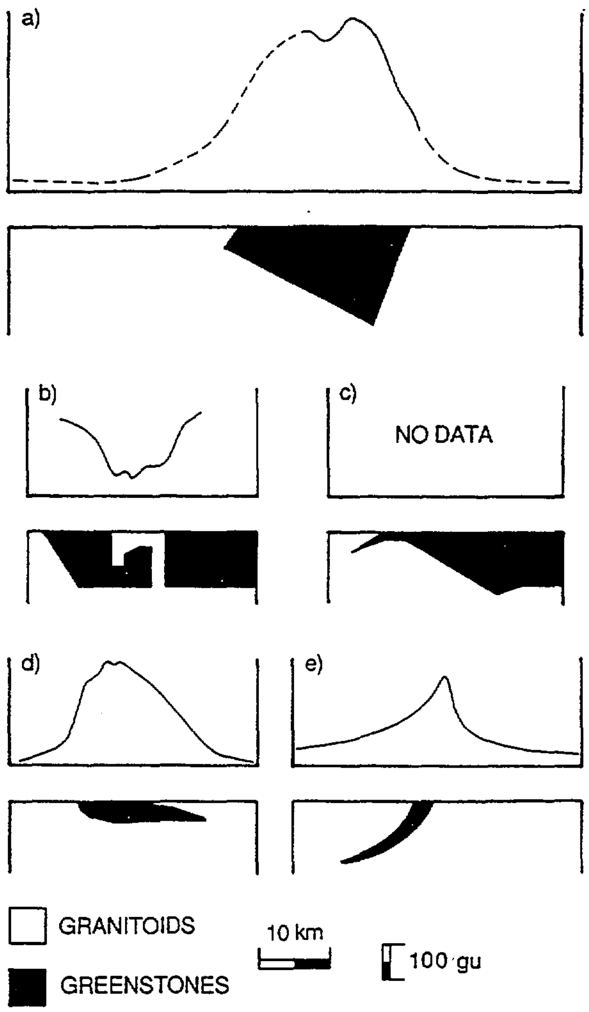

Fig. 3. Cross-sections of greenstone belts in Western Australia derived from gravity modelling. The variation in gravity along each profile which was modelled to obtain the sections is also shown. a) Norseman (Coggon 1984), b) and c) Widgiemooltha and Pioneer Domes (Bickle & Archibald 1984), d) Warriedar (Kevi 1982), e) Southern Cross (Constable 1978).

ure 3 shows a series of gravity models of various greenstone belts from within the craton.

Coggon (1984) presents a very simple gravity model of a greenstone belt near Norseman (Fig.3a). The belt is shown as having steeply dipping margins, on of which dips away from the belt, with a planar base dipping at about 30°. The belt is assumed to have a density contrast with the surrounding granites of +0.17 g/cm^3. This model is intentionally simple. It is designed to define the gravity effect of the belt as a whole, so this can be removed to isolate the gravity anomaly associated with felsic intrusions within the belt. This is a useful by product of gravity models of greenstone belt structure. See, for instance, Dentith & others (in press).

Bickle & Archibald (1984) present the results of gravity modelling along east-west traverses across the Widgiemooltha and Pioneer Domes (Figs. 3b & 3c). The greenstone sequence is assigned a density of 2.95 g/cm^3, the granites a density of 2.65 g/cm^3. No data gravity data are included in Bickle and Archibald's paper, however, Archibald (1979) presents data from the Widgiemooltha traverse where there is a negative anomaly of more than 150 gu. The Widgiemoooltha traverse is modelled in terms of a granite dome which intrudes the greenstone sequence. The dome is interpreted to be of diapiric origin from structural studies of the area. The Pioneer traverse is modelled in terms of the greenstone belt thinning to the west and there appears to be a thrust contact between the granitoid and greenstone rocks. A 'high' in the granitoid basement is inferred to occur close to the contact, an interpretation that is supported by studies of the metamorphic history of the greenstone rocks. In both profiles the greenstone rocks have relatively flat bases and reach a maximum thickness of 8-10 km.

Kevi (1982) describes the results of gravity traverses across the Warriedar Belt in the Murchison Province of the Yilgarn Craton (Fig. 3d). The station spacing was about 4 km. Based on density measurements a density of 2.64 g/cm^3 was assigned to the granitic rocks surrounding the greenstone belt, 2.89 g/cm^3 for the bulk of the greenstone belt, and 3.09 g/cm^3 for banded iron formations within the greenstone belt. The observed gravity anomaly associated with the greenstone belt has an amplitude of between 280 and 390 gu and is markedly asymmetrical. This asymmetry requires that the granite-greenstone contact on the northeastern side of the belt dips at about 10° to the northeast. The opposite margin also dips in this direction but more steeply. The belt is modelled as being about 3 km deep with an approximately flat base.

Constable (1978) describes the results of a gravity survey across the Southern Cross Greenstone Belt near the town of Southern Cross (Fig. 3e). Station spacing was between 1 and 2.5 km along a profile 60 km in length. An asymmetrical positive anomaly of about 220 gu was recognised. Based on analysis of the anomaly assuming simple causative bodies, and published density data, the density contrast between granitoids and greenstones was estimated at 0.18-0.25 g/cm^3 with the higher figure being chosen for modelling. A series of possible geometries for the greenstone belt were presented with the favoured model being a body dipping steeply to the west with its dip decreasing with depth. The base of the belt was estimated to be at a depth of about 9 km.

Clearly the greenstone belts of Western

Australia show many of the features recognised elsewhere in the world, for instance, flat bases, basement ridges and considerable variation in the dip of their margins. Whether there is a link between concealed granitoid bodies and mineralisation and the relative abundance of sheet-like granitoid intrusions awaits further data acquisition and modelling.

References

Archibald, N.J. 1979, Tectonic-Metamorphic Evolution of an Archean Terrain: a Study of the Norseman-Widgiemooltha Granitoid-Greenstone Belt, Eastern Goldfields Province, Western Australia, Ph.D thesis, Department of Geology, University of Western Australia, unpubl.

Bickle, M.J., & Archibald, N.J. 1984, Chloritioid and staurolite stability: implications for metamorphism in the Archaean Yilgarn Block, Western Australia, *Journal of Metamorphic Petrology,* 2, pp 179-203.

Coggan, J. H. 1984, Geophysics as an aid to gold exploration in the Yilgarn Block, in *Geophysical Exploration for Precambrian Gold Deposits,* ed. H.A. Doyle, Geology Department and University Extension, The University of Western Australia, Publication No.10, pp 113-138.

Constable, S.C. 1978, Interpretation of the Bouguer anomaly over a greenstone belt, Southern Cross, Western Australia. B.Sc(Hons) thesis, Department of Geology, University of Western Australia, unpubl.

De Beer, J.H., Stettler, E.H., Duvenhage, A.W.A., Joubert, S.J. & De W. Raath, C.J. 1984, Gravity and geoelectrical studies of the Murchison greenstone belt, South Africa, *Transactions of the Geological Society of South Africa,* 87, pp 347-359.

De Beer, J.H., Stettler, E.H., du Plessis, J.G. & Blume, J. 1988, The deep structure of the Barberton greenstone belt: a geophysical study, *South African Journal of Geology,* 91, pp 184-197.

Dentith, M.C., House, M.J., Ridley, J.R. & Trench, A. 1992, Three-dimensional structure of greenstone belts in Western Australia: implications for gold exploration, *Exploration Geophysics,* 23, pp 105-110.

Dentith, M. C., Trench. A., & Jones, M., (in press), Geophysical exploration for gold: a case study from the Southern Cross Greenstone Belt, Western Australia, *Applied Geophysics.*

Jackson, S.L., Sutcliffe, R.H., Ludden, J.N., Hubert, C., Green, A.G., Milkereit, B., Mayrand, L., West, G.F., & Verpaeist, P. 1990, Southern Abitibi greenstone belt: Archean crustal structure from seismic reflection profiles, *Geology,* 18, pp 1086-1090.

Jebrak, M., Lequentrec, M.F., Mareschal, J.C. & Blais, D. 1991, A gravity survey across the Boulamaque massif, southern eastern Abitibi greenstone belt, Quebec, Canada: the relationship between the geometry of tonalite plutons and associated gold mineralisation, *Precambrian Research,* 50, pp 261-268.

Kevi, L, 1982, Gravity traverses across the Warriedar Belt, *Geological Survey of Western Australia Record,* 1982/8.

Kleywegt, R.J., Stettler, E.H., Brandl, G., Day, R.W., De Beer, J.H., & Duvenhage, A.W.A. 1987, The structure of the Giyani greenstone belt as derived from geophysical studies, *South African Journal of Geology,* 90, pp 282-295.

Olesen, O. & Solli, A. 1985, Geophysical and geological interpretation of regional structures within the Precambrian Kautokeino greenstone belt, Finnmark, north Norway, *Nore Geol Unders Bull,* 403, pp 119-129.

Subrahmanyam, C. & Verma, R.K. 1982, Gravity interpretation of the Dharwar greenstone-gneiss-granite terrain in the southern Indian Shield and its geological implications, *Tectonophysics,* 84, pp 225-245.

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Implications of metamorphic patterns to tectonic models of the Eastern Goldfields

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Understanding of the relations between regional metamorphism and crustal tectonics has been improved over the last dozen years through 'thermal modelling'—computer-based modelling of the temperature changes in the crust resulting from tectonic and magmatic events (England & Richardson, 1977; England & Thompson, 1984). In areas of unknown, or disputed, tectonic regime, such as the Eastern Goldfields Province, the metamorphic history is a potential constraint on tectonic models. Any tectonic model for an area should be able to explain, at least qualitatively:

- the pressure-temperature conditions of metamorphism,
- the variation across the terrain of metamorphic conditions, and the major features of the metamorphic history, (the pressure-temperature-time, or P-T-t, path, and
- the timing of metamorphism relative to deformation, the P-T-t-d history) and their variation across the terrain or with respect to depth of burial.

In this paper the nature of metamorphism in the Eastern Goldfields is discussed, with reference to and comparison with other granite-greenstone terrains world-wide. The constraints that the patterns and nature of metamorphism place on both the overall tectonic regime of the Goldfields, and on tectonic events within individual greenstone belts, are outlined.

Nature of greenstone belt metamorphism

Pressure–temperature conditions of metamorphism

Temperature conditions of metamorphism range from prehnite-pumpellyite to upper amphibolite facies in the greenstone-belt terrains of the Yilgarn Craton. Different terrains show differing dominance of metamorphic grade. In the Eastern Goldfields, the majority of greenstone belt exposure is of greenschist-facies or lower metamorphic grade: amphibolite-facies rocks occur in relatively narrow zones along belt margins. In contrast, large areas of the southern part of the Southern Cross Province are entirely in the amphibolite facies (Ahmat, 1986).

Pressure conditions of metamorphism (and hence geothermal gradients) are more difficult to determine, especially in greenschist-facies rocks, but greenstone belts world-wide appear almost invariably to belong to the low-pressure facies series. Geothermal gradients during greenstone-belt metamorphism also appear to be remarkably uniform world-wide (35-50°C/km, Grambling, 1981), though the determinations are not particularly precise.

Where it has been possible to estimate P-T conditions of metamorphism, the calculated geotherm always passes close to, or slightly to the low pressure side of the aluminosilicate triple point (530°C at 400 MPa, Salje, 1986; determinations from the Eastern Goldfields by Bavinton, 1981; McQueen, 1981; Bickle & Archibald, 1984; Purvis, 1984; Wong, 1986). Common minerals and assemblages present in greenstone belt rocks which confirm relatively low pressures of metamorphism throughout greenstone belts are andalusite, cummingtonite in mafic rocks, and cordierite-anthophyllite.

Isograd patterns

Greenstone belts have a characteristic isograd pattern: isograds are broadly zonal, with either progressively increasing metamorphic grades towards adjacent and surrounding granite-gneiss terrains, or fault-bounded blocks with progressively increasing grade towards the granitoids (e.g. Binns & others, 1976). Viewed over a whole craton, the isograd pattern of a granite-greenstone terrain contains low-grade 'holes'—the centres of most greenstone belts. In some cratons (e.g. Zimbabwe) there is also a general increase in metamorphic grade towards a craton margin, especially where the margin is against an Archaean or Proterozoic mobile belt (Saggerson & Turner, 1976). These patterns are mirror images of those mapped in most Phanerozoic orogenic belts—in which metamorphic grade generally increases towards the core of an orogen. Local higher-grade areas are present in many orogenic belts (e.g. Chamberlain & Rumble, 1988), but low grade 'holes' are rarely noted.

Field gradients

The variation in pressure measured in a traverse from low to high grade zones at the present level of exposure is an independent feature of a metamorphic history. Where this has been defined in greenstone belts, increasing temperature is mirrored by only minor changes in pressure (e.g. Bickle & others, 1985; Wong, 1986).

Recent studies in the Abitibi belt of the Superior Province, Canada, have also considered the spatial variations in pressure of crystallisation of broadly syn-tectonic granitoids within and marginal to greenstone belts (Feng & Kerrich, 1990), showing generally decreasing pressure from the granite–greenstone contact towards central, latest-crystallising phases of an individual pluton.

Pressure-temperature-time (P-T-t) paths and pressure-temperature-time-deformation (P-T-t-d) histories

The P-T-t paths of individual rocks in greenstone belts are generally poorly constrained. Where information is available, for instance from reaction textures and mineral compositional zonation, relatively small changes in pressure are indicated during prograde and retrograde metamorphism (e.g. Bickle & Archibald, 1984). Greenstone rocks have heated up and cooled without significant changes in the steepness of the geotherm.

Most deformational schemes proposed for greenstone belts involve an early phase of stratigraphic repetition through faulting (possibly low-angle thrusting), followed by one or two phases of upright folding and one or more phase of strike-slip shear-zone deformation. These folding and shearing events are possibly phases within a single progressive deformation event (Swager & others, 1992), or different expressions of the same deformation event (Clout, 1988). In the Yilgarn Block, the deformation is progressive, approximately east-west directed compression.

Metamorphic recrystallisation is closely related to the folding and shearing events (e.g. Knight & others, submitted). Textural evidence shows that greenstone belts are characterised by peak metamorphic temperatures and pressures broadly synchronous with a major phase of deformation. In detail, however, the peak of metamorphism may be either before, synchronous with, or after the main phase of deformation. A common texture indicating peak metamorphism post-dating deformation is the mimetic growth of cordierite porphyroblasts over aligned chlorite in cordierite-anthophyllite rocks; common structures indicating deformation during retrogression are discrete chloritic shear zones in amphibolitic mafic rocks.

Timing of metamorphism

In the Eastern Goldfields, estimation of the timing of metamorphism at 2660 Ma (e.g. Swager & others, 1992) has been based on a two stage correlation—the correlation noted above between metamorphism and deformation, and the correlation between dated granitoids or minor felsic intrusives and the deformational history.

There are a number of lines of evidence, however, which suggest that peak metamorphism may neither be synchronous throughout the Yilgarn Block, nor even within individual greenstone belts. In some areas multiple metamorphic events have been inferred from petrographic and field evidence. Important evidence includes:

- Concentric isograds around granitoid plutons, combined with textural evidence, suggests that high-grade zones are 'contact aureoles' overprinted on an earlier lower-grade regional event (Bickle & Archibald, 1984; Wong, 1986).
- The dating of syn-peak-metamorphic gold mineralisation at Griffin's Find in the Western Gneiss Terrain at approx. 2630 Ma (Barnicoat & others, 1991), together with similar dates from gneisses and granitoids in the surrounding, 'Wheat-Belt' region (Wilde & Pidgeon, 1987; Hill & others, 1992), suggest a later date for peak metamorphism in this region.

The relative timing of gold mineralisation and metamorphism gives further information. If gold mineralisation is synchronous throughout the Yilgarn Block at approx. 2630 Ma (see Groves & others, this volume), the apparent correlation of mineralisation with the peak of metamorphism in the Southern Cross Province suggests that this later date for metamorphism may be applicable to much of this Province. Dalstra (this volume) uses a similar argument to show that major deformation and the peak of metamorphism occurred later in the higher-grade, marginal parts of the Marda–Diemals greenstone belt than in the low-grade centre. There is thus evidence for a non-synchronous metamorphic peak, with a later peak characteristic of higher-grade, granitoid dominated parts of the Yilgarn Craton, or, as these are areas of deeper erosion (see below), the later timing may be characteristic of deeper levels in the crust.

Argon-argon studies of Napier (1993) have defined the time of cooling of the amphibolite facies terrains of the Craton below 300°C at about 2585 Ma. This suggests relatively slow cooling compared to most Phanerozoic orogenic belts.

Constraints from thermal modelling

The information available from the metamorphic histories on tectonic regimes will be discussed on two scales:

- (i) Constraints on the overall tectonic regime of the Eastern Goldfields Province, the amount of tectonic thickening, the role of mantle heat input, and
- (ii) Information on tectonics on a greenstone-belt scale, particularly relative to uplift and downthrow, and the role of granitoid bodies in metamorphism.

Constraints on overall tectonic model for the Eastern Goldfields

It was first argued by England & Thompson (1984) that it is extremely difficult to produce low-pressure facies series metamorphism through a tectonic and thermal history involving crustal thickening followed by conductive thermal re-equilibration of the crust during subsequent erosion. There are two main reasons for this conclusion:

- (i) in normal crustal regimes there is insufficient heat input, from the mantle and crustal radiogenic heat production, to produce the steep geotherms of low-pressure belts;
- (ii) if the geotherms are as steep as inferred, temperatures in the lower levels of a thickened crust will exceed liquidus temperatures, implying that heat transfer by magmas is likely to be important during metamorphism.

There are also contrasts between the metamorphic histories predicted during crustal thickening and those observed in the Eastern Goldfields. Models of crustal tectonic thickening and conductive cooling predict 'clockwise' P-T-t paths with peak pressures reached synchronously with the main phase of compressional deformation, but tens of millions of years before peak temperatures. In the Eastern Goldfields, as equally for most low-pressure metamorphic terrains world-wide, P-T-t-d histories show that peak temperatures and pressures occurred approximately synchronously during a major phase of (presumed compressional) deformation (e.g. Loosveld & Etheridge, 1990; Sandiford & Powell, 1991).

The problems of the production of low-pressure metamorphic conditions during regional compressional deformation have been considered by Loosveld & Etheridge (1990) and Sandiford & Powell (1991). These authors show that this style of metamorphism may occur as a result of small or moderate degrees of crustal thickening so long as there is significant simultaneous heating of the underlying mantle (e.g. through thinning of the mantle lithosphere) and some heat advection by magmas within the crust. Applying their models to the Eastern Goldfields, a possible geochronology of thermal events (following Swager & others, 1992; Hill & others, 1992; Napier, 1993) would be:

2710 Ma	thinning of the mantle lithosphere
2690-2660	partial melting of the lower crust
2660	metamorphic peak at high structural levels
2630	metamorphic peak in the middle crust
2585	cooling below 300°C.

Significant differences between this history and those of the published models are: the relative timing of metamorphism at different levels in the crust, and the reversed relative timing of mantle heating and compressional tectonics. Stüwe & others (1993) have considered the relative timings of the peak of metamorphism at different crustal levels in this style of tectonic history. Although some of their models do show metamorphism reaching a peak latest in the middle crust, no such models are consistent with the long time span indicated above for the Eastern Goldfields between mantle and lower-crustal heating, and upper and middle crustal metamorphism. In addition, it is worth pointing out, that thermal histories modelled for crustal thickening with synchronous mantle heat input are insensitive to the extent of crustal thickening, so long as it is relatively minor. Similar thermal histories are also predicted without crustal thickening, for instance, after magmatic underplating at the base of the crust (Bohlen, 1987), hence the metamorphic history is more a function of mantle heat input than of crustal thickening. Constraints on the extent of crustal thickening for the Eastern Goldfields are discussed further below.

Greenstone-belt scale tectonics

A number of metamorphic features, particularly the distribution of isograds and the spatial variations in the relative timing of peak metamorphism and deformation, can be understood as the result of relative vertical movements in the crust independent of the overall tectonic setting of the greenstone belts.

Greenstone belts are characterised by marked metamorphic zonation along their boundaries. Harte & Dempster (1987) showed that areas with such marked metamorphic zonation are often syn-metamorphic tectonic boundaries, generally with dip-slip, vertical components of motion. Across an isograd sequence, relative vertical movements may be confirmed from deformation-metamorphism timing relations: cooling should be synchronous with a phase of deformation in the higher-grade uplifted blocks, and heating in the lower-grade, downthrown blocks (Sleep, 1979; Ridley, 1989). This pattern appears common in greenstone belts. At Southern Cross, for instance, shear zones in granitoids (the upthrown block) are retrograde, whereas cordierite in cordierite-anthophyllite rocks in the centre of the belt (the downthrown block) has grown post-tectonically over an earlier chlorite fabric.

In all areas where similar features have been observed, the sense of movement implied is 'granitoid up'. On a greenstone-belt scale the patterns of metamorphism, particularly the low-grade holes can thus be understood as a result of syn-metamorphic relative downthrow of the centres of the belts. This observation does not distinguish the cause of movement, whether syn-magmatic (diapirism), doming, or fault or shear bounded block uplift. The results of Feng & Kerrich (1990) on crystallisation pressures at different points in granitoid masses suggest, however, that in at least some instances, the movement was diapiric.

Constraints on amount of crustal thickening

The models of Loosveld & Etheridge (1990) and Sandiford & Powell (1991) for low pressure metamorphism during regional compression involve maximum burial at the peak of metamorphism. Peak metamorphic assemblages, in conjunction with the present thickness of the crust (Goleby & others, 1993), may thus be used to estimate the syn-metamorphic crustal thickness, and hence the amount of crustal thickening during tectonism. The recognition in the Eastern Goldfields of syn-metamorphic relative vertical movements means, however, that individual pressure determinations may not be representative of the depth of erosion for the craton as a whole.

Typical metamorphic and igneous pressures of crystallisation in a cross section from the centre of a greenstone belt into adjacent granitoid in the Eastern Goldfields would be: greenschist-facies core of the belt, $P \approx 200$ MPa; amphibolite-facies margin, $P \approx 400$ MPa, margin of the granite pluton, $P \approx 400$ MPa; core of the granite, $P < 200$ MPa. If this pattern is the result of relative vertical movements along a tectonic boundary (Harte & Dempster, 1987) the higher-grade, higher-pressure assemblages may have been 'frozen in' during relative uplift, and will not be representative of regional depths of erosion. Regional depths of erosion will be closer to those indicated by the lower-pressure assemblages in the cores of both greenstone belts and granites, hence about 7 km, or equivalent to about 20% thickening of the crust.

In the southern parts of the Southern Cross Province in contrast, the lowest-grade rocks in the centres of the greenstone belts are of lower-amphibolite facies (Ahmat, 1986) formed at 300 - 400 MPa. The depth of erosion here is thus estimated at about 12 km. The difference of five kilometres between the two Provinces is similar to the difference in present-day crustal thickness (Eastern Goldfields seismic profile, Goleby & others, 1993), implying similar syn-metamorphic crustal thicknesses throughout this part of the craton.

Discussion

At our present state of knowledge, the tectonic model that best explains the metamorphism in the Eastern Goldfields is one involving small amounts of crustal thickening approximately simultaneous with heating from the mantle. Mantle heat input was the dominant control on metamorphic style. The best-fit model may, however, be significantly modified when more is known about the timing of metamorphism in different areas and levels of the crust, and about the control of relative vertical movements on the perceived timing of metamorphism.

One constraint from the metamorphism is clear: that crustal thickening during greenstone belt tectonism was relatively minor. Twenty percent thickening is the 'best-fit' value to date. The metamorphism does not easily allow models in which greater amounts of crustal thickening were followed by significant extensional collapse of the crust. However, as similar amounts of thickening are inferred for the Eastern Goldfields Province and the Southern Cross Province despite different depths of erosion, a more definitive value must await fuller isostatic calculations, for instance, of the effects of large volumes of magma formation and movement during greenstone development. Small amounts of crustal thickening are consistent with the lack of evidence in the Eastern Goldfields seismic profile (Goleby & others, 1993) for tectonic interleaving of greenstones and granitic basement.

The origin and overall tectonic significance of the inferred mantle heat input is unclear. It has been assumed here that mantle heat input correlates with abundant mafic and ultramafic volcanism at the early stages of greenstone belt development. This is a significantly different timing to that modelled by Loosveld & Etheridge (1990) and Sandiford & Powell (1991) for low pressure metamorphism. In these models, mantle heating is a result of tectonism, e.g. through convective delamination of mantle lithosphere. The long time span in the Eastern Goldfields between assumed mantle heating and crustal metamorphism suggests a differing, long-lasting heating event. An alternative explanation for the time lag is that the metamorphism of the middle crust was influenced more by granitic intrusion to these levels than by mantle heat input directly.

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References

Ahmat, A.L. 1986, Metamorphic patterns in the greenstone belts of the Southern Cross Province, Western Australia. *Geological Survey of Western Australia, Professional Paper*, 19, pp 1-21.

Barnicoat, A.C., Fare, R.J., Groves, D.I., & McNaughton, N.J. 1991, Syn-metamorphic lode-gold deposits in high-grade Archean settings, *Geology*, 19, pp 921-924.

Bavinton, O.A. 1981, The nature of sulfidic metasediments at Kambalda and their broad relationships with associated ultramafic rocks and nickel ores, *Economic Geology*, 76, pp 1606-1628.

Bickle, M.J., & Archibald, N.J. 1984, Chloritoid and staurolite stability: implications for metamorphism in the Archaean Yilgarn Block in Western Australia, *Journal of Metamorphic Geology*, 2, pp 179-203.

Bickle, M.J., Morant, P., Bettenay, L.F., Boulter, C.A., Blake, T.S., & Groves, D.I. 1985, Archean tectonics of the Shaw Batholith, Pilbara Block Western Australia: Structural and metamorphic tests of the batholith concept, *Geological Association of Canada Special Paper*, 28, pp 325-341.

Binns, R.A., Gunthorpe, R.J., & Groves, D.I. 1976, Metamorphic patterns and development of greenstone belts in the eastern Yilgarn Block, Western Australia, in *The Early History of the Earth*, ed. B.F. Windley, Wiley, New York, pp 303-313.

Bohlen, S.R. 1987, Pressure - temperature - time paths and a tectonic model for the evolution of granulites. *Journal of Geology*, 95, pp 617-632.

Chamberlain, C.P., & Rumble, D. III 1988, Thermal anomalies in a regional metamorphic terrane: the role of advective heat transport during metamorphism, *Journal of Petrology*, 29, pp 1215-1232.

Clout, J.M.F. 1988, The tectonic setting and plumbing system of the Golden Mile, Kalgoorlie, Western Australia, in *Bicentennial Gold 88, Extended Abstracts, Poster Programme, Volume 1*, Geological Society of Australia, Abstracts, 23, pp 65-67.

England, P.C., & Richardson, S.W. 1977, The influence of erosion upon the mineral facies of rocks from different metamorphic environments, *Journal of the Geological Society, London*, 134, pp 201-214.

England, P.C., & Thompson, A.B. 1984, Pressure-temperature-time paths of regional metamorphism. I. Heat-transfer during the evolution of regions of thickened continental crust. *Journal of Petrology*, 25, pp 894-928.

Feng, R., & Kerrich, R. 1990, Geobarometry, differential block movements, and crustal structure of the southwestern Abitibi greenstone belt, Canada, *Geology*, 18, pp 870-873.

Goleby, B.R., Rattenbury, M.S., Swager, C.P., Drummond, B.J., Williams, P.R., Sheraton, J.W., & Heinrich, C.A. 1993, Archaean crustal structure from seismic reflection profiling, Eastern Goldfields, Western Australia, *Australian Geological Survey Organisation Record*, 1993/15.

Grambling, J.A. 1981, Pressures and temperatures in Precambrian metamorphic rocks, *Earth and Planetary Science Letters*, 53, pp 63-68.

Harte, B., & Dempster, T.J. 1987, Regional metamorphic zones: tectonic controls, *Philosophical Transactions of the Royal Society, London*, series A, 321, pp 105-127.

Hill, R.I., Chappell, B.W., & Campbell, I.H. 1992, Late Archaean granites of the southeastern Yilgarn Block, Western Australia: age, geochemistry, and origin, *Transactions of the Royal Society of Edinburgh, Earth Sciences*, 83, pp 211-226.

Knight, J.T., Groves, D.I., & Ridley, J.R. submitted, District-scale structural and metamorphic controls on Archaean lode-gold mineralization in the amphibolite facies Coolgardie Goldfield, Western Australia, *Mineralium Deposita*.

Loosveld, R., & Etheridge, M.A. 1990, A model for low-pressure facies metamorphism during crustal thickening, *Journal of Metamorphic Geology*, 8, pp 257-267.

McQueen, K.G. 1981, Volcanic-associated nickel deposits from around the Widgiemooltha Dome, Western Australia, *Economic Geology*, 76, pp 1417-1443.

Napier, R. 1993, $^{40}Ar/^{39}Ar$ Geochronology of gold mineralization and Archaean tectonics in the Yilgarn Block, Western Australia, *Second Biennial SGA Meeting*, Granada Spain, September, 1993.

Purvis, A.C. 1984, Metamorphosed altered komatiites at Mt Martin, Western Australia - Archaean weathering products metamorphosed at the Aluminosilicate triple point, *Australian Journal of Earth Sciences*, 31, pp 91-106.

Ridley, J. 1989, Vertical movement in orogenic belts and the timing of metamorphism relative to deformation, in *Evolution of Metamorphic Belts*, eds. J.S. Daly, R.A. Cliff & B.W.D. Yardley, Special Publications of the Geological Society of London, 43, pp 103-115.

Saggerson, E.P., & Turner, L.M. 1976, A review of distribution of metamorphism in the ancient Rhodesian craton, *Precambrian Research*, 3, pp 1-53.

Salje, E. 1986, Heat capacities and entropies of andalusite and sillimanite: the influence of fibrolitization on the phase diagram of the Al_2SiO_5 polymorphs, *American Mineralogist*, 71, pp 1366-1371.

Sandiford, M., & Powell, R. 1991, Some remarks on high-temperature—low-pressure metamorphism in convergent orogens, *Journal of Metamorphic Geology*, 9, pp 333-340.

Sleep, N. 1979, A thermal constraint on the duration of folding with reference to Acadian geology, New England, USA, *Journal of Geology*, 87, pp 583-589.

Stüwe, K., Will, T.M., & Zhou S. 1993, On the timing relationship between fluid production and metamorphism in metamorphic piles: some implications for the origin of post-metamorphic gold mineralisation. *Earth and Planetary Science Letters*, 114, pp 417-430.

Swager, C.P., Witt, W.K., Griffin, T.J., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J., & Wyche, S. 1992, Late Archaean granite-greenstones of the Kalgoorlie Terrane, Yilgarn Craton, Western Australia, *Geology Department (Key Centre) & University Extension, University of Western Australia Publication*, 22, pp 107-122.

Wilde, S.A., & Pidgeon, R.T. 1987, U-Pb geochronology, geothermometry and petrology of the main areas of gold mineralization in the "Wheat Belt" region of Western Australia, *Western Australia Minerals & Petroleum Research Institute, Report, 30, 171 pp.*

Wong, T. 1986, Metamorphic patterns in the Kambalda area and their significance to Archaean greenstone belts of the Kambalda-Widgiemooltha area. BSc Honours thesis, The University of Western Australia, 153 pp (unpublished).

Archaean mantle plumes

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Convection in the Earth's mantle can be divided into two components, each driven by one of the mantle boundary layers (Fig. 1). The upper boundary layer is cold, oceanic lithosphere that forms at the mid-ocean ridges. It cools slowly by a combination of conduction and advection until eventually it becomes denser than the underlying material and sinks back into the mantle. This creates a low pressure region at spreading centres that leads to a passive upwelling of upper mantle that undergoes decompressional melting at the top of its ascent to produce mid-ocean ridge basalts.

The mantle's second boundary layer is a hot layer at the base of the mantle. The core is believed to be hotter than the overlying mantle. Heat conducted from the core heats the overlying mantle to form a hot boundary layer that is believed to be the source of mantle plumes. The boundary layer being hotter than the adjacent mantle is also lighter and it tends to rise. However, before it can rise at a significant rate it must acquire enough buoyancy to overcome the viscous forces that oppose its ascent. As a consequence a new plume consists of two parts: a large spherical head and a narrower tail. The head grows by entrainment as it rises reaching a diameter of about 1000 km as it approaches the top of the mantle. Here it flattens to form a disk 2000 km across and 200 km deep. The head consists of alternate layers of hot mantle from the plume source and cooler lower mantle material entrained into the head during its ascent (Fig. 2). The tail of the plume, provided its ascent remains vertical, entrains little of the overlying mantle during its rise. It retains a high temperature similar to that of the boundary layer source region from which the plume originates and it eventually melts to produce high-temperature magmas such as komatiites and picrites. The entrainment of relatively cool lower mantle material into the head of the plume cools the head so that its temperature is intermediate between that of the plume tail and the adjacent mantle. The plume head melts to produce lower-temperature magmas such as basalts.

Continental flood basalts provide convincing evidence for the validity of the plume hypothesis (Campbell & Griffiths, 1990). Flood basalts erupt rapidly and cover large equi-dimensional areas typically 2000 m across. Phanerozoic examples were invariably over a known hot spot at the time of eruption. They are connected to the current position of the hotspot by a narrow chain of volcanoes ~200 km wide. The Deccan Traps, connecting to Reunion Island by the Chagos–Laccadive Ridge is a good example (White & McKenzie, 1989). The flood basalt is produced by melting the plume head and the ridge, connecting the flood basalt to the current position of the hotspot, by melting the plume tail.

The existence of plumes in the modern mantle is as widely accepted as plate tectonics, but did they exist in the Archaean and if they did how can we recognise them? Plumes exist in the modern mantle because the core is hotter than the mantle. The modern core consists of a solid inner core in a liquid outer core, implying that it is solidifying from the inside out. That being the case, the Archaean core must have been hotter (it may have been completely molten) than the modern core. The abundance of basalts in Archaean greenstone belts suggests that the Archaean mantle was only slightly hotter than the modern mantle. The core-mantle temperature difference can therefore be expected to be greater in the Archaean than it is today and plumes are predicted to have been more abundant in the Archaean mantle than they are today.

Mantle plumes can be identified by the high temperature magmas they produce. Temperature variations within the convecting mantle away from subduction zones, boundary layers and plumes are thought to be small and within few tens of degrees of the adiabatic gradient. McKenzie & Bickle (1988) suggest that the potential temperature (T_P: the temperature after adiabatic decompression to 1 bar) of the modern upper mantle is 1280°C and that the maximum MgO content of basalts produced by decompressional melting of mantle of this temperature

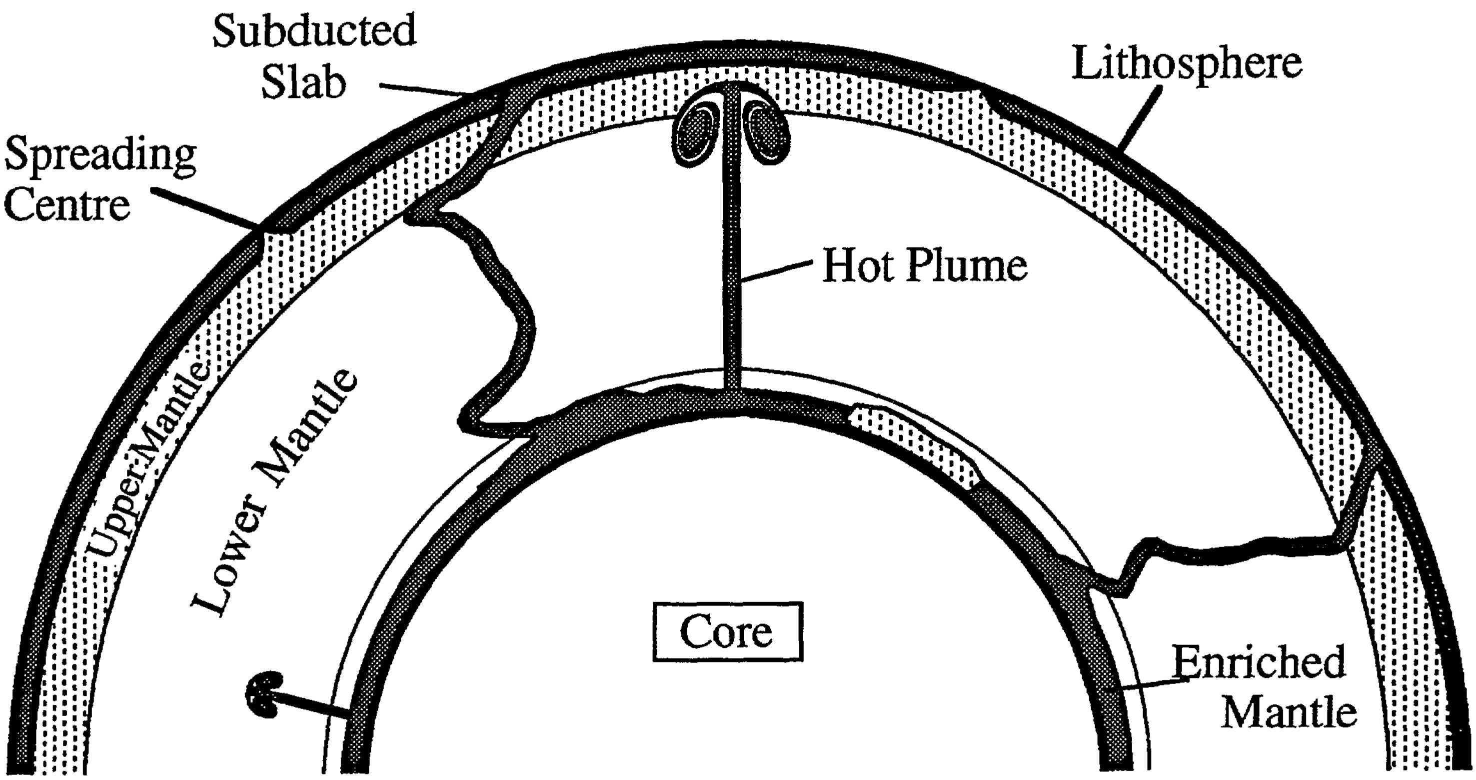

Fig. 1. Diagrammatic sketch section through the mantle showing subducted slabs and mantle plumes, the two main forms of mantle convection.

is about 11 wt.%. Since the liquidus temperature of dry magmas is a function of the MgO content of the melt, dry magmas with MgO contents appreciably above 11% must be produced by melting anomalously hot zones within the mantle, that is by melting mantle plumes. For the modern mantle, it is likely that any dry magma with an MgO content well above 11 wt.% (say 14 wt.%) is the product of melting of a plume (Campbell & Griffiths, 1992). For the Archaean mantle a slightly higher value is recommended, say 16 wt.%.

The widespread occurrence of spinifex textured komatiites with MgO contents as high as 32 wt.% in Archaean greenstone belts, provides convincing evidence that mantle plumes were an important component in the Archaean mantle and their high MgO contents suggest that they were 200-300°C hotter than modern plumes (Campbell & Jarvis, 1984; Campbell & others, 1989). It therefore appears likely that mantle plumes play an important role in the generation of Archaean greenstone belts. There are a number of observations that support this hypothesis. First, major greenstone belts, such as the Norseman–Wiluna greenstone belt, consist of vast outpourings of mafic magma that erupted in a short period of time. In this respect, they are similar to flood basalts (Campbell & Hill, 1988). Secondly, basaltic sequences in Archaean greenstone belts can be correlated over large distances. Again, this is a character they share with flood volcanism but not with island arc volcanics. Finally, the geochemistry of Archaean tholeiites and komatiites is characterised by high Ni and chrondritic Nb/La and Ti/Y ratios. In these respects they are similar to modern plume derived basalts and picrites but differ from MORB-type magmas which have lower Ni and from island arc magmas which have both lower Ni and Nb/La and Ti/Y ratios well below the chrondritic value.

It has been suggested that the voluminous 2.7 Ga basaltic-komatiitic event in the Kalgoorlie–Norseman region was produced by melting of a mantle plume head. The komatiites are believed to be the products of melting of the hot plume tail and the basalts the products of melting of the cooler plume tail. Isotopic and geochemical differences between basalts and komatiites are consistent with this hypothesis (Campbell & others, 1989).

Large granite batholiths, with ages ranging from ~2.63 to 2.85 Ga occur throughout the Yilgarn Block. The heat required to produce this massive thermal event is believed to have been derived from the same mantle plume that produced the basalts and komatiites, the time difference of ~25 Ma between the onset of mafic and felsic volcanism being the time taken to conduct heat from the top of the plume to the base of the crust (Campbell & Hill, 1988). Minor komatiitic activity seen in the Southern Cross and Murchison sub-provinces may be the product of melting of a plume tail. These events are also associated with crustal anatexis but these melting events are small compared with the 2.7 Ga event.

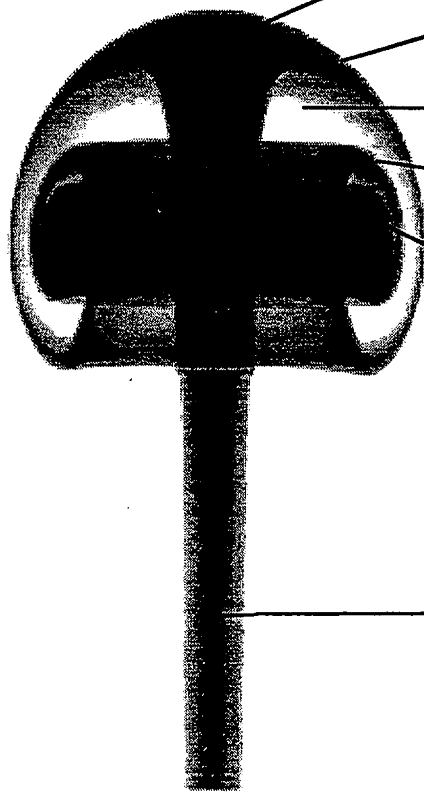

Fig. 2. A photograph of a laboratory starting thermal plume. Dark material comes from the plume source region and may be chemically and isotopically different from the surrounding mantle. Conduction of heat during the rise of the plume causes entrainment of cooler mantle and smoothing of temperature gradients within the head, where the mean temperature is intermediate between the source and ambient mantle. Temperature variations within the conduit of the plume and axis of the plume head are small because this material is not diluted by entrainment. The temperature of the mantle in the axis of the plume is therefore greater than that of the remainder of the head. If melting occurs, the bulk of the plume head will yield low temperature melts such as tholeiitic basalts, whereas the high temperature material in the plume axis may melt to produce picrites or komatiites.

References

Campbell, I.H., & Griffiths, R.W. 1990, Implications of mantle plume structure for the evolution of flood basalts. *Earth & Planetary Science Letters,* 99, 79-93.

Campbell, I.H., & Griffiths, R.W. 1992, The changing nature of mantle hotspots through time: implications for the geochemical evolution of the mantle. *Journal of Geology*, 92, 497-523.

Campbell, I.H., Griffiths, R.W., & Hill, R.I. 1989, Melting in an Archaean mantle plume: heads it's basalts, tails it's komatiites. *Nature*, 339, 697-699.

Campbell, I.H., & Hill, R.I. 1988, A two-stage model for the formation of the granite-greenstone terrains of the Kalgoorlie-Norseman area, Western Australia. *Earth & Planetery Science Letters,* 90, 11-25.

Campbell, I.H. and Jarvis, G.T. 1984, Mantle convection and early crustal evolution. *Precambrian Research*, 26, 15-56.

McKenzie, D., & Bickle, M.H. 1988, The volume and composition of melt generated by extension of the lithosphere. *Jounal of Petrology,* 29, 625-679.

White, R., & McKenzie, D. 1989, Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Jounal of Geophysical Research*, 94, 7685-7729.

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Archaean crustal processes as indicated by the structural geology, Eastern Goldfields Province of Western Australia

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In considering the tectonic environments in which distinctive late Archaean "granite-greenstone" terranes such as those of the Yilgarn Block in Western Australia (e.g. the Norseman–Wiluna Belt) and the Canadian Shield (e.g. the Abitibi Greenstone Belt of southeastern Canada) developed, geoscientists have advanced fundamentally different models. Contemporary schools of thought are significantly different to those of a decade or more ago (e.g Silver, 1980; Glover & Groves, 1981) when it was largely accepted that the processes of Archaean crustal evolution were very different to those of the Phanerozoic. More recent discussions explore concepts based on conventional intracratonic basin and rift scenarios (Groves & Batt, 1984; Hallberg, 1986), or conventional, convergent plate margin plate tectonics scenarios (e.g. Ludden & others, 1986; Wyman & Kerrich, 1988; Barley & others, 1989; Hoffman, 199?).

In the Archaean Eastern Goldfields Province, evidence for, and the consequences of;

- crustal shortening (e.g. Platt & others, 1978; Archibald & others, 1981, Martyn, 1987; Swager, 1989; Swager & others, 1992),
- wrench tectonics concepts (e.g. Harris, 1987; Eisenlohr & others, 1989),
- uniformitarian convergent plate margin models based on litho-stratigraphic arguments (e.g. Barley & others, 1989; Barley & Groves, 1992), and
- marginal basin or plate accretion scenarios (Myers, 1990; Swager & others, 1992) have been addressed.

Nonetheless, a cohesive model for the evolution of this terrane accounting for the distinctive structural and lithological associations, has not emerged.

In a recent conceptual synthesis (Hammond & Nisbet, 1992), we outline a rationalised history of tectonism for the Eastern Goldfields Province, and argue that the greenstone successions and early granitoid phases in the Norseman–Wiluna Belt developed in a continent scale extensional terrane, which may have been initiated as early as 2.9 Ga. A protracted early history of north-northwest–south-southeast extension episodes (**D_E**) is proposed, resulting in extensional tectonic slides (lags), now preserved along many of the contacts between greenstone belts and granitic complexes. It is inferred from available dating (e.g. McNaughton & Dahl, 1987; Barley & McNaughton, 1988; Claoué-Long, 1990) that compressional tectonism immediately followed **D_E**, beginning with low angle thrusting and stratigraphic repetition (**D_1**) with a northwest transport direction occurring seemingly throughout the belt (e.g. Martyn, 1987; Williams & others, 1989; Swager & others, 1992). **D_1** may have terminated extension at about 2.68 to 2.69 Ga. The dominantly north-northwest regional strike is ascribed to very large-scale, westward verging, thrust imbrication of much of the upper crust with related large-scale folding (**D_2**), in response to east-northeast–west-southwest shortening. **D_2** reflects a major change in shortening direction and a new tectonic regime. Common, north-south striking dextral strike slip fault systems are thought to represent a relatively late northeast-southwest shortening event (**D_3**).

The geological features ascribed to the so-called **D_E** event are addressed here, and we examine the wider implications of the evidence for early crustal extension as it concerns the geology of the northern Eastern Goldfields Province, granite-greenstone terranes, and Archaean crustal processes.

The extensional process

Modern and well preserved examples of crustal extension such as rifts (Ebinger & others, 1987; Chorowicz & Sorlien, 1992; Scott & others, in press), continental passive margins (e.g. Le Pichon & Sibuet, 1981; White & McKenzie, 1989; Lister & others, 1986; 1991), intracratonic basins (e.g. Gibbs, 1984; 1987; Blundell, 1991) and Cordilleran Metamorphic Core Complexes (e.g. Crittenden & others, eds. 1980; Davis & others, 1986; Davis & Lister, 1988) with small to very large overall extensions, and low to high extension rates, have been well documented. The main elements of the continental crustal extension process are well established, and are summarised below.

- In the more brittle upper crust, extension initiates with rotational block faulting above a detachment;
- faulting patterns are dominated by half graben bounding faults and extension parallel "transfer fault" accommodation structures;
- Mechanical delamination of the crust occurs, with the ramping downward and widening of the above detachment shear zone into the lower crust and mantle lithosphere, where pure shear increasingly accommodates extensional strains;
- Asymmetric extension geometries develop; the locus of rotational block faulting is laterally displaced from the loci of mid- and lower-crustal extension, accommodated by the above mechanical delamination of the crust;
- The passive rise of mantle occurs in response to thinning of the crust, commonly also decompression partial melting of still hot mantle, and the generation of varied and voluminous mafic magmas;
- Potential for net uplift exists, dependant on the magnitude of the mantle thermal anomaly that initiates, or develops in response to extension, and the rate of extension, e.g. Metamorphic Core Complexes of the Cordilleran type reflect rapid extension, failure over much narrower zones with large extensions, and exhumation of the detachment(s) underlying extended upper crust;
- More gradual extension rates or lesser mantle thermal anomalism might produce subsidence dominated basins lacking volcanics;
- Rift successions progressing from locally derived coarse clastic half graben fill, to potentially abundant volcanics (see above, White & others, 1987) and shallow water/terrestrial deposition, and ultimately to deep water sedimentation reflecting post-extension thermal subsidence (i.e. sag phase sedimentation).

Deliberations over the strength of continental lithosphere (e.g. Lynch & Morgan, 1987; Kusznir & Park, 1987; Ord & Hobbs, 1989) affirm the propensity of the crust for delamination; a consequence of the strength-determining mineral changing with depth (e.g. quartz-rich rocks may be strength controlling in the upper 15 km, plagioclase-rich rocks to approximately 25 km, mafic rocks in the lower crust to the crust-mantle boundary, and olivine-rich rocks in the lithosphere mantle), such that, given high geothermal gradients and significant tensile loads, large contrasts in strength occur at these mechanical boundaries, which are then amenable to detachment, provided appropriate lithologies are present to give effect to these mechanical transitions. Major lithological boundaries may also be amenable to detachment.

Lister & others (1991) examine extension in relation to the evolution of passive continental margins and show that asymmetric crustal delamination and sub-crustal pure shear best account for what is observed. Nonetheless, a uniformitarianist application of their, or any other models for crustal extension (e.g. McKenzie, 1978; Le Pichon & Sibuet, 1981; Davis & others, 1986; Wernicke, 1985) to Archaean terranes, is not appropriate because of the probable differences in thickness, composition and heat flow between modern continental lithosphere and that of the Archaean (see Bickle, 1990). Nonetheless, the main elements of these models must guide our discussion of Archaean crustal extension.

Granitic complex–greenstone contacts

The contacts between granitic complexes and greenstones in the Eastern Goldfields Province are ubiquitously tectonised. Although central to an understanding of the evolution of the Eastern Goldfields Province, documentation of the character of these commonly complex zones (e.g. Williams & others, 1989), and the internal structure of granitic complexes is uncommon.

Reconnaissance structure mapping throughout the Laverton, Duketon and Wiluna regions, and investigations locally of a more detailed nature, indicate that many greenstone-granitic complex contacts typically entail: a) greenstones overlying granitic complex rocks, b) some thousands of metres of very strongly foliated (mylonitic) granitic rock underlying the contact, c) commonly quartz-rich, and probably magnetite bearing mylonitic rock at the contact, d) a contrastingly narrow zone (<1,000 metres) of very strongly foliated and lineated amphibolite above the contact, commonly entraining some talc and tremolite-rich ultramafic lithologies, and passing rapidly outward into greenstones with low metamorphic grades e) in some examples clear evidence of granitoid emplaced into contact zones during the kinematic history, and f) commonly north-northwest or south-southeast mineral lineation plunge azimuths and top to the south-southeast movement senses.

Clearly all granitoid-greenstone contacts do not conform to the above pattern, but a significant proportion of those examined fall into this class. Such contacts are distinctive, and are known to occur throughout the central and northern Eastern Goldfields Province. Of particular note are; the apparent compressed metamorphic gradients evident in the greenstones adjacent to these contacts (Williams & Currie, 1993), and their early timing relative to the phases of deformation recognised.

Discussion

Crustal shortening and the evolution of orogenic belts is matched in the history of the earth by crustal extension, the evolution of depositional basins, and the deposition of the rock successions that become entrained in these orogens. Our understanding of the inter-relationship between the processes of lithospheric plate movement, and attendant crustal extension and shortening could be said to be relatively sound for the present, and for Cainozoic and Mesozoic terranes where a direct correlation to the present exists (Silver, 1980). The level of understanding for progressively older terranes is necessarily increasingly less good for reasons of preservation, particularly where they are distinctively different from those of the Cainozoic and Mesozoic, such as the "granite-greenstone" terranes of Archaean cratonic blocks.

Although uniformitarian plate-margin models and discussion of magmatic arc and back-arc basin associations (e.g. Barley & Groves, 1988; Barley & others, 1989; 1992; Barley & Groves, 1990; Swager & others, 1992) have been recently popular, fundamental problems exist with such interpretations in the Eastern Goldfields Province:

- Direct physical evidence of an "arc", and evidence of an adjacent plate margin or suture to the east, such as the remnants of an accretionary complex, are lacking;
- Litho-stratigraphic evidence is very poorly constrained (largely an outcrop limitation);
- Geochemical characteristics are not reliable indicators of Archaean tectonic environment (Bickle, 1990);
- The geometrical constraints of the early structural history are inconsistent with a plate margin to the east, and imply a "plate margin" to the south or southeast. It is only later shortening (D_2) that is oriented east-west to northeast-southwest;
- A crucial problem lies in the nature of Archaean oceanic crust. Given that such a thing occurred, assessments of its potential character infer that it may have been far too thick to subduct. Bickle, (1986) estimates a 20 km thickness with an average komatiitic basalt composition.

An early extensional history in Proterozoic orogenic belts is increasingly recognised (e.g. Etheridge & others, 1987; Loosveld, 1989; Windh, 1992) and it is reasonable to consider extension tectonics as a potential explanation for major elements of Archaean geology. The Norseman–Wiluna Belt has also commonly been regarded as an ensialic (intra-cratonic) basin or rift (Williams, 1974, Archibald & others, 1981; Groves & Batt, 1984; Hallberg, 1986; Martyn, 1987) and crustal extension is inherent in an intracratonic basin model. Such an environment readily accounts for the early dominance of mafic and ultramafic rocks, and a critical concern is the means by which Archaean crust might have accommodated this.

Lags

We have used the term "lag", in reference to the class of structure discussed here, in recognition of their probable origin as low angle, extensional tectonic slides (the reverse of "thrust"; a low angle, *compressional* tectonic slide; Fleuty 1964).

The high strain zones we have referred to as lags could be interpreted as major thrusts where greenstone succession is thrust over granitic basement flanking the original greenstone "basin". However, their presence throughout the region (Hammond & Nisbet, 1992), rather than just occurring in the periphery of the orogenic belt as one might expect, militates against this. In addition, the effect of thrusting is more commonly to emplace basement over cover sequence, the reverse of the relationship we have generally encountered. However, rare examples of granitic complex thrust over greenstones are known (e.g. 30 km south of Wiluna), but, the movement sense is top block to the north-northwest (consistent with D_1), the reverse of that generally observed in the D_E tectonic slides, and one example (eastern flank of the Lawlers Anticline) can be shown to overprint a lag.

The extensional tectonic slides seem to have originated at or near the detached base of the greenstone succession in an actively extending terrane, and are easily explained by the kind of scenario outlined below, which is akin to modern metamorphic core complex models (e.g. Crittenden & others, 1980; Lister & Davis, 1983; Davis & others, 1986) and encompasses elements of models for passive margin evolution (Le Pichon & Sibuet, 1981; Lister & others, 1991). However, given that subsequent considerable shortening in both a north-northwest–south-southeast sense (D_1), and an east-northeast–west-southwest sense (D_2) has occurred, the indicated original areal extent of the lags presents conceptual difficulties:

- Do the identified lags represent a single regionally occurring detachment, subsequently segmented, or,
- Can the lags be ascribed to several discrete and essentially separate extensional fault and shear systems or basin forming events?
- Did such a detachment or detachments develop during one relatively brief tectonic episode, or diachronously over a considerable period?

The distribution of recognised lags is readily accounted for by the effects of D_2, and the character of the lags in question is consistent, from which an affirmative answer to the first question above can be inferred, rather than the second. No outcrop, or map scale evidence for the extensional segmentation of a pre-existing lag, or the overprinting of a lag by a newer lag has been encountered. Possible answers to the third question above are less clear, but diachronous extension may have to be invoked to account for the immense areal extent of the original greenstone extensional terrane and its distinctive basal lag.

Constraints on Archaean crustal extension

Given higher Archaean mantle temperatures, stretching and thinning alone of the lithosphere at moderate rates could have produced significant volumes of mafic melt (decompression melting of asthenosphere), whereas a modern example (e.g. the North Sea) would produce none (McKenzie & Bickle, 1988; White & McKenzie, 1989; Bickle, 1990). It follows that depressions developed as a response to Archaean extension would have been largely filled by mafic and ultramafic lavas. Nonetheless, the abundance of komatiite flows in the greenstone successions could be taken to infer some anomalous mantle activity, with the condition that too high a thermal anomaly in the mantle could have led to considerable net uplift (White & McKenzie, 1989) rather than basin formation, although the asymmetry allowed by delamination (Lister & others, 1991) may partly resolve problems of this type (see below). Much of the Archaean mid- and upper crustal section appears to have been dominated by granitic rock, with compositional ranges adequate to give effect to the mechanical transitions discussed above, and thence to favour crustal delamination under load. Indeed, it is probable that a very weak layer of partial melt was present in the mid crust during Archaean tectonism (Ridley, 1992), promoting delamination, and providing granitic melt for remobilisation into varied sites at shallower levels.

A further consequence of crustal thinning would be decompression of mid- and lower-crustal granitic and gabbroic rocks, which, with the added heat flow due to the passage of high temperature mafic and ultramafic magmas, ought to result in the generation of a range largely A- and I-type granitic melt (see Etheridge & others, 1987). Hence, after the initiation and early development of an extensional belt, continuing extension should accompany mafic and felsic magmatism, the former tending to dominate volcanism, and the latter plutonism. Even at large extensions, underplating at the base of a highly attenuated sialic crust may continue to provide a source for felsic partial melt.

As occurs in modern extending terranes, rotational block faulting must have also initially occurred in Archaean conditions in the upper 10 to 15 km of sialic material. The simplest model (see Lister & others, 1991) might involve one major detachment shear zone developing at the base of this brittlely extending upper crust, and stepping down to successively deeper mechanical transitions, and into the lithospheric mantle, possibly as a very thick zone of non-coaxial strain. However, the scale of the development of greenstone belts in the Norseman–Wiluna Belt militates against a narrow locus of extension and a single stepping detachment. Delamination could also encompass independently extending layers of crust between detachments developed along mechanical transitions (i.e. a very large scale extensional duplex geometry), accompanied by dominantly pure shear of the mantle lithosphere (mildly asymmetric). The latter scenario is intuitively more likely, and would have involved a much broader portion of the mid- and lower-crust initially thus allowing an areally more extensive extensional orogen (see discussion of lags above).

It is also possible that the thickness of Archaean lithosphere (200 km, Bickle, 1986; 1990; McKenzie and Bickle, 1988) may have allowed for larger overall extensions over much larger areas than in modern examples, before an Archaean analogue of oceanic crust developed.

The common occurrence of thin shale,

silicic shale and chert units between volcanic units in both felsic and mafic volcanic sequences, and the presence of pillowed mafic lavas, indicates the deposition of the greenstone succession largely in a subaqueous environment indicating the presence of a basin rather than a terrestrial volcanic terrain. Moderate extension rates, and no more than a minor mantle thermal anomaly might be inferred from this.

Despite the direct evidence of early rifting, coarse clastic half graben fill (e.g. Jones Creek Conglomerate), rotated fault blocks of granitic basement that would have initially formed the upper plate have not been identified in the Eastern Goldfields Province, although the preservation locally of half graben fill indicates that some suggestion of the upper plate fault blocks must somewhere be preserved. However, that they do not still occur as prominent basement blocks in the terrane can be used to infer that they were not widely developed, or they have somehow been largely removed. It is thought most likely that this would occur through substantial thermal uplift and erosion at an early stage of the extension cycle. This observation might be used to infer either or both relatively rapid extension and a significant initial thermal anomaly, in contrast to the inference made above.

How might these contradictory inferences be rationalised? We argue (Hammond & Nisbet, 1992) that the well defined and preserved stratigraphy in the Kalgoorlie and Kambalda region is the least disrupted because it is the youngest sequence in the Norseman–Wiluna Greenstone Belt succession. One implication of such a conclusion could be that progressively younger greenstones sequences occur southwards along the length of the Norseman–Wiluna Greenstone Belt, and existing dating evidence is loosely supportive of this assertion (Barley & McNaughton, 1988; Browning & others, 1987). It is possible, then, that extension was diachronous with a progressive south-southeastward migration of the extension axis. The potential exists in such a scenario for the development of a diachronous lag at the base of a progressively younger sequence southward. A migrating extension locus can also account for the areal extent of the extensional terrane that is now reflected in the Norseman–Wiluna Greenstone Belt.

A further potential implication of the above might be that the onset of sag phase sedimentation would also have been diachronous, starting in the north. Indeed, significant volumes of fine-grained metasedimentary rocks, that might be the consequence of such a sag phase, locally dominate greenstone sequences in the far north of the Norseman–Wiluna Belt (observed as cuttings from recent regional exploratory Rotary Air Blast drilling undertaken by BHP). Significant volumes of fine-grained metasedimentary rocks, although proportionately less dominant, also occur in the Laverton area.

Origin of D_E tectonic slides

Given all of the considerations outlined above, a plausible history of the evolution of an Archaean Norseman–Wiluna Belt extensional basin is outlined below, which accommodates the possibility that a driving mechanism may have been a mantle thermal anomaly, though perhaps not as major an anomaly as the mantle plume envisaged by Campbell & Hill (1988).

With progressing extension:

- Brittle failure of the upper crust and formation of a rift zone;
- Broadening of the rift by rotational block faulting above a ductile detachment with locally derived, granitic coarse clastic fill, isostatic (& thermal off-axis?) uplift of the basin floor and its immediate flanks (e.g. Fig. 1A);
- Continued thermal uplift (with competing mechanical thinning) and deep erosion of upper plate rotational fault blocks;
- Generation and influx of ultramafic and mafic volcanics, and potential underplating at the base of the crust;
- Effects of thermal relaxation and mechanical thinning generate net subsidence and early accumulation of mafics increasingly in a sub-aqueous environment, with the lower plate ultimately drawn out from beneath extended upper crust to directly underlie this fill (e.g. Fig. 1);
- Partial melting of lower crust and underplated material to generate A and I type felsic magmas, emplacement of early granitic magmas;
- Extensional detachments in and at the base of the basin fill "capture" ascending felsic magmas (see Hutton & others, 1990) by providing favourable sites for lateral spread (magmas could have thermally lubricated detachments and potentially accommodated much of the shear strain until crystallised), potential felsic volcanism;
- Relatively hot, strongly non-coaxially deformed mid-crustal granitic material progressively drawn out into contact with extending basin fill generating compressed metamorphic gradients, continued generation of mafic and felsic magmas, underplating, possible deep exhumation of the original basin flanks and local exposure of the detachment due to uplift;

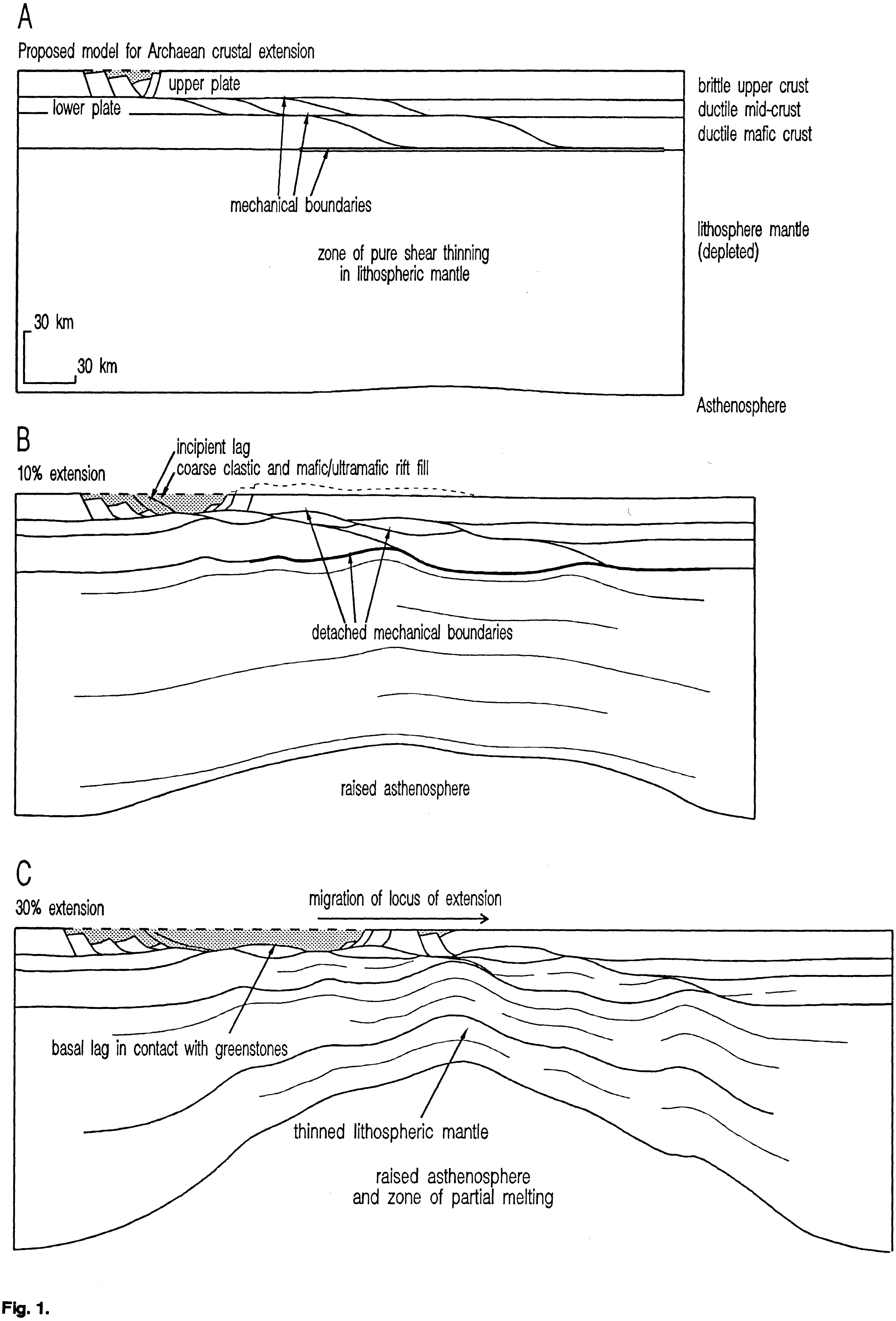
A
Proposed model for Archaean crustal extension
upper plate
lower plate
brittle upper crust
ductile mid-crust
ductile mafic crust
mechanical boundaries
lithosphere mantle
(depleted)
zone of pure shear thinning
in lithospheric mantle
30 km
30 km
Asthenosphere
B
10% extension
incipient lag
coarse clastic and mafic/ultramafic rift fill
detached mechanical boundaries
raised asthenosphere
C
30% extension
migration of locus of extension
basal lag in contact with greenstones
thinned lithospheric mantle
raised asthenosphere
and zone of partial melting

Fig. 1.

- Migration of the locus of extension toward the higher heat flow flank of the widening "Eastern Goldfields Basin" (e.g. Fig. 1C);
- Thermal sag and deep water sedimentation on the old and cold side of the basin (north), synchronously with continuing extension and volcanics accumulation (south);
- Ultimately deposition of Kalgoorlie–Kambalda sequence followed by onset of D_1.

The above scenario can provide for one, or few, areally extensive basal detachment shear zones, through the migration of the locus of extension such that, at a given time, the newer portion of this detachment is most active. Elsewhere, older portions of the detachment may be largely inactive, though still an appropriate site for the emplacement of granitoid sheets. Cordilleran Metamorphic Core Complex-like domal granitic complexes might develop through the emplacement of large granitoid sheets into the basal detachment or lags within the greenstone succession (e.g. Hutton & others, 1990), or through large scale irregularities developed in the basal lag. Large variations in the ultimate thickness of the greenstone succession are implicit.

With higher levels of mantle activity, underplating and remelting, and repeated partial melting of crustal rocks is envisaged, and a consequent variety of melt compositions is possible, although the generation of calc-alkalic magmas, a constituent of the greenstone belts, remains a problem.

Conclusions

The structural, metamorphic and lithological associations of many contact zones between granitic complexes and greenstone belts throughout the northern Eastern Goldfields Province are entirely consistent with their origin as major extensional detachments or lags that are demonstrably the earliest structures in the terrane, and may represent a diachronous basal lag underlying most of the Norseman–Wiluna Greenstone Belt succession.

It is possible that portions of this detachment mantled large scale, low relief domal granitic complexes (e.g. the Menzies–Leonora–Lawlers bounded complex, see Williams and Whitaker, 1993), in part composed of syn-kinematic granitoids, but which may never have been exposed in the manner of Cordilleran Metamorphic Core Complexes. Overall extension was great enough to structurally juxtapose largely basement derived granitic complex rocks with greenstone cover succession over very large areas. However, in order to account for the immense area of the original greenstone "basin" and the apparently areally extensive basal lag, we propose that extension was probably also diachronous with a southward migration of the locus of extension.

The extensional scenario predicts the presence of significantly thinned sialic crust with a veneer of greenstone, perhaps only locally over 10 km in thickness, and with only the youngest depositional phase likely to be undisrupted by extensional structures (i.e. Kalgoorlie–Kambalda sequence, Martyn, 1987; Swager & others, 1990) on the "upper plate" (see Lister & others, 1991) side of the extensional system in the south, perhaps with a sediment dominated sag sequence in the older portions of the basin in the north.

It is possible that a mantle thermal anomaly initiated the extensional process, although the presence of a plate margin-like feature may have exerted some control on the extension direction and geometry, as can be inferred from the "Wilson Cycle"-like kinematic relationship between D_E and D_1. However, no inference can be drawn with regard to the character of such a plate margin.

References

Archibald N.J, Bettenay L.F., Binns R.A., Groves D.I. & Gunthorpe R.J. 1978, The evolution of Archaean greenstone terrains, Eastern Goldfields Province, Western Australia. *Precambrian Research.*, 6, pp 103-131.

Archibald N.J., Bettenay L.F., Bickle M.J. & Groves D.I. 1981, Evolution of Archaean crust in the Eastern Goldfields Province of the Yilgarn Block, Western Australia, in *Archaean Geology,* eds Glover J.E. & Groves D.I. *Special Publications of the Geological Society of Australia,* 7, pp 491-504.

Barley M.E. & Groves D.I. 1990, Deciphering the tectonic evolution of Archaean greenstone belts: the importance of contrasting histories to the distribution of mineral deposits in the Yilgarn Block. *Precambrian Research,* 46, pp 3-20.

Barley, M.E. & McNaughton, N.J. 1988, The tectonic evolution of greenstone belts and setting of Archaean gold mineralisation in Western Australia: geochronological constraints on conceptual models, in *Advances in understanding Precambrian gold deposits Vol. II,* eds Ho S.E. & Groves D.I. Geology Department (Key Centre) & University Extension, The University of Western Australia, Publication No. 12, 23-40.

Barley M.E., Eisenlohr B., Groves D.I., Perring C.S., & Vearncombe J.R. 1989, Late Archaean convergent margin tectonics and gold mineralisation: a new look at the Norseman-Wiluna Belt, Western Australia. *Geology,* 17, pp 826-829.

Barley, M.E., Groves, D.I., & Blake, T.S. 1992, Archaean Metal Deposits Related to Tectonics: Evidence from Western Australia, in *The Ar-*

chaean: *Terrains, Processes and Metallogeny*, eds. Glover, J.E. and Ho, S.E., Geology Department (Key Centre) & University Extension, The University of Western Australia, Publication No. 22, pp 307-324.

Bickle, M.J. 1986, Implications of melting for stabilisation of the lithosphere and heat loss in the Archaean. *Earth and Planetary Science Letters*, 80, pp 314-324.

Bickle, M.J. 1990, Archaean magmatism, in *Third International Archaean Symposium, Extended Abstracts Volume*, eds. Glover J.E. & Ho S.E., pp 143-145.

Blundell, D.J. 1991, Some observations on basin evolution and dynamics, *Journal of the Geological Society of London*, 148, pp 789-800.

Browning, P. , Groves D.I., Blockley J.G. & Rosman K.J.R. 1987, Lead isotope constraints on the age and source of gold mineralisation in the Archaean Yilgarn Block, Western Australia. *Economic Geology* 82, pp 971-986.

Campbell, I.H. & Hill, R.I. 1988, A two-stage model for the formation of the granite-greenstone terrains of the Kalgoorlie Norseman area, Western Australia, *Earth and Planetary Science Letters*, 90, pp 11-25.

Chorowicz, J., & Sorlien, C. 1992, Oblique extensional tectonics in the Malawi Rift, Africa, *Geological Society of America, Bulletin*, 104, pp 1015-1023.

Claoué-Long J.C. 1990, High resolution timing constraints on the evolution of the Kalgoorlie-Kambalda mineral belt, in *Third International Archaean Symposium, Extended Abstracts Volume*, eds. Glover J.E. & Ho S.E. pp 355-356.

Crittenden M.D., Coney P.J. & Davis G.H, eds. 1980, Cordilleran metamorphic core complexes. *Geological Society of America, Memoir* 153, 490pp.

Davis G.A., Lister G.S. & Reynolds S.J. 1986, Structural evolution of the Whipple and South Mountain Shear Zones, southwestern United States. *Geology*, 14, pp 7-10.

Ebinger, C.J., Rosendahl, B.R., & Reynolds, D.J. 1987, Tectonic model of the Malawi rift, Africa, *Tectonophysics*,141, pp 215-235.

Eisenlohr B.N., Groves D.I. & Partington G.A. 1989, Crustal-scale shear zones and their significance to Archaean gold mineralisation in Western Australia. *Mineralium Deposita*, 24, pp 1-8.

Etheridge M.A., Rutland R.W.R. & Wyborn L.A.I. 1987, Orogenesis and tectonic processes in the Early to Middle Proterozoic of northern Australia, in *Proterozoic lithosphere evolution*, ed. Krner A., *American Geophysical Union, Geodynamics Series*, 17, pp 131-147.

Fleuty M.J. 1964, Tectonic slides. *Geological Magazine*, 101, pp 452-456.

Gibbs A.D. 1984, Structural evolution of extensional basin margins, *Journal of the Geological Society of London*, 141, pp 609-620.

Gibbs A.D. 1987, Development of extension and mixed mode basins, in *Continental Extension Tectonics, Geological Society Special Publication*, No. 28, pp 19-33.

Glover, J.E. & Groves, D.I. eds. 1981, Archaean Geology, Second International Archaean Symposium, Perth 1980, *Special Publications of the Geological Society of Australia*, 7.

Groves D.I., & Batt W.D. 1984, Spatial and temporal variations of Archaean metallogenic associations in terms of evolution of granitoid-greenstone terrains with particular emphasis on the Western Australian Shield, in *Archaean Geochemistry*, eds Krner A., Hanson G.N. & Goodwin A.M. Springer-Verlag, Berlin, pp. 73-98.

Hammond, R.L., & Nisbet, B.W. 1990, Towards a Structural and Tectonic Framework for the Laverton-Wiluna region, Yilgarn Block, Western Australia, in *Third International Archaean Symposium, Extended Abstracts Volume*, eds Glover J.E. & Ho S.E., pp 461-465.

Hammond, R.L., & Nisbet, B.W. 1992, Towards a Structural and Tectonic Framework for the Central Norseman-Wiluna Greenstone Belt, Western Australia, in *The Archaean: Terrains, Processes and Metallogeny*, eds. Glover, J.E. & Ho, S.E., Geology Department (Key Centre) & University Extension, The University of Western Australia, Publication No. 22, pp 39-49.

Hallberg J.A. 1985, *Geology and Mineral Deposits of the Leonora-Laverton area, Northeastern Yilgarn Block, Western Australia*. Hesperian Press, Perth, 140 pp.

Hallberg J.A. 1986, Archaean basin development and crustal extension in the northeastern Yilgarn Block, Western Australia. *Precambrian Research*, 31, pp 133-156.

Harris L.B. 1987, A tectonic framework for the Western Australian Shield and its significance to gold mineralisation: a personal view, in *Recent advances in understanding Precambrian gold deposits*, eds. Ho S.E. & Groves D.I. Geology Department (Key Centre) & University Extension, The University of Western Australia, Publication No. 11, 1-27.

Hutton, D.H.W., Dempster T.J., Brown P.E. & Becker, S.D. 1990, A new mechanism of granite emplacement: intrusion in active extensional shear zones, *Nature*, 343, pp 452-455.

Kusznir N.J. & Park R.G. 1987, The extensional strength of the continental lithosphere: its dependence on geothermal gradient, and crustal composition and thickness, in *Continental Extensional Tectonics*, eds. Coward M.P., Dewey J.F. & Hancock P.L., Geological Society Special Publication, No. 28, 35-52.

Le Pichon X. & Sibuet J.-C. 1981, Passive margins: a model of formation. *Journal of Geophysical Research*, 86, pp 3708-3720.

Lister G.S. & Davis G.A. 1983, Development of mylonitic rocks in an intracrustal laminar flow zone, Whipple Mountains, SE California. *Geological Society of America, Abstracts with Programs,* 15, p 310.

Lister G.S., Etheridge M.A. & Symonds P.A. 1986, Detachment faulting and the evolution of passive continental margins. *Geology,* 14, pp 246-250.

Lister G.S., Etheridge M.A. & Symonds P.A. 1991, Detachment models for the formation of passive continental margins, *Tectonics,* 8, pp 1038-1064.

Loosveld, R.J.H. 1989, The Intra-cratonic Evolution of the Central Eastern Mount Isa Inlier, Northwest Queensland, Australia, *Precambrian Research,* 44, pp 243-276.

Ludden, J., Hubert, C., and Gariepy, C. 1986, The tectonic evolution of the Abitibi greenstone belt of Canada, *Geological Magazine,*123, pp.153-166.

McKenzie D.P. 1978, Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters,* 40, pp 25-32.

McKenzie D.P. & Bickle M.J. 1988, The volume and composition of melt generated by extension of the lithosphere, *Journal of Petrology,* 29, pp 625-679.

McNaughton N.J. & Dahl N. 1987, A geochronological framework for gold mineralisation in the Yilgarn Block, Western Australia, in *Recent advances in understanding Precambrian gold deposits,* eds. Ho S.E.& Groves D.I., Geology Department (Key Centre) & University Extension, The University of Western Australia, Publication No. 11, 29-49.

Martyn J.E. 1987, Evidence for structural repetition in the greenstones of the Kalgoorlie district, Western Australia. *Precambrian Research,* 37, pp 1-18.

Ord A. & Hobbs B.E. 1989, The strength of the continental crust, detachment zones and the development of plastic instabilities, *Tectonophysics,* 158, pp 269-290.

Platt J.P., Allchurch P.D. & Rutland R.W.R. 1978, Archaean tectonics in the Agnew supracrustal belt, Western Australia. *Precambrian Research,* 7, pp 3-30.

Ridley, J.R. 1992, The Thermal Causes and Effects of Voluminous, Late Archaean Monzogranite Plutonism, in *The Archaean: Terrains, Processes and Metallogeny.* eds. Glover, J.E. & Ho, S.E., Geology Department (Key Centre) & University Extension, The University of Western Australia, Publication No. 22, pp 275-285.

Silver, L.T. 1980, Problems of Pre-Mesozoic Continental Evolution, in *Continental Tectonics,* National Academy of Sciences, Washington D.C. 1980, pp 26-29.

Swager C.P. 1989, Structure of Kalgoorlie greenstones - regional deformation history and implications for the structural setting of the Golden Mile gold deposits. *Geological Survey of Western Australia, Report* 25. pp 59-84.

Swager C.P. & Griffin T.J. 1990, An early thrust duplex in the Kalgoorlie-Kambalda greenstone belt, Eastern Goldfields Province, Western Australia. *Precambrian Research,* 48, pp 63-73.

Swager C.P., Griffin T.J., Witt W.K., Wyche S., Ahmat A.L., Hunter W.M. & McGoldrick P.J. 1990, Geology of the Archaean Kalgoorlie terrane - an explanatory note. *Geological Survey of Western Australia, Record* 1990/12.

Swager, C.P., Witt, W.K., Griffin, T.J., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J., & Wyche, S. 1992, Late Archaean Granite-Greenstones of the Kalgoorlie Ternae, Yilgarn Craton, Western Australia, in *The Archaean: Terrains, Processes and Metallogeny,* eds. Glover, J.E. and Ho, S.E., Geology Department (Key Centre) & University Extension, The University of Western Australia, Publication No. 22, pp 107-122.

Wernicke, B. 1985, Uniform-sense normal simple shear of the continental lithosphere. *Canadian Journal of Earth Science,* 22, pp 108-125.

White R.S. & McKenzie D.P. 1989, Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research,* 94, pp 7685-7729.

Williams, I.R. 1974, Structural Subdivision of the Eastern Goldfields Province, Yilgarn Block, *Geological Survey of Western Australia, Annual Report 1973,* pp 53-59.

Williams, P.R. & Currie, K.L. 1993, Character and implications of the sheared Archaean granite-greenstone margin near Leonora, Western Australia, *Precambrian Research,*62, pp 343-365.

Williams, P.R. & Whitaker, A.J. 1993, Gneiss domes and extensional deformation in the highly mineralised Archaean Eastern Goldfields Province, Western Australia, *Ore Geology Reviews,* 8, pp 141-162.

Williams, P.R., Nisbet B.W. & Etheridge M.A. 1989, Shear zones, gold mineralisation and structural history in the Leonora district, Eastern Goldfields Province, Western Australia. *Australian Journal of Earth Sciences,* 36, pp 383-403.

Windh, J. 1992, Tectonic evolution and metallogenesis of the early Proterozoic Glengarry Basin, Western Australia, unpublished Ph.D. Thesis, Key Centre for Teaching and Research in Strategic Mineral Deposits, Geology Department, The University of Western Australia.

Witt W.K. & Swager C.P. 1989, Structural setting and geochemistry of Archaean I-type granites in the Bardoc-Coolgardie area of the Norseman-Wiluna Belt, Western Australia, *Precambrian Research,* 44, pp 323-351.

Wyman, D., & Kerrich, R. 1988, Alkaline magmatism, major structures, and gold deposits: Implications for greenstone belt metallogeny, *Economic Geology,* 83, pp 454-461.

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An integrated model for genesis of Archaean gold mineralisation within the Yilgarn Block, Western Australia

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This paper concerns the nature and genesis of Archaean lode-gold deposits which are abundant in the Yilgarn Block. Such lode-gold deposits are widespread in other Archaean granitoid-greenstone terranes (for example, Colvine, 1989; Foster, 1989), and similar deposits occur in the Phanerozoic Cordilleran terranes of North America (for example, Nesbitt & others, 1986). Following early controversy over syngenetic vs. epigenetic models for these deposits, there has been general acceptance of an epigenetic origin, with dominant structural and host-rock controls, even for BIF-hosted deposits, and major controversy has shifted to the timing and crustal levels at which mineralisation took place and to the ultimate source of the ore fluids and ore solutes that formed the deposits.

Although most of the lode-gold deposits in the Yilgarn Block represent the so-called 'mesothermal' deposits hosted in greenschist-facies host rocks, there has been a growing realization that significant deposits may occur in sub-greenschist facies and amphibolite- to granulite-facies host rocks (for example, Barnicoat & others, 1991; Witt, 1991). This paper presents a concise review of the characteristics of the deposits in different metamorphic settings (summarised in Figs 1 & 2), demonstrates that they represent a genetic group, presents evidence that they were deposited at broadly the crustal levels indicated by P-T conditions indicated by either (or both) metamorphic or metasomatic-alteration assemblages in host rocks, and discusses the implications for genetic models, particularly the sources of ore fluids and solutes.

The crustal continuum model

Lode-gold deposits: a coherent genetic group

If gold deposits from varying metamorphic settings, inferred to broadly correspond to different crustal levels, are to be integrated into a unifying genetic model, it has to be demonstrated that they are a coherent group and that they formed over a restricted time interval.

As suggested by numerous authors, the great majority of lode-gold deposits, both in the Yilgarn Block and in other worldwide Archaean cratons, have a large number of features (albeit dominated by data from deposits in greenschist facies environments) in common. The deposits are epigenetic and structurally controlled, generally in late (commonly reactivated?) shear zones. They have consistent enrichments in Au (normally 10^3-10^4 times background), Ag, As, and W, with variable enrichments in Bi, Sb, Te, and B, and minor enrichments in Cu, Zn, and Pb. The alteration assemblages, although varying in mineralogy with metamorphic setting (Fig. 2), are characteristically enriched in CO_2, S, K (and other LILE), plus the ore metals, and there is commonly volume increase or conservation in proximal zones. Lateral alteration zoning is characteristic on the scale of centimetres to tens of metres, whereas vertical zonation, where present in the Western Australian deposits, is normally more subtle and on the scale of hundreds of metres (for example, Mikucki & others, 1990): 'telescoped' alteration may be present in sub-greenschist facies ore environments (Hagemann & others, in press). In addition, as determined from fluid inclusion studies, most deposits were formed from a similar, low-salinity, H_2O-CO_2-CH_4 fluid, albeit with variable H_2O:CO_2:CH_4 ratios for different deposits, but generally an XCO_2 of 0.1 to 0.2 before phase-separation or mixing with other fluids (see Groves & others, 1992, table 1, for summary). Thus, the lode-gold deposits do form a coherent group.

Available evidence also supports broadly contemporaneous gold mineralisation in the

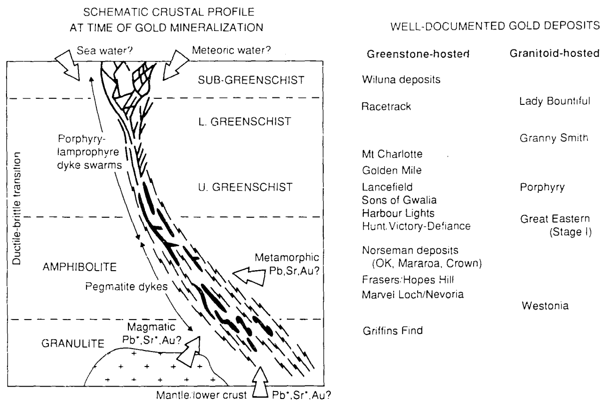

Fig. 1. Schematic reconstruction of a hypothetical, continuous, hydrothermal system extending over a crustal range of 25 km showing potential fluid and radiogenic isotope sources. Schematic hydrothermal system adapted from Colvine (1989), Foster (1989) and Barnicoat & others (1991), and diagram adapted from Groves & others (1992). Note that this continuous section is derived from study of deposits in a number of discrete areas that show specific sections of vertical profile. It is not implied that a series of deposits will occur in the same vertical plane from the top to the bottom of the system in any one area.

late Archaean in the Yilgarn Block. Most importantly, the three published precise ages on mineralisation, for a greenschist-amphibolite transition setting at Kambalda in the Eastern Goldfields (Clark & others, 1989), a granulite-hosted deposit at Griffins Find in the Southern Cross Province (Barnicoat & others, 1991), and a lower amphibolite facies setting at Reedys in the Murchison Province (Wang & others, in press) are within error at ca. 2.63 despite their wide geographic spread and contrasting settings. In addition, Pb model ages on least-radiogenic ore-related sulphides are essentially within error (±30Ma) of each other over the entire Yilgarn Block (McNaughton & others, 1990), supporting the majority of field evidence which suggests late structural timing of gold mineralisation (for example, Witt, 1993).

Thus, available evidence supports the assertion that most of the lode-gold deposits can be classed as a single genetic group.

The infiltration of ore fluids into heated host rocks is indicated by the lack of significant temperature differences between fluid and wallrock, as exemplified by the general lack of 'telescoped' vertical zonation of wallrock alteration, and by the gross correlation between mineral assemblages of proximal metasomatic wallrock alteration and regional-scale metamorphism (Fig. 2). This appears to implicate the formation of gold deposits during a regional metamorphic event, but there is variable timing of mineralisation with respect to peak metamorphism. Interpreted post metamorphic-peak deposits are abundant in greenschist facies domains whereas syn-peak metamorphic deposits are common in amphibolite facies domains (summary in Groves & others, 1992). Some deposits are considered to be pre-peak metamorphic (for example, Big Bell; Phillips, 1985) but this interpretation is controversial (Wilkins, 1993).

Lode-gold deposits: formation at a variety of crustal depths

If the lode-gold deposits are a coherent genetic group, they potentially represent a continuum spanning a depth range from less than 5 km (for example, Wiluna) to greater than 20 km (Griffins Find). For the 'mesothermal' deposits, many of which appear to have formed under post-peak metamorphic conditions, the crustal depths indicated by the P-T conditions of peak metamorphism must be considered a *maximum* depth limit for mineralisation. Evidence is presented, in summary form below, to illustrate that the deposits show a number of parameters consistent with formation at variable crustal depths.

The deposits show a gross trend in structural style (Fig. 2) from more brittle structures in sub-greenschist facies domains (for example, Wiluna, Mt Pleasant area) through brittle to brittle-ductile hosting structures in greenschist facies domains (for example, Golden Mile, Mt. Charlotte, Granny Smith), to ductile-hosting structures in amphibolite (for example, Marvel Loch) to lower-granulite facies (for example, Griffins Find) domains. As shown in Fig. 2, deposit styles show progressively fewer breccias and transgressive quartz-vein sets and generally more foliation-parallel quartz veins and shear-zone replacements with increasing metamorphic grade: similar trends are discussed by Witt (1993). Quartz vein textures show a grossly parallel trend (Fig. 2) from plumose, comb, and cockade textures and vugh fillings at the lowermost metamorphic grades through bucky or laminated quartz with partial annealing textures at intermediate grades, to coarse grained veins with granoblastic textures at the highest metamorphic grades.

As shown schematically in Fig. 2, wallrock alteration assemblages in the ore (proximal) zone of mafic/ultramafic-hosted deposits (the major well-studied group) also vary systematically with the metamorphic grade of the enclosing rocks (for example, Mueller & Groves, 1991; Witt, 1991). At sub-greenschist to mid-greenschist grades, low P-T assemblages, such as ankerite/dolomite-white mica-chlorite are common (for example, Phillips, 1986),

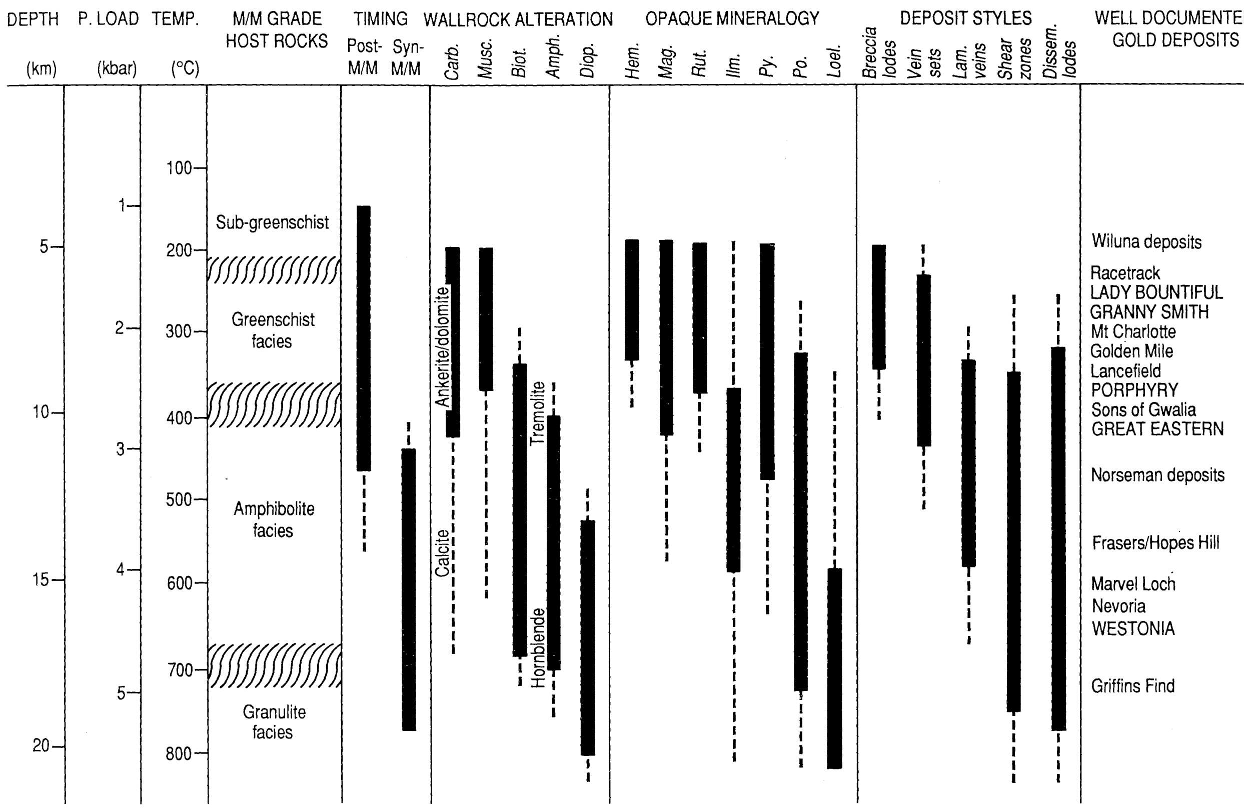

Fig. 2. Summary of various features of late-Archaean lode-gold deposits over the crustal continuum of their deposition. Note that the P-T depth conditions shown do not correspond to those of peak metamorphism but to the conditions at the time of gold mineralisation. The metamorphic grades shown are for peak metamorphic conditions of the host rocks to mineralisation. The characteristics shown are based on a small number of well-documented examples and are, of necessity, generalised. Individual alteration minerals are shown for simplicity although it is recognised that wallrock alteration assemblages are the critical features characterizing the different P-T-XCO_2 conditions of alteration. Typical examples of well-documented gold deposits are listed, with granitoid-hosted deposits in capitals. Abbreviations used:
i) timing, m/m = metamorphism, ii) wallrock alteration, amph. = amphibole, biot = biotite, diop. = diopside, musc. = white mica, iii) opaque mineralogy, hem. = hematite, ilm = ilmenite, loel. = loellingite, mag. = magnetite, po. = pyrhotite, py = pyrite, rut. = rutile, (Arsenopyrite is present at all crustal levels and is not shown), iv) deposit styles, dissem. = disseminated (or shear-parallel veins), lam. = laminated.
Diagram designed by K. F. Cassidy and D.I. Groves, based on Groves & others (1992).

whereas ankerite/dolomite-white mica-biotite (phlogopite)-chlorite ± albite assemblages occur at mid-greenschist to the greenschist-amphibolite transition facies (for example, Clark & others, 1989). At low-to mid-amphibolite grade, amphibole-biotite-plagioclase assemblages are dominant (for example, Golding & Wilson, 1982), in contrast to garnet-diopside-biotite-K feldspar assemblages at mid-amphibolite to lower granulite grade (for example, Barnicoat & others, 1991). The opaque mineralogy of the gold deposits shows a broadly complementary trend from S-rich assemblages dominated by pyrite (± arsenopyrite ± pyrite) at low metamorphic grades, through pyrrhotite (± arsenopyrite) dominated assemblages, to pyrrhotite-arsenopyrite (± loellingite) assemblages at high metamorphic grade. Tellurides, stibnite, tetrahedrite, and sulphosalts are more abundant in the deposits from low metamorphic grade environments and electrum may locally be present in place of gold (Gebre-Mariam & others, in press; Hagemann & others, in press). Perring & others (1991) also show that Bi and Cu contents of bulk-ore samples are higher in high-grade environments whereas Ag, Sb, Pb, and S appear relatively enriched in ores from lower-grade domains, albeit from a restricted data set.

As noted above, vertical zonation of wallrock alteration is not commonly recorded from individual lode-gold deposits, although Mikucki & others (1990) discuss upwards vertical transitions from pyrrhotite to pyrite-dominated assemblages at Mt Charlotte, and from biotite (± white mica) to white mica (± chlorite) assemblages over a vertical profile of about 1 km at Sons of Gwalia. McCuaig & others (in press) also present evidence for transitions from high- to low-temperature wallrock alteration style from south to north in the Norseman District, in parallel with declining metamorphic grade.

Finally, as summarised by Groves & others (1992), a combination of both published and, as yet, unpublished fluid inclusion data and mineral equilibria calculations suggests that the lode-gold deposits reflect P-T conditions ranging from about 180°C at 100 MPa to 700°C at about 500 MPa.

Lode-gold deposits: syn-metamorphic timing in deeper crustal settings

As discussed by many authors, most lode-gold deposits in greenschist- to lowermost amphibolite-facies domains have wallrock alteration assemblages that overprint metamorphic assemblages, and in some well-documented examples (for example, in the Kambalda region: Clark & others, 1989) the temperatures of mineralisation clearly indicate post-peak metamorphic timing. Therefore, if the lode-gold deposits do represent a crustal continuum, it is a requirement that the mineralisation and alteration in the higher-grade metamorphic settings formed at the P-T conditions indicated by the present alteration assemblages and are not the result of superimposed metamorphic recrystallization as suggested, for example, by Phillips (1985) for Big Bell in the Murchison Province.

There are few *detailed* published studies of amphibolite-hosted lode-gold deposits in Western Australia, although Barnicoat & others (1991) and Mueller & Groves (1991) do review the critical evidence available. Petrological and mineralogical studies of wallrock alteration, and the structures and textures of mineralised veins, have been used to support a broadly syn-metamorphic timing for these deposits.

Critical evidence includes:

- the high thermodynamic variance (low number of phases) of the high P-T alteration assemblages, indicating an open metasomatic system at those conditions,
- the occurrence of fine oscillatory zoning in vein minerals (for example, diopside), also indicating growth under conditions of high fluid flux, and
- the variable textures of the quartz and diopside veins from deformed and annealed grains through to coarse grained, undeformed crystals with some undeformed alteration phases (for example, amphibole) aligned perpendicular to the vein walls.

Lode-gold deposits: a mid- to upper-crustal continuum

The evidence presented above supports the concept that the majority of the late-Archaean lode-gold deposits do represent a single genetic group, and that these formed from a similar, but evolving, ore fluid at a variety of crustal depths. The model is shown schematically in Fig. 1, and the implications of its acceptance are briefly outlined below.

An integrated genetic model for lode-gold deposits

Scale of hydrothermal circulation systems

A major implication of the model is that the scale of the hydrothermal system was very large, and that the fluid conduits were potentially very long. This is compatible with the regional-scale association of many of the lode-gold deposits with crustal-scale deformation zones, commonly in association with swarms of lamprophyres and felsic porphyries derived from mantle and lower crustal depths, respectively, although many individual gold deposits occur in second- or third-order structures (for example, Eisenlohr & others, 1989), and some deposits may show no obvious relationships to crustal-scale structures (Witt, 1993). Witt (1991) mapped metasomatic isograds based on the wallrock alteration assemblages of lode-gold deposits in the Menzies–Kambalda greenstone segment, over lengths of tens to hundreds of kilometres, again pointing to the large scale of the hydrothermal systems.

Fluid and solute source

Potentially, the most important implications from the crustal continuum model are the constraints that it provides on the nature and source of the ore fluid(s) and solutes.

The interpretation that the lode-gold deposits were deposited over the entire range of crustal depths represented by exposed Archaean greenstone belts, and that some were formed in amphibolite-granulite facies domains only a few hundred metres from synkinematic granitoid domes, effectively rules out metamorphic devolatilisation of greenstones alone (for example, Phillips & Groves, 1983, Groves & Phillips, 1987) as the fluid and solute sourc: this is further reinforced by the seismic evidence for lack of any greenstone belts within the felsic crust underlying exposed belts in the Yilgarn Block (for example, Goleby & others, 1993). Similarly, models involving *in situ* release of fluids from high-level felsic intrusions are unlikely given that they are only abundant in mine environments representing high crustal levels. Pegmatites are the dominant felsic intrusive phases in higher metamorphic-grade environments, but normally post-date gold mineralisation.

Although stable isotope data (for example, Golding & others, 1989) are compatible with a variety of sources, including greenstone belts, for some components of the ore fluids that infiltrated to relatively high crustal levels, there is growing evidence from radiogenic isotope data for involvement of fluids and solutes from the underlying felsic crust and/or granitoids derived from it. For example, the least-radiogenic Pb-isotopic compositions of ore-related sulphides (mainly pyrite and galena) from Yilgarn gold deposits in a variety of settings are too radiogenic (for example, Browning & others, 1987) to have been derived from greenstones alone, and implicate a component from older felsic crust or granitoids derived from it (McNaughton & others, 1990). Of particular importance is the observation that there is regional scale variation in the Pb isotopic compositions of ore-related sulphides, and that there is a complementary variation between these compositions and the initial Pb-isotopic ratios of neighbouring crustally derived rocks, implying derivation of Pb in ore fluids from the crustal segment underlying the deposits (McNaughton & others, 1990).

In support of the Pb isotope data, Mueller & others (1991) show that the initial $^{87}Sr / ^{86}Sr$ ratios of some ore-related scheelites are higher than the estimated initial ratios of the greenstone belts at the time of mineralisation (ca. 2.63 Ga). A contribution of Sr from anatectic granitoids or their old crustal source rocks is implicated, with the scheelites from higher metamorphic grade settings, normally closer to the margins of these anatectic granitoids, commonly having the higher initial Sr-isotope ratios.

Finally, Ridley (1990) argues that the wallrock alteration assemblages in gold deposits are consistent with formation from a fluid with a relatively restricted range in XCO_2 and activities of major mineral-forming ions in solutions. The fluid is calculated to be saturated throughout with respect to quartz and a K-bearing phase (biotite or K-feldspar), and thus has a composition that best fits its equilibrium with, or derivation from, a rock of broadly granitic composition. Wallrock alteration is most cryptic in granitoids from the highest metamorphic-grade mineralized domains (for example, Westonia), supporting this assertion.

Thus, the majority of radiogenic isotope and thermodynamic data favour either derivation of the deeply sourced ore fluid from granitic magmas or equilibration of a fluid derived from even deeper levels (for example, subduction zone or overlying wedge: Barley & others, 1989) with the source rocks for these granitoids. The majority of the data favour an anatectic granitoid source, for the former of the two possible models, but to date no granitoids of this type with an age equivalent to the gold mineralisation (that is, ca. 2.63 Ga) have been clearly identified.

It should be emphasised that, although the primary, deeply-sourced ore fluid (the fluid common to all deposits) is interpreted to be largely derived from, or to have interacted with, granitic rocks below the greenstone belts some stable isotope data implicate other sources for at least part of the fluid components. This would be expected from a crustal-scale hydrothermal system in which deeply sourced, hot ore fluids infiltrated the upper granitic crust and greenstone belts on their passage to dominantly greenstone-belt depositional sites.

Involvement of surface water

The possibility that either meteoric water or seawater was a component of the upper-level hydrothermal system is raised by the recognition that some deposits are hosted by brittle structures and are sited in lower- or sub-greenschist facies settings. mineralisation is normally post-peak metamorphism, and hence the P-T conditions of peak metamorphism represent the *maximum* crustal depths at the time of gold mineralisation. Both Gebre-Mariam & others (in press) and Hagemann & others (in press) provide stable isotope evidence for the involvement of surface waters in the upper levels of the proposed giant hydrothermal system, but evidence is lacking for their presence at deeper levels.

Outstanding problems

Although a deeply-sourced primary ore-fluid is clearly implicated by the crustal-continuum model, the precise source is still unknown. Magmas crystallizing at mid-crustal depths may evolve low-salinity fluids without the extensive release of mechanical energy. However, to date, granitoids of an appropriate age have not been identified in the Yilgarn Block except perhaps in the Murchison Province (Wang & others, in press). For a lower crustal-or mantle-derived fluid, a potential problem is transfer throughout the crust at temperatures above the granite water-saturated solidus without causing partial melting with incorporation of the fluid into a melt (for example, Ridley, 1990).

A further problem raised by the model is the timing of the major regional metamorphic event at different levels of the crust. The available absolute-age data on gold deposits, combined with Pb model-age data, suggest that mineralisation was synchronous, across the Yilgarn Block, yet it was apparently post-peak metamorphism, at least for many deposits, at relatively high crustal levels (<low-amphibolite grade domains) but syn-peak

metamorphism at deeper crustal levels (>low-amphibolite grade domains). This suggests that peak metamorphism, as recorded by preserved metamorphic assemblages, was diachronous within the greenstone terranes across the Yilgarn Block. It is possible to explain the earlier timing of peak metamorphism at upper crustal levels if crustal thickening occurred through structural (thrust) repetition (compare England and Thompson, 1984), but there is no evidence preserved of medium to high pressure metamorphic assemblages that might be expected in an overthrust terrane. It is possible that the presently preserved metamorphic assemblages record only the highest T portion of the P-T path due to the late domal emplacement of voluminous granitoids into the terrane. Alternatively, the terranes may be recording two (or more) metamorphic events, an early sea-floor metamorphism and/or regional metamorphism related to the same thermal event that induced the uprise of the voluminous anatectic granitoids. If so, gold mineralisation was related to the second granitoid-related metamorphic event. It is evident that more detailed study of the metamorphism of the greenstone belts is required, with special attention to precise dating of metamorphic minerals from different metamorphic-grade environments.

The gold mineralising event is clearly an integral part of the late-tectonic evolution of the granitoid-greenstone belts, but lack of a comprehensive understanding of this tectonism currently limits complete resolution of the genesis of the late-Archaean lode-gold deposits. In the Archaean terranes, it may always be difficult to define the precise mechanism(s) which triggered craton-wide gold mineralisation, and analogies may have to be made with more recent examples. For example, Goldfarb & others (1991) have shown that extensive Eocene gold mineralisation in Alaska coincided with a change in plate motion which caused a shift from convergent to partly transcurrent tectonics, and such a change may be evident in the structural record of the Archaean granitoid-greenstone terranes, for example in the reactivation of earlier structures and/or the change from one structural régime to another during mineralisation.

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References

Barley, M.E., Eisenlohr, B., Groves, D.I., Perring, C.S., & Vearncombe, J.R. 1989, Late Archean convergent margin tectonics and gold mineralisation : a new look at the Norseman-Wiluna Belt, Western Australia, *Geology,* 17, pp 826-829.

Barnicoat, A.C., Fare, R.J., Groves, D.I., & McNaughton, N.J. 1991, Syn-metamorphic lode-gold deposits in high-grade Archean settings, *Geology*, 19, pp 921-924.

Browning, P., Groves, D.I., Blockley, J.R., & Rosman, K.J.R. 1987, Lead isotopic constraints on the age and source of gold mineralisation in the Archean Yilgarn Block, Western Australia, *Economic Geology*, 82, pp 971-986.

Clark, M.E., Carmichael, D.M., Hodgson, C.J., & Fu, M. 1989, Wallrock alteration, Victory gold mine, Kambalda, Western Australia: processes and P-T-XCO_2 conditions of metasomatism, *Economic Geology Monograph*, 6, pp 445-459.

Colvine, A.C. 1989, An empirical model for the formation of Archean gold deposits : products of final cratonization of the Superior Province, Canada, *Economic Geology Monograph*, 6, pp 37-53.

Eisenlohr, B.N., Groves, D.I., & Partington, G.A. 1989, Crustal-scale shear zones and their significance to Archaean gold mineralisation in Western Australia, *Mineralium Deposita*, 24, pp 1-8.

England, P.C., & Thompson, A.B. 1984, Pressure-temperature-time paths of regional metamorphism. I. Heat-transfer during the evolution of regions of thickened continental crust. *Journal of Petrology,* 25, pp 894-928.

Foster, R.P. 1989, Archean gold mineralisation in Zimbabwe: Implications for metallogenesis and exploration, *Economic Geology Monograph,* 6, pp 54-70.

Gebre-Mariam, M., Groves, D.I., McNaughton, N.M., Mikucki, E.J., & Vearncombe, J.R. in press, Archaean Au-Ag mineralisation at Race-track, near Kalgoorlie, Western Australia: a high crustal-level expression of the Archaean composite lode-gold system, *Mineralium Deposita.*

Goldfarb, R.J., Snee, L.W., Miller, L.D., & Newberry, R.J. 1991, Rapid dewatering of the crust deduced from ages of mesothermal gold deposits, *Natue,* 354, pp 296-298.

Golding, S.D., McNaughton, N.J., Barley, M.E., Groves, D.I., Ho, S.E., Rock, N.M.S., & Turner, J.V. 1989, Archean carbon and oxygen reservoirs : their significance for fluid sources and circulation paths for Archean mesothermal gold deposits of the Norseman-Wiluna Belt, Western Australia. *Economic Geology Monograph,* 6, pp 376-388.

Golding, S.D., & Wilson, A.F. 1982, Geochemical and stable isotope studies of the Crown and Mararoa reefs, Norseman, Western Australia, *Revista Brasiliera de Geociencias*, 12, pp 445-456.

Goleby, B.R., Rattenbury, M.S., Swager, C.P., Drummond, B.J., Williams, P.R., Sheraton, J.W., & Heinrich, C.A. 1993, Archaean crustal structure from seismic reflection profiling, Eastern Goldfields, Western Australia, *Australian Geological Survey Organisation Record*, 1993/15, 54 p.

Groves, D.I., Barley, M.E., Barnicoat, A.C., Cassidy, K.F., Fare, R.J., Hagemann, S.G., Ho, S.E., Hronsky, J.M.A., Mikucki, E.J., Mueller, A.G., McNaughton, N.J., Perring, C.S., Ridley, J.R., & Vearncombe, J.R. 1992, Sub-greenschist to granulite-hosted Archaean lode-gold deposits of the Yilgarn Craton: a depositional continuum from deep-sourced hydrothermal fluids in crustal-scale plumbing systems, *Geology Department (Key Centre) & University Extension, The University of Western Australia Publication*, 22, pp 325-337.

Groves, D.I., & Phillips, G.N. 1987, The genesis and tectonic control on Archaean gold deposits of the Western Australian Shield: a metamorphic-replacement model, *Ore Geology Reviews*, 2, pp 287-322.

Hagemann, S.G., Groves, D.I., & Ridley, J.R. in press, The lode-gold deposits at Wiluna: a case study of an epizonal Archaean lode-gold system, *Mineralium Deposita*.

McCuaig, T.C., Kerrich, R., Groves, D.I. & Archer, N. in press, The nature and dimensions of regional and local gold-related hydrothermal alteration in tholeiitic metabasalts in the Norseman goldfields: the missing link in a crustal continuum of gold deposits? *Mineralium Deposita*.

McNaughton, N.J., Cassidy, K.F., Dahl, N., Groves, D.I., Perring, C.S., & Sang, J.H. 1990, Sources of ore fluid and ore components: lead isotope studies, *Geology Department (Key Centre) & University Extension, The University of Western Australia Publication*, 20, pp 226-236.

Mikucki, E.J., Groves, D.I., & Cassidy, K.F. 1990, Alteration patterns: wallrock alteration in sub-amphibolite facies gold deposits, *Geology Department (Key Centre) & University Extension, The University of Western Australia Publication*, 20, pp 60-78.

Mueller, A.G., de Laeter, J.R., & Groves, D.I. 1991, Strontium isotope systematics of hydrothermal minerals from epigenetic Archean gold deposits in the Yilgarn Block, Western Australia, *Economic Geology*, 86, pp 780-809.

Mueller, A.G., & Groves, D.I. 1991, The classification of Western Australian greenstone-hosted gold deposits according to wallrock alteration mineral assemblages, *Ore Geology Reviews*, 6, pp 291-331.

Nesbitt, B.E., Murowchick, J.B., & Muhlenbachs, K. 1986, Dual origins of lode-gold deposits in the Canadian Cordillera, *Geology*, 14, pp 501-509.

Perring, C.S., Groves, D.I., Shellabear, J.N. 1991, The geochemistry of Archaean gold ores from the Yilgarn Block of Western Australia: Implications for gold metallogeny. *Mineral & Energy Research Institute of Western Australia Report* 82, 126p.

Phillips, G.N. 1985, Interpretation of Big Bell/Hemlo-type gold deposits: precursors, metamorphism, melting and genetic constraints, *Transactions of the Geological Society of South Africa*, 88, pp 159-173.

Phillips G.N., 1986. Geology and alteration in the Golden Mile, Kalgoorlie. *Economic Geology*, 81, 779-808.

Phillips, G.N., & Groves, D.I. 1983, The nature of Archaean gold-bearing fluids as deduced from gold deposits of Western Australia, *Journal of the Geological Society of Australia*. 30, pp 25-39.

Ridley, J.R.1990, Source of ore fluid and ore components: alteration assemblages. *Geology Deptment Key Centre) & University Extension, The University of Western Australia, Publication*, 20 pp, 268-272.

Wang, L.G., McNaughton, N.J., & Groves, D.I. in press, An overview of the relationship between granitoid intrusions and gold mineralisation in the Archaean Murchison Province, Western Australia, *Mineralium Deposita*.

Wilkins, C. 1993, A post-deformational, post-peak metamorphic timing for mineralisation in the Archaean Big Bell gold deposit, Western Australia, *Ore Geology Reviews*, 7, pp 439-484.

Witt, W.K. 1991, Regional metamorphic controls on alteration associated with gold mineralisation in the Eastern Goldfields Province Western Australia: Implications for the timing and origin of Archean lode-gold deposits, *Geology*, 19, pp 982-985.

Witt, W.K. 1993, Lithological and structural controls on gold mineralisation in the Archaean Menzies-Kambalda area, Western Australia, *Australian Journal of Earth Sciences*, 40, pp 65-86.

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Hydrothermal fluids in epi- and katazonal crustal levels in the Archaean: implications for P-T-X-t evolution of lode-gold mineralisation

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Studies on ore fluids of Archaean lode-gold deposits world-wide have traditionally focussed on classical mesothermal-type mineralisation in greenschist to lower-amphibolite facies terrains. Well documented deposits are Mount Charlotte (Ho, 1986), Sons of Gwalia (Skwarnecki, 1990), Pamour mine in Ontario (Walsh & others, 1988), and Sigma mine in Quebec (Robert & Brown, 1986). A number of different fluids are preserved as inclusions in vein quartz at these deposits, but from textures and considerations of the compositions of fluids likely to have been in equilibrium with wallrock alteration assemblages, a single ore fluid has been distinguished: a low- to moderately-saline (eq. wt % NaCl) H_2O-CO_2 ± CH_4 (typically X_{CO_2} = 0.2 ± 0.05) fluid of near neutral pH. Fluid inclusion homogenisation temperatures imply T-P conditions during mineralisation of 200 to 350°C at 100 to 300 MPa, corresponding to 3 to 10 km crustal depths assuming lithostatic fluid pressures (Colvine & others, 1988; Ho & others, 1992).

Recent research on Archaean lode-gold deposits, however, has recognised mineralisation formed both at shallower, epizonal (1-5 km) and deeper, katazonal (10-20 km) depths, in host rocks metamorphosed to prehnite-pumpellyite to lower-greenschist and amphibolite to lower-granulite facies, respectively (e.g. Barnicoat & others, 1991). This contribution reviews new fluid-inclusion data and calculations of fluid composition in these deposits. The implications of fluid inclusion characteristics on the depth of formation and cooling history of the deposits, and for the evolution of gold-bearing hydrothermal systems are discussed.

Nature of ore fluids in epi- and katazonal Archaean lode-gold deposits

The following section summarizes new data on ore-fluid compositions, pH, oxidation state and total sulfur content in epi- and katazonal Archaean lode-gold deposits in the Yilgarn Block of Western Australia, and prospects in the Pilbara craton.

Epizonal lode-gold deposits

Studies of fluid evolution from fluid inclusions and petrography in high-level lode-gold deposits are for the Wiluna lode-gold deposits (Hagemann, 1992; Hagemann & Brown, 1992), the Racetrack and Lady Bountiful deposits near Mount Pleasant (Gebre-Mariam & others, submitted; Cassidy, 1992 respectively), and the Granny Smith deposits (Ojala & others, 1993). All of these deposits show a more complex suite of potentially primary fluids than is recognised in mesothermal deposits.

Ore fluid components: The Wiluna lode-gold deposits are characterized by at least four 'fluid regimes'—associations of fluids with different entrapment conditions and relations to mineralisation. Fluid Regime 1 is an early, non-metal bearing hydrothermal phase, and is characterized by high X_{CO_2} (mean 95 mole %), and CH_4 (up to 12 mole %) with probably small amounts of H_2O. Fluid Regime 2 is associated with gold-pyrite-arsenopyrite mineralisation and comprises three coexisting fluid inclusion types:

- (1) aqueous inclusions with a range of apparent salinities of 0-22 eq. wt % NaCl (mean 3.7),
- (2) H_2O-CO_2 ± salt inclusions with salinities of 1-8 eq. wt % NaCl, and
- (3) CO_2 ± CH_4 inclusions with rare, thin water rims.

Fluid Regime 3 is associated with gold-stibnite mineralisation and is characterized by:

- (1) aqueous inclusions of medium salinity (mean 5 eq. wt % NaCl), and
- (2) H_2O-CO_2 inclusions of slightly lower salinity

(mean 3.8 eq. wt % NaCl), and lower average X_{CO2} (= 0.16) than Fluid Regime 2. Fluid Regime 4 is a simple medium-salinity (mean 7.4 eq. wt % NaCl) aqueous fluid restricted to shear veins and breccia matrices.

Main, Stage II mineralisation at the Racetrack deposit contains a simple H_2O-NaCl fluid with salinities of 1-8 eq. wt % NaCl. At the granitoid-hosted Lady Bountiful gold deposit, two types of fluid inclusion occur with the main, Stage II mineralisation:

- (1) moderately saline H_2O-CO_2 inclusions with X_{CO2} of 0.06 to 0.19, and
- (2) aqueous inclusions of either moderate (≈7 eq. wt % NaCl) or high salinity (28-30 eq. wt % NaCl).

At the Granny Smith deposit CO_2-H_2O-NaCl ± CH_4 inclusions with variable liquid:vapour ratios were trapped during gold mineralisation: CO_2-rich fluids are characteristic of the main high-grade ore zone. Salinities range from 0-8 eq. wt % NaCl, with higher salinities in water-rich fluids. Nahcolite is the most common daughter mineral. Other fluid inclusion types include high salinity aqueous (20 eq. wt % NaCl), and pure CH_4 inclusions.

Oxidation state and sulfur activit: For the Racetrack deposit the ore fluid f_{O2} is calculated as relatively reducing (0.5-1 log unit above the CO_2-CH_4 redox buffer). Total sulfur molalities ($m_{\Sigma S}$) of $10^{-3.6}$-$10^{-3.2}$ bar at Racetrack and $10^{-2.5}$ to $10^{-4.0}$ bar at Lady Bountiful indicate that the fluids are S-poor compared to mesothermal gold deposits, which have $m_{\Sigma S}$ of $10^{-2.4}$ to $10^{-2.0}$ bar or higher (Neall & Phillips, 1987; Mikucki & Groves, 1990).

pH conditions: Sericite-quartz alteration assemblages limit pH of the Racetrack ore fluids to 3.7-5.5 at 225°C. These values overlap, but extend to slightly more acidic values than, those typical of 'mesothermal' gold deposits (pH = 5.2-6.2; Mikucki & Groves, 1990). In contrast, proximal alteration assemblages of muscovite-albite, and the replacement of K-feldspar by albite, imply a near neutral to slightly alkaline pH for mineralisation at Lady Bountiful. The presence of nahcolite at Granny Smith possibly indicates relatively alkaline conditions, though quantitative calculations have yet to be performed.

Katazonal lode-gold deposits

Interpretation of fluid histories at deep-level deposits is complicated by (1) the more ductile nature of quartz at the conditions of deposit formation, (2) the greater likelihood of modification to fluid inclusion properties during cooling, and (3) almost invariable partial retrogression of ore and wallrock alteration assemblages, implying post-mineralisation fluid flux through deposits. Nevertheless, from textural criteria, and observations on rare fluid inclusions in vein minerals other than quartz (e.g. diopside and garnet), probable ore fluids have been recognised in reconnaissance studies at the Corinthia–Hopes Hill and Marvel Loch deposits (Bloem & Brown, 1991; this study), Westonia (Cassidy, 1992), Griffins Find (this study), Three Mile Hill, Coolgardie (McCall, 1992; Knight & others, submitted; this study), and the Mt York prospect, Pilbara craton (P. Neumayr, pers. comm. 1993).

Ore fluid components: At the Corinthia–Hopes Hill deposits CO_2-CH_4-H_2O fluids with widely variable CH_4 contents (X_{CH4}<0.8) and highly saline aqueous inclusions with variable amount of divalent cations are indicated. Laser-Raman studies on the Marvel Loch deposit confirm variable CH4 contents (X_{CH4} = 0.02-0.88) in CH_4-CO_2-H_2O inclusions. At Westonia there are monophase CO_2-rich inclusions, two- and three-phase CO_2-H_2O inclusions with variable phase proportions and dominantly low- to moderate-salinities, and aqueous inclusions with a wide range of salinities (up to 25 eq wt % NaCl). Studies on the Griffins Find deposit have revealed three types of fluid inclusions:

- (1) CH_4-H_2O-NaCl inclusions with variable phase ratios and CH_4 contents (X_{CH4}<0.8),
- (2) CH_4-H_2O inclusions with high vapour:liquid ratio, and
- (3) highly saline aqueous inclusions with variable amount of divalent cations.

The Three Mile Hill deposit contains variably abundant:

- (1) CH_4-CO_2 inclusions with X_{CH4} of up to 0.25,
- (2) low salinity CO_2 ± CH_4-H_2O inclusions (<1.8 eq. wt % NaCl, X_{CO2} = 0.2-0.6, X_{CH4}<0.1), and
- (3) H_2O-NaCl inclusions with daughter minerals.

Coexisting CH_4-CO_2-H_2O fluids (X_{CH4}<0.7) and highly saline (<25 eq. wt % NaCl) fluids during gold mineralisation are recorded in the Mt York prospect.

Oxidation state and sulfur activity: Estimates of f_{O2} and $m_{\Sigma S}$ from combined fluid-inclusion and paragenetic data at the Westonia, Frasers, Marvel Loch and Nevoria deposits are summarized in Mikucki & Ridley (submitted). They conclude that a range of ore-fluid oxidation states is present.

Reduced ore assemblages, characterized by loellingite-arsenopyrite ± magnetite ± ilmenite, constrain maximum f_{O_2} values to 1-1.5 log units above the CO_2-CH_4 buffer. Oxygen fugacity at the Nevoria BIF-hosted deposit could have been as low as one log unit below this buffer, as determined by the assemblage arsenopyrite-loellingite and the composition of coexisting hedenbergitic pyroxene (Mueller, 1990). In contrast, the Westonia, Corinthia and Renco (Zimbabwe) deposits contained ore fluids which were moderately oxidized, with f_{O_2} values corresponding to pyrite-magnetite-pyrrhotite equilibrium at 1 to 3 log units above the CO_2-CH_4 buffer. Total sulfur molalities ($m_{\Sigma S}$) in these deposits were probably in the range 1-10 m, with the range in ore fluid $m_{\Sigma S}$ at any temperature limited, but generally higher at higher temperatures.

pH conditions: The only available pH estimate, based on proximal alteration assemblages in the Hopes Hill deposit, suggests neutral to mildly alkaline conditions (pH = 5.0-6.0 at 600°C and 400 MPa).

Depth and pressure estimates from fluid inclusions

Typical temperatures of homogenisation of fluid inclusions in the epizonal deposits discussed above are 270 ± 50°C. Lower temperatures are recorded for Fluid Regimes 3 and 4 (approx. 230°C) at Wiluna, and for aqueous-saline fluids at Racetrack. Higher, and more variable homogenisation temperatures (125-460°C) are recorded at Granny Smith. Most fluid inclusions from deep-level deposits homogenise at relatively low temperatures (250-350°C); a minority, however, homogenise at temperatures close to the inferred temperatures of mineralisation (approx. 500°C for amphibolite facies deposits, <695°C at the granulite-facies, Griffins Find deposit).

Using assumptions about fluid-pressure:depth relationships (Roedder & Bodnar, 1980; Roedder, 1984), estimates of the depth of mineralisation can be made from this data. Figure 1 summarises estimated depth and fluid pressure conditions for katazonal and epizonal deposits from the Yilgarn Block, and shows the depth separation of epizonal, 'mesothermal', and katazonal deposits. Metamorphic P-T conditions, ore textures and the structural setting of mineralisation corroborate the shallow emplacement of epizonal deposits (Hagemann & others, 1992; Gebre-Mariam & others, submitted; Ojala & others, 1993). The wide range of fluid-pressure estimates at these shallow-level deposits, together with their dominantly brittle structural style and associated ore textures, can be interpreted as the result of large fluid pressure variations in the channelways (fault systems) with possible short-lived hydrostatic pressure conditions in the lodes.

Pressure–temperature–time paths for katazonal lode-gold deposits

Three types of fluid inclusion appear common in katazonal lode-gold deposits:

- (1) CO_2-rich inclusions which may contain substantial CH_4,
- (2) CO_2-H_2O-NaCl inclusions with minor to moderate amounts of CH_4 and other salt species, and
- (3) highly saline and complex aqueous inclusions which may contain daughter crystals, and have either high or low temperatures of homogenisation.

In Fig. 2 representative isochores for these fluid inclusion types are plotted. Isochores for CO_2-rich and mixed CO_2-H_2O-NaCl inclusions pass through the inferred conditions of mineralisation, and could have been trapped during mineralisation, whereas the isochore of low T_h aqueous inclusions lies at higher pressures, suggesting these inclusions were later, as is supported by their textural characteristics.

The high density of type 3 fluids precludes them being trapped later at shallower levels - these 'high pressure' inclusions must have been trapped along a convex retrograde P-T-t path with little decompression during initial cooling (Fig. 2). Allowable, more complex, retrograde P-T-t paths involve an initial period of isothermal decompression followed by isobaric cooling at pressures of 250 to 300 MPa (compare with Schenk, 1989; Lamb & others, 1991). This has important implications for tectonic models of the Yilgarn Block, but more detailed fluid inclusion studies (e.g. modelling of complex fluid systems) and geobarometric studies are needed in order to elucidate the timing of fluid movements associated with Au-bearing fossil hydrothermal systems.

Discussion

Comparison of fluids at different crustal levels

A mixed carbonic–aqueous, low- to moderate-salinity fluid is present as a primary fluid in lode-gold deposits at all crustal levels. The range of f_{O_2} determined from alteration and ore assemblages remains constant relative to the CO_2:CH_4 buffer, and extends from moderately reducing to relatively oxidising conditions. Neutral to mildly

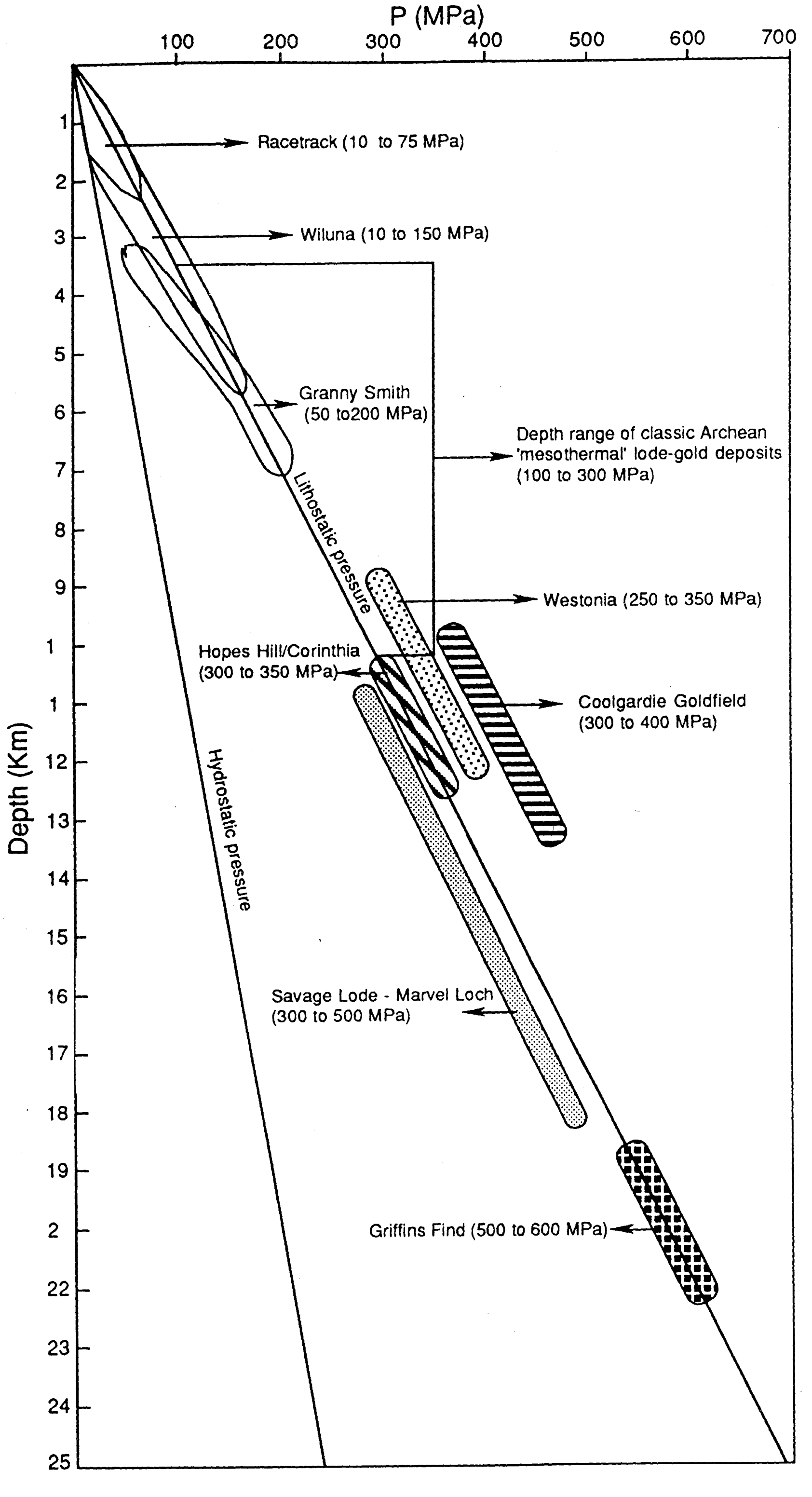

Fig. 1. Pressure-depth conditions of Archaean epi- meso- and katazonal lode-gold deposits. Depths for different deposits were estimated using mean pressures from isochores, phase equilibria or sphalerite-pyrrhotite-pyrite geobarometer: see references on individual deposits quoted in the text. Lithostatic and hydrostatic lines assume pressure gradients of 36 and 100 m/MPa, respectively. Note that for the epizonal lode-gold deposits pressures vary between lith- and hydrostatic values, whereas for katazonal deposits constant lithostatic pressures are assumed, and the ranges given indicate the uncertainties of estimation.

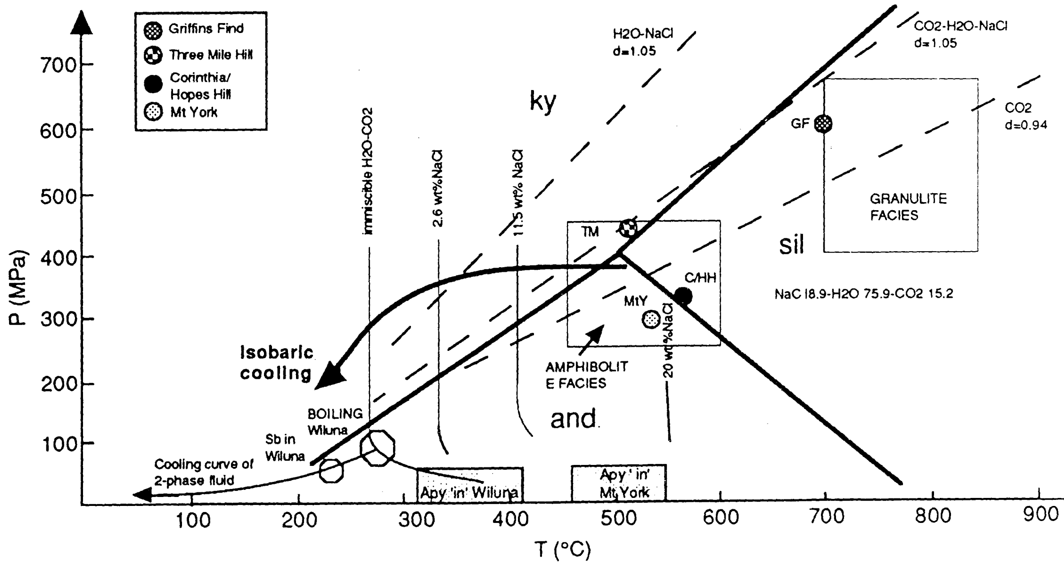

Figure 2. Exhumation and cooling path of Archaean lode-gold deposits. Selected isochores (dashed lines) are plotted for the different fluid inclusion types (see text). The inferred exhumation and cooling path is shown by the long arrow. The four fine solid lines illustrate H_2O-CO_2 immiscibility for different salt contents (Bowers & Helgeson, 1983; Frantz & others, 1992). The boiling and Sb 'in' conditions for the Wiluna lode-gold deposits are from Hagemann (1992); amphibolite and granulite metamorphic conditions from Ridley (1992). References for P-T conditions of gold mineralisation of katazonal lode-gold deposits are given in the text, and include estimates based on arsenopyrite geothermometry as indicated (Apy 'in').

alkaline conditions are also inferred at all temperatures, although the fluid at the Racetrack deposit may have been more acidic, and at Granny Smith more alkaline. Importantly, however, there are variations in the exact composition of the fluid with depth, and also a variable presence of other fluids associated with the ore assemblage. Significant variations of fluid composition with depth are:

- (1) the common presence of higher-salinity, CO_2-poor fluids at both ends of the depth spectrum,
- (2) a presence of either CO_2-poorer or CO_2-richer fluids at specific stages in the evolution of epizonal, high-crustal level deposits,
- (3) consistently higher CH_4:CO_2 ratios in high temperature deposits, and
- (4) a clear general trend towards lower $m_{\Sigma S}$ with decreasing temperature. These points of variation are discussed below, particularly in respect to whether the changes can be the result of evolution of a single fluid, or whether they may be reflecting variable fluid sources.

Presence of higher-salinity, CO_2-poor fluids: Within a single fluid inclusion population, trends have been noted at both Wiluna and Granny Smith of increasing salinity with decreasing X_{CO2}. The differences in salinity are too great to be interpreted as the result of phase separation at the P-T conditions of mineralisation, and together with isotopic evidence (Hagemann, 1992), and other parameters (the presence of complex salts, inclusion homogenisation temperatures), suggests that the trend is the result of mixing with a cool surface-derived, relatively saline (5-10 eq. wt % NaCl) aqueous fluid. The composition of this 'diluting' fluid is similar at all deposits at which it has been recorded. For main stage mineralisation at Racetrack a CO_2-phase is undetectable with microthermometric measurements. Interestingly, a gas-phase is distinctly lacking, which could indicate either a lack of boiling or that the gas-phase became spatially separated.

Two generations of low-X_{CO2} saline fluids have been recorded at many high-temperature deposits. One is retrograde, as shown from textural and isochore evidence (Fig. 2), and is presumably the result of later hydrothermal activity unrelated to ore deposition, using the same fluid 'channelway'. The other (high T_h) high-salinity fluid, with in most instances daughter minerals present, is, from textural and isochore evidence, primary. Its relationship to gold mineralisation is currently unclear. Isochores can as yet not be located due to restricted thermodynamic data on complex salt systems and the lack of data on fluid inclusion salts (e.g. leachate analysis). Recent experimental data on high-temperature fluid-phase relations suggest that it may have been a fluid that was immiscible with the carbonic-aqueous fluid at magmatic temperatures (Frantz & others, 1992), hence at deeper levels in the crust, presumably travelling upwards along the same channelway.

Temporal variability of X_{CO2} at low-

temperature deposits: The variable X_{CO2} of fluid at low-T deposits can be explained in part by dilution and mixing (see above), and in part by phase separation. The uniformly higher X_{CO2} (± X_{CH4}) fluids trapped along the Graphite Fault at Wiluna, and in the core of the mineralised zone at Granny Smith can not however be explained simply as a result of these processes. Rather they suggest that high $X_{CO2+CH4}$ (>0.5) fluids were the dominant hydrothermal fluid at one stage in the evolution of the hydrothermal system (pre-gold-arsenopyrite-pyrite mineralisation at Wiluna, syn-mineralisation at Granny Smith), and that the hydrothermal fluids evolved with time at these deposits. An evolving hydrothermal fluid has been predicted for copper porphyry systems as a result of fluid-solid-magma equilibria during granitoid crystallisation (Bodnar & Cline, 1990). Similar evolution may be implied for fluid exsolution from deeply crystallising granitoids, or through metamorphic devolatilisation reactions, and the nature of such evolution may constrain fluid source processes.

High X_{CH4} in high-temperature deposits: Thermodynamic calculations show a constant range of f_{O2} relative to the fluid CO_2-CH_4 buffer across the spectrum of mineralising conditions. The fluid inclusion CO_2:CH_4 ratios at high-T deposits do not correspond with these calculations. The most likely explanation of this contrast is a post-entrapment modification of fluid inclusion compositions, particularly through H_2 diffusion (inducing reactions such as $CO_2+4H_2 \rightarrow 2H_2O+CH_4$, Morgan & others, 1993). This can not by itself explain the variability of X_{CH4} in a single deposit, or even with a single fluid inclusion cluster, and the causes of such variable CO_2:CH_4 ratios remain unclear at present.

Correlations of sulfur fugacity with temperature: Wallrock sulfidation is a ubiquitous feature of lode-gold deposits. Qualitatively, the reduction in sulfur contents of the fluid with temperature can thus be understood as a result of progressive desulfidation of a deeply-sourced fluid. No mass balance calculations have yet been undertaken to confirm this, nor is there data on whether there may be alternative controls on sulfur contents of fluids at different crustal levels.

Implications for genetic models for Archaean lode-gold deposits

This investigation shows that fluid compositions and histories of fossil hydrothermal systems depend on crustal level. Differing fluid sources at different crustal levels argues against a single fluid for Archaean lode-gold systems. Rather the fluid source(s) responsible for any one deposit or group of deposits depend on the crustal level in which they are situated (e.g. availability of surface water). Temporal and spatial evolution of individual hydrothermal systems has been recognised. At the Wiluna deposit, early non-metal bearing CO_2-CH_4 fluids is succeeded by CO_2-H_2O-NaCl and H_2O-NaCl fluids. At Granny Smith a markedly CO_2-richer (± CH_4) fluid is observed in proximal alteration zones. In upper-crustal level hydrothermal systems, under varying hydrostatic-lithostatic fluid pressure conditions, the influx of cooler, more saline fluids may induce mixing and significant metal (gold) precipitation (e.g. the Au-Sb lodes in Wiluna). At lower crustal levels, under essentially lithostatic pressures, there is no evidence for surface water influx.

Ridley & others (1993) argue that the composition of ore fluids is consistent with derivation from a CO_2-bearing granitic magma that crystallised at pressures of a few kilobars. Fluid inclusion and thermodynamic investigations on epizonal and katazonal lode-gold deposits do not rule out that hot, variably complex and saline, ascending H_2O-CO_2 fluids are sourced also from relatively shallow granitoids located within the greenstone sequences rather than from the commonly postulated deep source external to the greenstone belt (Colvine & others, 1988).

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References

Barnicoat, A.C., Fare, R.J., Groves, D.I., & McNaughton, N.J. 1991, Syn-metamorphic lode-gold deposits in high-grade Archaean settings, *Geology*, 19, pp 921-924.

Bloem, E., & Brown, P.E. 1991, Fluid inclusion evidence from amphibolite facies lode-gold deposits: variations on the greenschist theme, *Geological Society of America, Abstracts with Program 25*, No 5, A173-174.

Bodnar, R.J., & Cline, J.S. 1990, Microthermometric and phase behavior of magmatic hydrothermal fluid inclusions: an analysis based on PVTX data for the system albite-H_2O-NaCl, *PACROFI III*, Toronto, Program and Abstracts, p 17.

Bowers, T.S. & Helgeson, H.C. 1983, Calculation of thermodynamic and geochemical consequences of nonideal mixing in the system H_2O-CO_2-NaCl on phase relations in geologic systems: Equation of state for H_2O-CO_2-NaCl fluids at high pressures and temperatures, *Geochimica et Cosmochimica Acta*, 47, pp 1247-1275.

Cassidy, K.F. 1992, Archaean granitoid -hosted gold deposits in greenschist to amphibolite facies terrains: a high P-T to low P-T depositional continuum equivalent to greenstone-hosted deposits, Unpub. Ph.D. thesis, *The University of Western Australia*, Australia, pp 250.

Colvine, A.C., Fyon, J.A., Heather, K.B., Marmont, S., Smith, P.M., & Troop, D.G. 1988, Archaean lode gold deposits in Ontario, *Ontario Geological Survey, Miscellaneous. Paper 139*, pp136.

Frantz, J.D., Popp, R.K. & Hoering, T.C. 1992, The compositional limits of fluid immiscibility in the system H_2O-NaCl-CO_2 as determined with the use of synthetic fluid inclusions in conjunction with mass spectrometry, *Chemical Geology*, 98, pp 237-255.

Gebre-Mariam, M., Groves, D.I., McNaughton, N.J., Mikucki, E.J., Vearncombe, J.R. submitted, Archaean Au-Ag mineralisation at Racetrack, near Kalgoorlie, Western Australia: a high crustal-level expression of the Archaean lode-gold continuum, *Mineralium Deposita*

Hagemann, S.G. 1992, The Wiluna lode-gold deposits, Western Australia: A case study of a high crustal level Archaean lode-gold system, Unpub. Ph.D. thesis, *The University of Western Australia*, Australia, pp 181.

Hagemann, S.G., & Brown, P.E. 1992, Evidence for retrograde boiling and subsequent fluid mixing in a shallow Au-As-Sb Archaean lode-gold deposits at Wiluna, Western Australia [abs]: *PACROFI IV Abstract with Program*, p 37.

Hagemann, S.G., Groves, D.I., Ridley, J.R., & Vearncombe, J.R. 1992, The Archaean lode-gold deposits at Wiluna, Western Australia: high-level brittle-style mineralization in a strike-slip regime, *Economic Geology*, 87, pp 1022-1053.

Ho, S.E. 1986, A fluid inclusion study of Archaean gold deposits of the Yilgarn Block, Western Australia, Unpub. Ph.D. thesis, *The University of Western Australia*, Australia, 90 p.

Ho , S.E., Groves, D.I., McNaughton, N.J., & Mikucki, E.J. 1992, The source of ore fluids and solutes in Archaean lode-gold deposits of Western Australia: *Journal of Volcanology and Geothermal Research*, 50, pp 173-196.

Knight, J.T., Ridley, J.R., & Groves, D.I. submitted, District scale structural and metamorphic controls on lode gold mineralization in the amphibolite-facies Coolgardie greenstone belt, Western Australia, *Mineralium Deposita.*

Lamb, W.M., Brown, P.E. & Valley, J.W. 1991, Fluid inclusions in Adirondack granulites: implications for the retrograde P-T path, *Contribution to Mineralogy and Petrology*, 107, pp 472-483.

McCall, C. 1992, The timing and controls on gold mineralization in the gabbro-hosted Three Mile Hill deposit, Coolgardie, Western Australia, Unpub. Honours thesis, *The University of Western Australia*, Australia, 54 p.

Mikucki, E.J., & Ridley, J.R. submitted, The hydrothermal fluid of Archaean lode-gold deposits: constraints on its composition inferred from ore and wallrock alteration assemblages over a spectrum of metamorphic grades, *Mineralium Deposita*

Mikucki, E.J., & Groves, D.I. 1990, Gold transport and depositional models, *University of Western Australia, Geology Department (Key Centre) University Extension Publication, 20*, pp 278-284.

Morgan, G.B VI, Chou, I-M, Pasteris, J.D., & Olsen, S.N. 1993, Re-equilibration of CO_2 fluid inclusions at controlled hydrogen fugacities, *Journal of Metamorphic Geology*, 41, pp 155-164.

Mueller, A.G. 1990, The nature and genesis of high- and medium-temperature Archaean gold deposits in the Yilgarn Block, including a specific study of scheelite-bearing gold skarn deposits, Unpub. Ph.D. thesis, *The University of Western Australia*, Australia, 144 p.

Neall, F.B., & Phillips, G.N. 1987, Fluid-wall rock interaction in an Archaean hydrothermal gold deposits: A thermodynamic model for the Hunt Mine, Kambalda, *Economic Geology*, 82, pp 1679-1694.

Ojala, V.J., Ridley, J.R., Groves, D.I., & Hall, G.C. 1993, Granny Smith: An example of a granitoid-hosted Archaean lode-gold deposit, in Abstracts, 2nd national meeting, Specialist group in Economic Geology, Geological Society of Australia, Armidale, February 1993, *Geological Society of Australia*: Abstracts No 34, pp 55-56.

Ridley, J.R. 1992, The thermal causes and effects of voluminous, late Archaean monzogranite plutonism, *Geology Department (Key Centre) and University Extension, University of Western Australia, Publication 22*, pp 275-286.

Ridley, J.R., Groves, D.I., Mikucki, E.J., & McNaughton, N.J. 1993, Indirect evidence for a granitoid fluid source of Archean lode-gold deposits, in Abstracts, 2nd national meeting, Specialist group in Economic Geology, Geological Society of Australia, Armidale, February 1993, *Geological Society of Australia*: Abstracts No 34, pp 66-67.

Robert, F. & Brown, A.C. 1986, Archaean gold-bearing quartz veins at the Sigma mine, Abitibi greenstone belt, Quebec: part I. Geologic relations and formation of the vein system; part II. Vein paragenesis and hydrothermal alteration, *Economic Geology*, 81, pp 578-616.

Roedder, E. 1984, Fluid inclusions: *Reviews in Mineralogy*, 12, 644 p.

Roedder, E. & Bodnar, R.J. 1980, Geologic pressure determinations, from fluid inclusions studies, *Annual Reviews Earth Planetary Sciences,* 8, pp 263-301.

Schenk, V. 1989, P-T-t path of the lower crust in the Hercynian fold belt of southern Calabria, in *Evolution of metamorphic belts,* eds, Daly, J. S., Cliff, R. A. & Yardley, B. W. D, *Geological Society Special Publication,* 43, pp 337-342.

Skwarnecki, M.S. 1990, Sons of Gwalia, *University of Western Australia, Geology Department and University Extension Publications, 20,* pp 149-152.

Walsh, J.F., Kesler, S.E., Duff, D. & Cloke, P.L. 1988, Fluid inclusion geochemistry of high-grade, vein-hosted gold ore at the Pamour mine, Porcupine camp, Ontario, *Economic Geology,* 83, pp 1347-1367.

Geology of the Kalgoorlie gold deposits

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The Kalgoorlie gold deposits have produced a total of 1300 t (43 Moz) of gold, out of 150 Mt of ore, since their discovery in 1893. This equates to approximately 1% of the total world gold production. The majority of this production has come from the lodes of the Golden Mile, historically mined by underground methods, and currently the site of a large-scale open pit operation. Other significant production has come from the Mt Charlotte and Hannans North underground mines and the Mt Percy open pit mine. Current resources are in excess of 18 Moz.

Stratigraphy

The Kalgoorlie sequence, located within the Kalgoorlie Terrane (Swager & others, 1990) of the Norseman–Wiluna greenstone belt, consists of a series of komatiitic to high-magnesian to tholeiitic volcanics (Hannans Lake Serpentinite, Devon Consols Basalt and Paringa Basalt), intercalated with thin sedimentary horizons, including the sulphidic black shales and cherts of the Kapai Slate. This sequence is overlain by the volcanic-sedimentary series of the Black Flag Beds. Several differentiated, concordant doleritic sills are found concordantly within or between the stratigraphic units. The economically most important of these is the Golden Mile Dolerite, a differentiated gabbroic sill, subdivided into ten units (Travis & others, 1971).

Structure

The structure at the Kalgoorlie Gold Field is dominated by tight, northwest-trending, upright folds, strike-parallel faults and late, north-trending, oblique faults (Fig.1).

The Kalgoorlie Syncline and Anticline are the earliest, D_1 (Swager, 1989) structures recognized. The Kalgoorlie Syncline is an asymmetrical structure, with a very steep westerly limb, and a moderately dipping easterly limb. The core of the syncline is intersected by the Golden Mile Fault, interpreted as a normal fault with a west-block up movement of about 3km (Woodall, 1965), or as a D_1 thrust fault, later refolded by the regional D_2 deformation (Swager, 1989).

This folded and faulted Kalgoorlie sequence has been refolded around the northerly plunging D_3 Boomerang Anticline, which itself has been truncated by the regional north-northwest striking Boulder Fault.

Late (D_4), north-trending, predominantly oblique dextral strike-slip faults crosscut and appear to offset all structures. The relationship between the Boulder Fault and the oblique faults is unclear. Interpretations for the Boulder Fault vary from an early D_1 age, similar to the Golden Mile Fault (Clout, 1989), to later D_3 sinistral movement with D_4 dextral reactivation (e.g. Swager, 1989)

Mineralisation

Several styles of mineralisation have been recognized within the Kalgoorlie area (e.g. Clout & others, 1990)

The Golden Mile mineralisation consists of a complex array of shear zones within the Golden Mile Dolerite and Paringa Basalt, between the oblique Golden Pike and Adelaide Faults. The mineralised "lodes", consisting of a high-grade lode shear zone and a low-grade alteration halo, form a subset of these shear zones. The lodes may have dimensions of up to 1800m in length, 1200m in depth, and several meters wide. Historically, several lode orientations have been recognized:

- steep-dipping lodes of the Main Lode-style, in several orientations (Main, Caunter, No.2, Cross lodes); and
- flat-dipping and Oroya-style, mainly at the Golden Mile Dolerite and Paringa Basalt contact.

The lodes are thought to have originated during the D_1 formation of the Kalgoorlie anticline (Boulter & others, 1987), as a result of sinistral movement on the Boulder Fault (Mueller & others, 1988, Swager, 1989), or during east-northeast/west-southwest shortening (Clout, 1989).

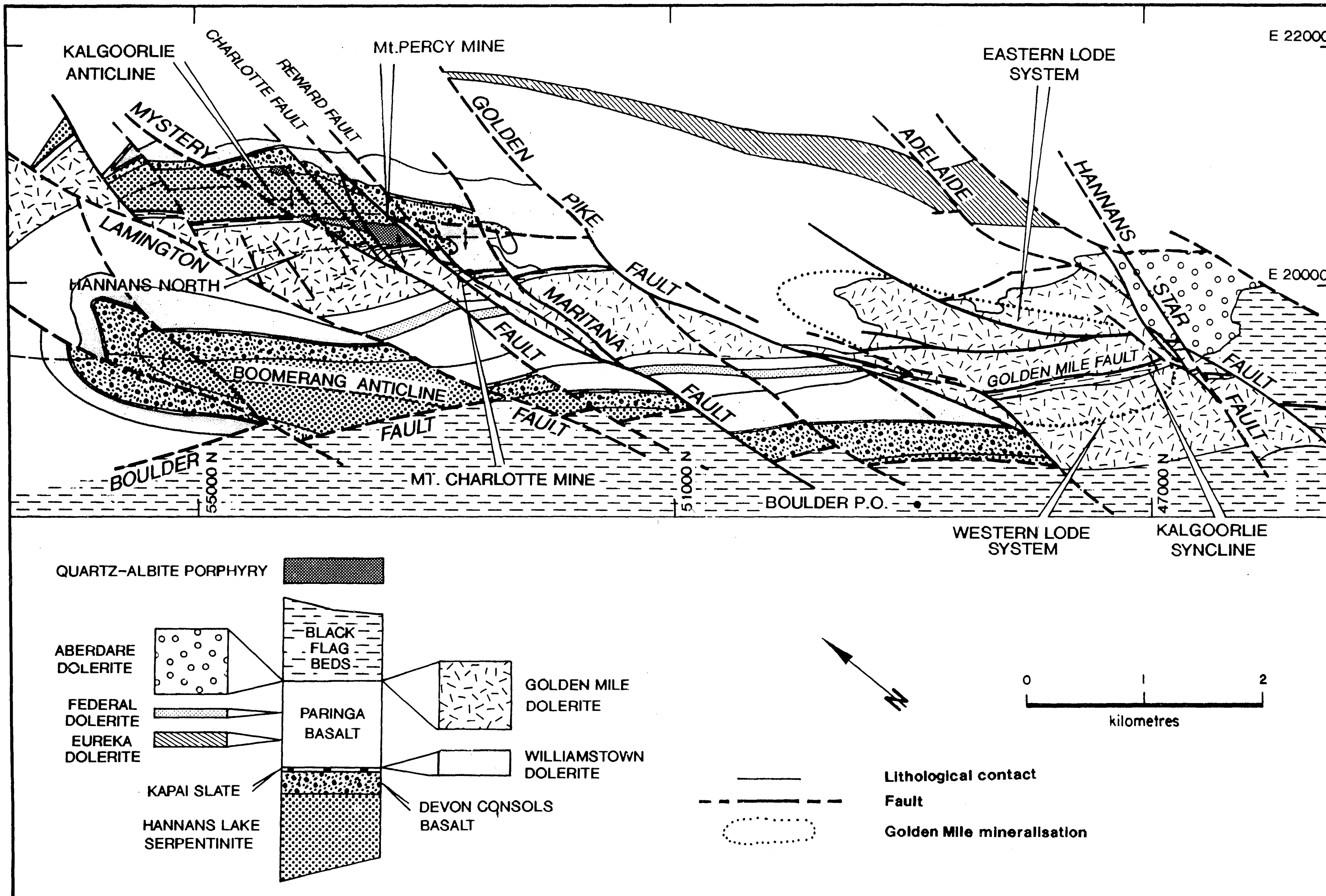

Fig. 1. Interpreted geology of the Kalgoorlie area. After Clout & others (1990).

The Mt Charlotte-style of mineralisation (Clout & others, 1990, Bischoff & Morley, in press), consists of a quartz-stockwork, mainly confined to the granophyric Unit 8 of the Golden Mile Dolerite. The best example of this mineralisation style is the Mt Charlotte orebody. Mineralisation has developed as a result of brittle fracturing in dolerite, bounded by a series of steep, westerly-dipping oblique dextral faults. Veins are usually between 5 and 100 mm wide, with two preferred orientations, with steep northerly and flat northerly dips. The mineralised alteration halos are up to 1 m wide. The Mt Charlotte-style of mineralisation is younger than the Golden Mile mineralisation.

At Mt Percy, mineralisation has developed in stockworks and shears, in the Devon Consols Basalt, and in porphyries intruded into the Hannans Lake Serpentinite. Mineralisation appears to have been mainly controlled by the oblique Reward, Charlotte and Mystery Faults and their splays.

At the Hannans North Mine, mineralisation is mainly concentrated in a single lode shear structure, approximately 1000 m long, and mined to a depth of about 500 m. The structure, within Golden Mile Dolerite Units 6 and 7, is truncated by the D_4 Mystery Fault.

Alteration

The regional metamorphic upper-greenschist assemblage of albite-epidote-actinolite-quartz-ilmenite/sphene, has been overprinted, on a Kalgoorlie-wide scale, by a chlorite-calcite alteration assemblage.

At the Golden Mile lode-scale, mineralisation is associated with an outer, low grade, ankerite-dolomite zone, a sericite zone, with sericite-pyrite-telluride assemblages, and a central dilational brecciation zone with a quartz-hematite core. (Clout, 1989, Clout & others, 1990). Locally, anhydrite and albite zones are developed, while ephesite (brittle mica) and V-sericite zones (also known as "green leader") mainly occur at the top of the lodes. The vanadium-bearing minerals and tellurides indicate very high gold tenors. Gold at the Golden Mile occurs as free gold or as gold and silver tellurides, often intimately associated with pyrite. The ore is refractory.

At Hannans North, only a narrow chlorite alteration zone adjoins the lode (Bartram, 1969, Roberts, 1993). The gold is in association with pyrite, but free milling.

At Mount Charlotte, ankerite-sericite-sulphide alteration haloes surround the quartz veins (Clark, 1980, Clout & others, 1990). Pyrite and pyrrhotite are the dominant sulphide species, pyrrhotite becoming more abundant with depth. Gold is present as 5 to 15 m grains in sulphide fractures or grain boundaries. Minor tellurides are present. The ore is free milling.

At Mt Percy, porphyries and basalts show a widespread sericite-carbonate-pyrite alteration. At the contacts with the mineralised porphyries, the ultramafics show a characteristic fuchsite alteration. Gold is associated with pyrite, although rare tellurides have been found (Sund & others, 1984).

Source of fluids, deposition of gold and geological setting

Light stable isotope studies, such as by Golding (1982), favoured a metamorphic derivation of the ore fluids, but recent work by Clout (1989) has proposed a more mixed source, involving varying proportions of magmatic and seawater or meteoric waters.

Sulphur isotopes of the Golden Mile mineralisation reflect the rare, for Archaean gold deposits, oxidised nature of the ore fluids. Additional evidence for oxidised ore fluids is the presence of hematite, vanadium oxides and sulphates. The presence of oxidised fluids has been explained as the result of fluid–wall rock interaction (Phillips & others, 1986), or as a result of phase separation and/or mixing with surface fluids (Clout, 1989).

Fluid inclusions have provided some further constraints on the nature of the ore fluids, as well as on the temperature and pressures of deposition. Results reported by Ho & others (1990), mainly from late-stage Golden Mile mineralisation, display values typical for Archaean gold deposits: low to moderate salinities, 20-40 wt% CO_2, Tt of 195-355°C and Pt of 150 to 400 MPa. In contrast, Clout (1989) suggests much lower pressures, maximum 26 Mpa, for the ore fluids, with gold being deposited in the 170 to 250°C range. Fluid mixing and phase separation are proposed to explain widely varying salinities and homogenisation behaviour. Based on fluid characteristics, Clout (1989) proposes that different fluids were involved in each of the stages of chlorite-calcite alteration, lode mineralisation and late extensions veins, although consistent K/Rb ratios for the alteration zones (Phillips, 1986) suggest that these fluids may have been generated from a single evolving source.

;Apart from sulphidation, phase separation or fluid mixing (Clout, 1989) has been proposed as the gold depositional mechanism at the Golden Mile.

The structural, alteration, fluid inclusion and isotopic studies by Clout (1989), augmented by some zircon U-Pb age determinations, suggest a much higher level depositional environment for the Golden Mile mineralisation, in contrast to the more conventional Archaean mesothermal setting (e.g. Groves & Phillips, 1987).

Acknowledgements

This paper has drawn heavily from the experiences of many geologists involved with the Kalgoorlie gold deposits over many years. The permission by Kalgoorlie Consolidated Gold Mines Pty. Ltd. to present this paper is gratefully acknowledged. Len Harmelin and staff are kindly thanked for the drafting.

References

Bartram, G.D. 1969, *Wall rock alteration associated with auriferous lodes at Kalgoorlie*. Ph.D.Thesis (unpubl.), University of Western Australia.

Bischoff, K. and Morley, C. in press. Geology, resource definition and reserve estimation at Mount Charlotte, Kalgoorlie, Western Australia. *The International Mining Geology Conference, Kalgoorlie-Boulder 1993*. The Aus.I.M.M. Melbourne.

Boulter, C.A., Fotios, M.G. and Phillips, G.N. 1987, The Golden Mile, Kalgoorlie: A giant gold deposit localized in ductile shear zones by structurally induced infiltration of an auriferous metamorphic fluid. *Economic Geology*, 82, 1661-1678.

Clark, M.E. 1980, *Localisation of gold, Mt. Charlotte, Kalgoorlie, Western Australia*. B.Sc.(Hons) Thesis (unpubl.), University of Western Australia.

Clout, J.M.F. 1989, *Structural and isotopic studies of the Golden Mile Gold-Telluride deposit, Kalgoorlie, Western Australia*. Ph.D.Thesis (unpubl.), Monash University.

Clout, J.M.F., Cleghorn, J.H. & Eaton, P.C. 1990, Geology of the Kalgoorlie Gold Field, in *Geology of the mineral deposits of Australia and Papua New Guinea* (Ed.F.E. Hughes), pp 411-431. (The Aus.I.M.M. Melbourne)

Golding, S.D. 1982, *An isotopic and geochemical study of gold mineralisation in the Kalgoorlie-Norseman region, Western Australia*. Ph.D. Thesis (unpubl.), Univ. Queensland.

Groves, D.I. and Phillips, G.N. 1987, The genesis and tectonic control on Archaean gold deposits of the Western Australian Shield - A metamorphic replacement model. *Ore Geology Reviews*, 2, 287-322.

Ho, S.E., Bennett, J.M., Cassidy, K.F., Hronsky, J.M.A., Mikucki, E.J. and Sang, J.H. 1990, Fluid inclusion studies, in *Gold deposits of the Archaean Yilgarn block: Nature, genesis and exploration guides*. Geology Department (Key Centre) and University Extension, The University of Western Australia, Publication 20, 198-211.

Keats, W. 1987, Regional geology of the Kalgoorlie-Boulder gold-mining district. *Geological Survey of Western Australia*, Report 21, 44pp.

Mueller, A.G., Harris, L.B. and Lungan, A. 1988, Structural control of greenstone-hosted gold mineralisation by transcurrent shearing: a new interpretation of the Kalgoorlie Mining District, Western Australia. *Ore Geology Reviews*, 3, 359-387.

Phillips, G.N. 1986, Geology and alteration in the Golden Mile, Kalgoorlie. *Economic Geology*, 81, 779-808.

Phillips, G.N., Groves, D.I., Neall, F.B., Donnelly, T.H. and Lambert, I.B. 1986, Anomalous sulfur isotope compositions in the Golden Mile, Kalgoorlie. *Economic Geology*, 81, 2008-2015.

Roberts, F.I. 1993, Geology of the Hannans North Gold Deposit, in *Mineral Exploration and Mining Geology in the Eastern Goldfields*, 2nd Annual Geology Symposium, Western Australian School of Mines, p.49-52.

Sund, J.O., Schwabe, M.R., Hamlyn, D.A. and Bonsall, E.M. 1984, Gold mineralisation at the north end of the Kalgoorlie Field, Mount Percy, Kalgoorlie, Western Australia, in *Proceedings of the regional conference on Gold-mining, Metallurgy and Geology*. The Aus.I.M.M. Melbourne, 397-404.

Swager, C. 1989, Structure of Kalgoorlie greenstones - Regional deformation history and implications for the structural setting of the Golden Mile deposits. *Geological Survey of Western Australia*, Report 25, 59-84.

Swager, C.P., Witt, W.K., Griffin, T.J., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J. and Wyche, S. 1990, Late Archaean granite-greenstones of the Kalgoorlie Terrane, Yilgarn craton, Western Australia, in *The Archaean: Terrains, processes and metallogeny*. Geology Department (Key Centre) and University Extension, The University of Western Australia, Publication 22, 107-122.

Travis, G.A., Woodall, R.W. & Bartram, G.D. 1971, The geology of the Kalgoorlie Goldfield. *Special Publications of the Geological Society of Australia*, 3, 175-190.

Woodall, R.W. 1965, Structure of the Kalgoorlie Gold Field. in: *Geology of Australian Ore Deposits* (Ed.J.McAndrew), pp 71-79. (8th Commonwealth Mining and Metallurgical Congress, Melbourne).

Vein- and mine-scale wall-rock alteration and gold mineralisation in the Archaean Mount Charlotte deposit, Kalgoorlie, Western Australia

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Mount Charlotte, a major, currently active gold mine within the Golden Mile district of the Norseman–Wiluna Greenstone Belt of Western Australia, has been the object of several previous petrological and geochemical studies due to its relatively simple geometry of veining and alteration, and to the absence of major post-ore deformation (Clark, 1980; Neall, 1987; Clout & others, 1990; Golding & others, 1990). These, and other investigations, clearly demonstrate the close spatial relationship between gold and Fe-sulphide-sericite-albite-carbonate alteration haloes, and suggest that desulphidation of an H_2S-rich vein fluid by reaction with wall rock Fe-silicates and carbonates contributed to the precipitation of gold from aqueous Au-bisulphide-complexes (Phillips & Groves, 1983; Neall & Phillips, 1987). However, insufficient information is presenly available to identify the overall chemical reaction at the scale of individual alteration haloes, which is required to quantitatively determine the chemical driving force for gold precipitation and the chemical controls on ore-grade distribution within and beyond the presently accessible mine limits.

Measurements of the mineralogical, chemical and isotopic mass balances attending fluid-rock interaction provide perhaps our best opportunity to develop and test more predictive models for the chemical evolution of Archaean ore fluids (for example, Ridley & others, 1990). Quantitative models for the chemical aspects of such large-scale metal enrichment processes are now within reach, due to recent improvements in multicomponent thermodynamic mass-transfer modelling codes and progress in predicting the thermodynamic properties of fluid and mineral species at high temperature and pressure (Turnbull & Wadsley, 1986; Holland & Powell, 1990; Johnson & others, 1992; Heinrich, Walshe and Harrold, unpublished work), in combination with the development of techniques for trace-element analysis of individual fluid inclusions (Heinrich & Ryan, 1992).

This paper is a progress report on a collaborative project between the Key Centre for Strategic Minerals, University of Western Australia, and the Australian Geological Survey Organisation that aims at a better understanding of the geochemical and mass transfer processes responsible for mineralisation and alteration at the Mount Charlotte mine. The current work is being carried out under the umbrella of the National Geoscience Mapping Accord. This contribution reports on recent mapping of the 3-dimensional distribution of alteration assemblages, and discusses some of the implications for palaeo-fluid evolution in the Mount Charlotte hydrothermal system.

Geological setting

The Mount Charlotte deposit is situated within the western limb of the Kalgoorlie syncline, and is hosted by the Golden Mile Dolerite, a layered doleritic sill within the steeply-dipping mafic-ultramafic and felsic volcano-sedimentary greenstone succession. In the mine area, host rocks to mineralisation are crosscut by an early series of moderately southwest-dipping reverse faults (including the Flanagan Fault) which are themselves displaced along steeply west-dipping, north-striking 'oblique' faults that include the Mount Charlotte, Reward and Maritana Faults. Movement along each of these fault sets largely pre-dated mineralisation, but both sets are thought to have played an important role in controlling the geometry and distribution of ore in the Mount Charlotte deposit.

Mineralisation and alteration

Ore mineralisation at Mount Charlotte comprises a series of broadly stratabound vein stockwork systems that form pipe-like to irregularly shaped orebodies situated predominantly within the

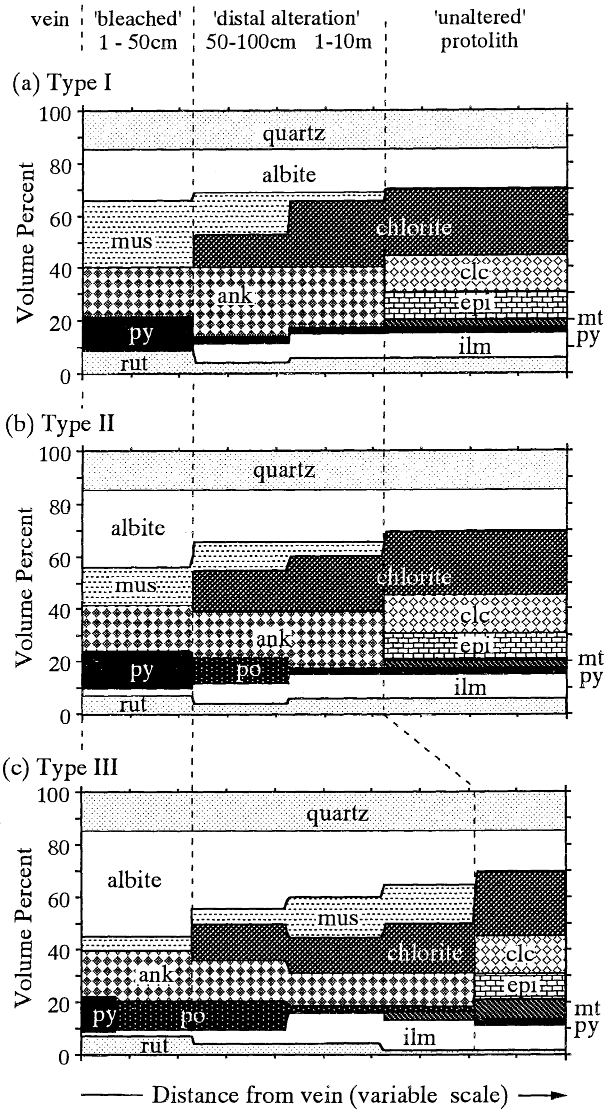

Fig. 1. Estimated average mineralogy of three alteration zoning types observed at Mount Charlotte.

footwalls of the major oblique faults. Veining and mineralisation are largely restricted to the granophyric Unit 8 of the Golden Mile Dolerite. The latter represents the most differentiated and structurally competent unit of the Dolerite and, therefore, acted as the locus for brittle failure and vein formation during late movement along the bounding fault structures. The largest and most continuous of these vein arrays, the Charlotte orebody, reaches horizontal dimensions of up to 75 x 200 m and extends to at least 800 mBD (metres below mine datum) before being terminated by its intersection with the Flanagan Fault. Below the Flanagan Fault, mineralisation continues within the Charlotte Deeps and parts of the Reward orebodies to depths of at least 1050 mBD.

Vein minerals include coarsely-crystalline to massive quartz, with minor euhedral to anhedral scheelite, ankerite and sulphide grains, and late calcite and chlorite. Vein walls are commonly overgrown by early selvedges that are up to 1cm thick and dominated by subhedral albite, ankerite, pyrite, scheelite and/or quartz crystals. Pyrrhotite, when present, is paragenetically late, and occurs in veins as anhedral, interstitial grains filling open space near vein centres. Both vein mineral textures and matching walls across vein boundaries attest to the dilatant, open space nature of vein formation at Mount Charlotte and to the lack of subsequent deformation.

Alteration studies

Earlier investigations by Clark (1980) identified three distinct types of alteration haloes surrounding the Mount Charlotte veins based on differences in the sequence of mineralogical changes that occur within each. Systematic variations in the distribution of these three contrasting types of alteration sequence were also noted. Improved access to the deeper portions of the mine, in combination with re-logging of alteration types in diamond drill core, now allows a more extensive assessment of the mine-scale distribution of alteration types developed within the Charlotte and Charlotte Deeps orebodies.

Figure 1 summarises the overall mineralogical changes for each of the different alteration halo types. Effects of vein-related wallrock alteration extend for several metres beyond the proximal bleached zones that comprise the most visible products of hydrothermal alteration, and that host most of the gold in close textural association with pyrite. 'Least-altered' dolerite samples from Units 7, 8 and 9 of the Golden Mile Dolerite all include the assemblage chlorite-epidote-calcite-magnetite-quartz ± pyrite. Ilmenite (± rutile) is also common as relict igneous (?) grains and as exsolution products of original titanomagnetite. In 'Type I' alteration haloes (Fig. 1a), the onset of hydrothermal alteration is marked by conversion of host rock epidote-magnetite-calcite to chlorite-ankerite-sericite assemblages. Increasing intensity of alteration results in a zone of greater sericite and pyrite abundance at the expense of chlorite within 50-100 cm of vein margins. Boundaries between this zone and inner, pyritic bleached zones are sharp, and result from the complete reaction of any remaining chlorite to form sericite, ankerite and pyrite. Ilmenite, a stable relict phase in chlorite-rich distal alteration zones, also breaks down to pyrite-rutile at this zone boundary. Albite becomes progressively recrystallised during wallrock alteration but remains an apparently stable phase.

In 'Type II' profiles (Fig. 1b), pyrrhotite appears in chlorite+ankerite-bearing rocks up to 1 m from the pyrite-sericite bleaching front. 'Type III' profiles (Fig. 1c) still have pyrite as the most

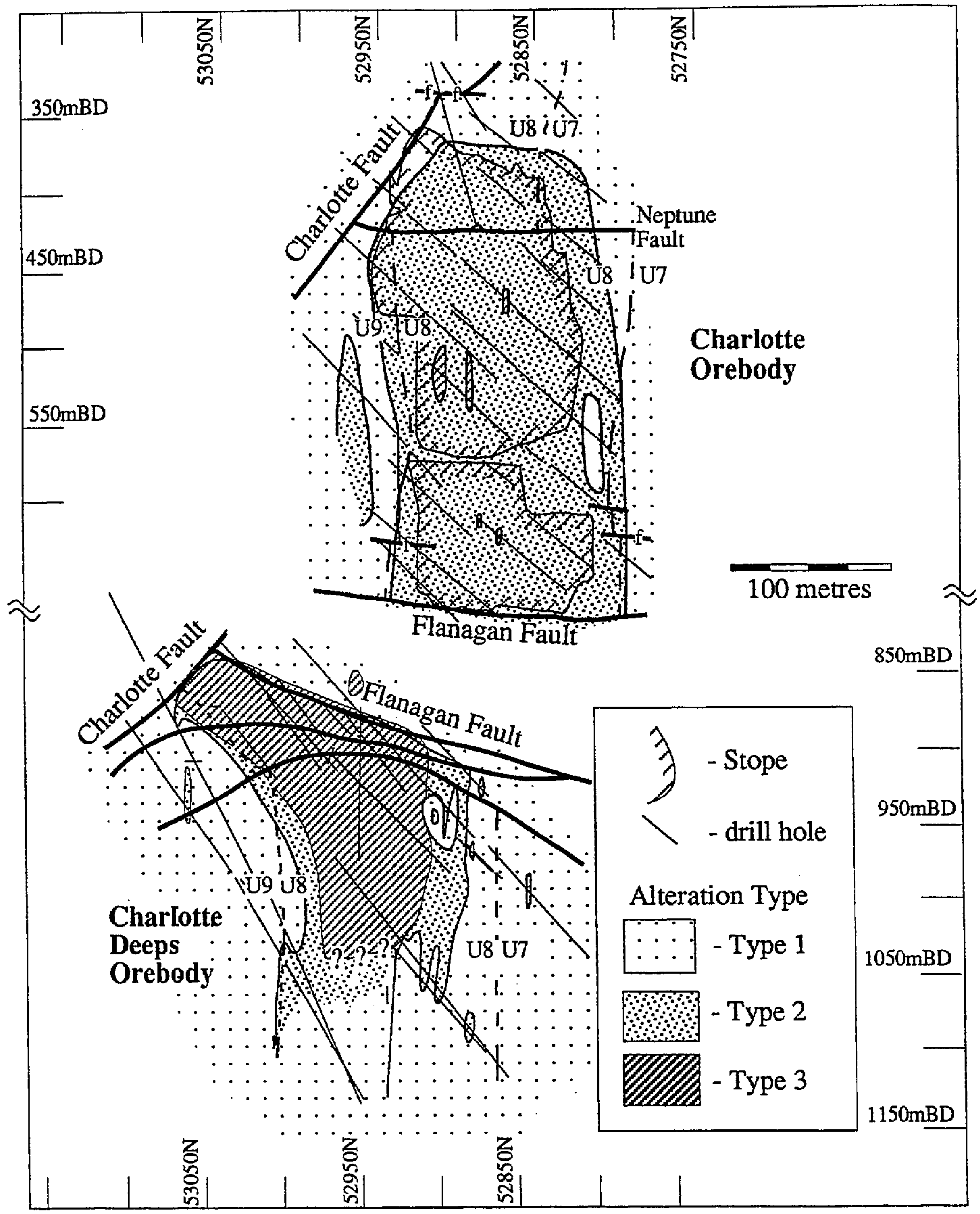

Fig. 2. Distribution of alteration halo types in a composite vertical section through the Charlotte orebody (Q Drill Section) above, and the Charlotte Deeps orebody (136 Drill Section) below, the Flanagan Fault. Both sections cut approximately through the centre of the vein stockwork, but are offset out of the plane of the figure due to the displacement of the Unit 8 (U8) granophyre along the early Flanagan Fault.

vein-proximal sulphide but are characterised by pyrrhotite as the dominant Fe-sulphide in the outer part of the bleached haloes, as well as in the adjacent chlorite-bearing zone. In contrast to 'Type I' sequences, in 'Type II & III' alteration haloes sericitisation occurs mainly in the more distal, chloritic alteration zones, whereas albite is added and most prominent in the proximal bleached zone (Fig. 1). Ilmenite can also be found as relict, partially replaced grains within the proximal bleached zones of 'Type III' alteration haloes.

Alteration mapping within the Charlotte and Charlotte Deeps orebodies (Figs. 2 and 3) illustrates the systematic 3-dimensional distribution of alteration halo types. A clear zonation at the mine-scale is evident, with regions of contrasting alteration halo types forming a series of concentric shells. As shown, pyrrhotite-rich 'Type III' altera-

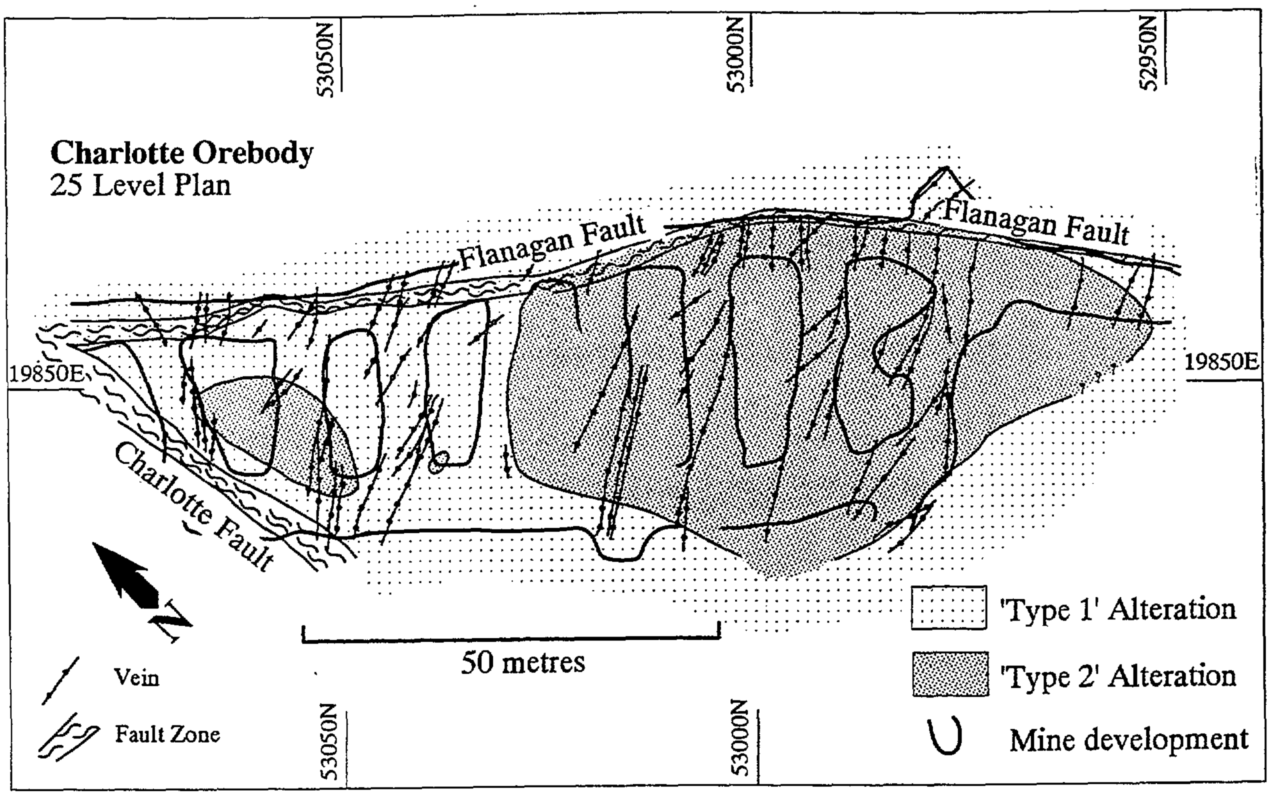

Fig. 3. Distribution of alteration zoning types in a horizontal section through the Charlotte orebody at the 25 Level (765 mBD).

tion haloes dominate within the core of the stockwork and at the deeper mine levels. 'Type II' alteration haloes occur peripheral at depth but dominate the intermediate levels of the main ore zone. 'Type I' haloes occur in distal, isolated veins in the Charlotte Deeps, are common along the periphery of the orebodies at intermediate levels, and dominate the economic ore zone at the highest levels of the deposit.

Mine-scale alteration boundaries commonly transgress lithological contacts, and thus rule out compositional variations in the protolith as the main control on alteration zoning within the two orebodies. Furthermore, within the main Charlotte orebody, areas characterised by 'Type I' alteration haloes often intercede between the Charlotte Fault and regions of pyrrhotite-rich 'Type II' mineralisation (Fig. 3). Alteration zones are centred on areas of highest vein density within the stockwork rather than emanating from the Charlotte Fault, and thus preclude the latter as a major channelway for the ore-fluids (at least above the Flanagan Fault). In contrast, veining along some sections of the Flanagan Fault exhibit the same alteration zoning pattern noted above; from 'Type III' haloes near to the fault through to more distal 'Type II' and 'Type I' alteration haloes. This observation and the geometry of the system suggest that parts of the Flanagan Fault acted as a hydraulic channelway linking the Charlotte Deeps with the Charlotte orebody. The distribution of alteration types is, therefore, best explained by channelling of the ore fluids through the vein stockwork itself, and not through the major bounding oblique faults (compare Golding & others, 1990).

Origin of the mine- and vein-scale alteration zoning patterns

Models for alteration zoning at both individual vein halo- and mine-scale must account for two factors:

- (i) the apparent reversal in pyrite-pyrrhotite spatial relationships between vein- and mine-scale alteration patterns; and
- (ii) the predominance of albite over sericite in proximal alteration zones of the 'Type III' zoning sequences that characterise the deepest portions of the exposed mine system.

As a first approximation, moderate (~50°C) gradients in ore fluid temperatures provide the most plausible explanation for mine-scale alteration patterns within the Charlotte and Charlotte Deeps orebodies, and are also consistent with observed gradients in the $\delta^{18}O$ values of vein quartz, as documented by Golding & others (1990). Phase equilibria between Na-K aluminous silicate phases (Montoya & Hemley, 1975) are consistent with increasing albite stability relative to sericite at higher

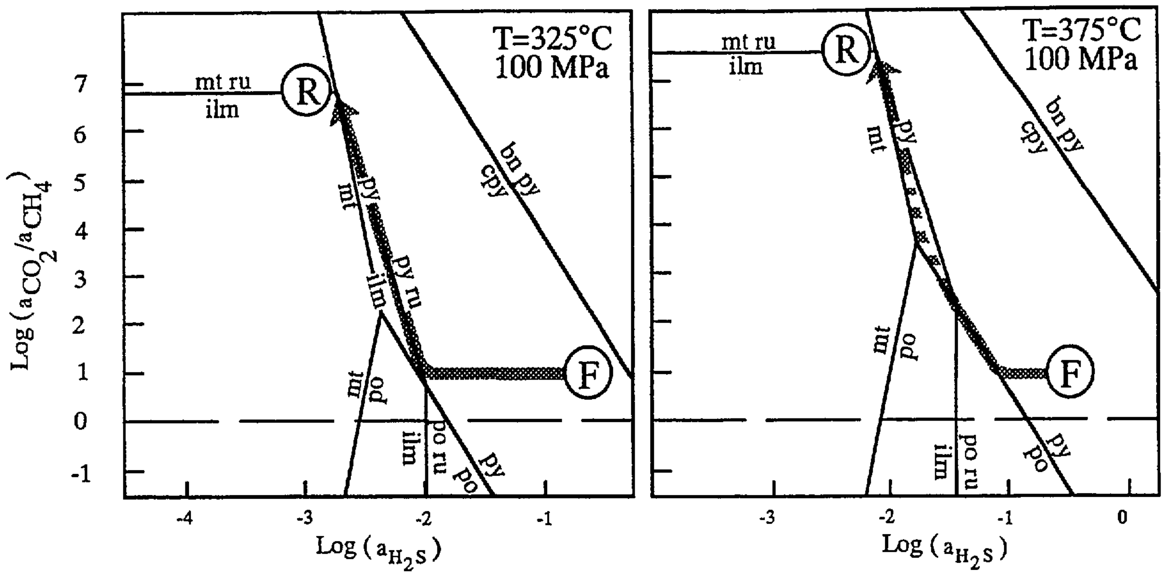

Fig. 4. Activity diagrams showing equilibrium stability relations between pyrite (py), pyrrhotite (po), chalcopyrite (cpy), bornite (bn), magnetite (mt), ilmenite (ilm) and rutile (rut) coexisting with a C- and S-bearing aqueous fluid at 325°C (a) and 375°C (b), and 100 MPa. Arrows indicate possible fluid evolution paths at the halo scale, for an ore fluid F infiltrating through a vein wall and progressively reacting towards equilibrium with the wall rock R, as discussed in the text. Thermodynamic data based on Johnson et al. (1992), Turnbull and Wadsley (1986) and Holland and Powell (1990).

temperatures, and thus can explain the predominance of albitisation in 'Type III' alteration haloes for ore fluids of nearly constant Na/K. Likewise, slightly higher mineralisation temperatures for 'Type II' and 'Type III' alteration could explain the restriction of pyrrhotite-rich alteration and vein mineral assemblages to the deeper and more central portions of the stockwork systems studied. This is best illustrated in Figs. 4a and b, which plot ore-fluid evolution in redox potential (expressed as CO_2/CH_4) and H_2S activity space, for 'Type I' and 'Type II & III' alteration profiles, respectively. The temperature range of 375-325°C assumed for the calculations is within the range of homogenisation temperatures for 'texturally early' fluid inclusions reported in Clark (1980), and Groves & others (1984), and is considered to be a reasonable estimate for ore fluid conditions. Initial vein fluid compositions, marked F in the diagrams, are assumed to be identical in both cases. Estimated CO_2/CH_4 and H_2S contents are based on published fluid inclusion data and preliminary Raman and PIXE fluid inclusion analyses. The latter indicate ore fluid CO_2/CH_4 of between 2 and 50, and high H_2S molalities on the order of $10^{-0.5}$m (Heinrich, Mernagh and Ryan, unpublished data).

At the lower range of likely ore fluid temperatures (Fig. 4a), H_2S in the infiltrating ore-fluids becomes rapidly depleted by forming pyrite within the proximal bleached zone. However, the presence of ilmenite and rutile coexisting with pyrite within the adjacent chloritic alteration zones indicates that further reaction in 'Type I' alteration haloes followed a path of decreasing H_2S activity and increasing oxidation potential governed by the reaction: ilmenite + H_2S + CO_2 = pyrite + rutile + CH_4. Infiltrating ore fluids thus failed to reach pyrrhotite saturation at these lower temperatures, and finally ceased reaction at the point of magnetite stability (ie. once conditions reached equilibrium with the initial host rock assemblage, indicated by R in Fig. 4).

At higher temperatures, partial desulphidation of an identical fluid reacting with the same wall rock is more likely to reach pyrrhotite saturation (Fig. 4b), thereby forming the pyrrhotite zones observed in the 'Type II' & 'III' alteration profiles. Further reaction in these profiles depends on the mass-balance between competing reactions involving iron silicates, oxides and carbonates, but probably passes near the magnetite-pyrrhotite-pyrite triple point, as indicated by the presence of magnetite-pyrrhotite assemblages in the outer portions of 'Type III' alteration zones. Alteration zoning of Fe-Ti oxide and sulphide assemblages within the Mount Charlotte alteration haloes thereby confirms earlier studies documenting the importance of desulphidation during fluid infiltration and gold deposition at the vein-scale (Neall, 1987), and furthermore, suggests that ore fluids also became progressively more oxidised during reaction with the wall rocks.

Summary and implications

Available data and preliminary thermodynamic analysis indicate that gold precipitation at Mount Charlotte occurred by a combination of desulphidation and slight oxidation of a moderately reduced ore fluid at the single-halo scale, but also indicates significant lateral as well as vertical temperature gradients at the mine scale. The shape of the zonation patterns suggest that the advecting ore fluids may have been cooled by several tens of degrees due to thermal interaction with initially colder wall rocks. If confirmed by further geothermometric measurements, this rather unexpected conclusion may require a process of fluid mixing and/or rapid advection of a relatively small flux of unusually hot fluid through the centre of the Charlotte stockwork.

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References

Clark, M.E. 1980, Localization of gold, Mt. Charlotte, Kalgoorlie, Western Australia. *B.Sc Thesis, The University of Western Australia* (unpublished).

Clout, J.M.F., Cleghorn, J.H., & Eaton. P.C. 1990, Geology of the Kalgoorlie goldfield, in *Geology and Mineral Deposits of Australia and Papua New Guinea*, ed. F.E. Hughes, Australasian Institute of Mining & Metallalurgy, pp. 411-432.

Golding, S.D., Clark, M.E., Keele, R.A., Wilson, A.F. & Keays, R.R. 1990, Geochemistry of Archaean epigenitic gold deposits in the Eastern Goldfields Province, Western Australia, in *Stable Isotopes and Fluid Processes in Mineralization*, eds. H.K. Herbert and S.E. Ho, Geology Department and University Extension, Publ. 23, The University of Western Australia, pp 141-176.

Groves, D.I., Phillips, G.N., Ho, S.E., Henderson, C.A., & Clark, M.E. 1984, Control on distribution of Archaean hydrothermal gold deposits in Western Australia, in *Gold '82: The Geology, Geochemistry and Genesis of Gold Deposits*, ed. R.P. Foster, A.A. Balkema Rotterdam, pp 689-712.

Heinrich, C.A. & Ryan, C.G. 1992, Mineral paragenesis and regional zonation of granite-related Sn-As-Cu-Pb-Zn deposits: a chemical model for the Mole Granite district (Australia) based on PIXE fluid inclusion analyses, in *Fluid—Rock Interaction*, eds. Y. K. Kharaka and A. S. Maest, Balkema Rotterdam, pp 1583-1587.

Holland, T.J.B. & Powell, R. 1990, An enlarged and updated internally consistent thermodynamic dataset with uncertainties and correlations: The system K_2O-Na_2O-CaO-MgO-MnO-FeO-Fe_2O_3-Al_2O_3-TiO_2-SiO_2-C-H_2-O_2. *Journal of Metamorphic Geology*, 8, pp 89-124.

Johnson J.W., Oelkers E.H., & Helgeson H.C. 1992, SUPCRT92: A software package for calculationg the standard molal thermodynamic properties of minerals, gases, aqueous species, and reactions from 1 to 5000 bars and 0° to 1000°C. *Computers and Geosciences*, 18, pp 899-947.

Montoya, J.W. & Hemley, J.J. 1975, Activity relations and stabilities in alkali feldspar and mica alteration reactions. *Economic Geology*, 70, pp 577-594.

Neall, F.B. 1987, Sulphidation of iron-rich rocks as a precipitation mechanism for large Archaean hydrothermal gold deposits in Western Australia: thermodynamic confirmation, in Recent Advances, in *Understanding Precambrian Gold Deposits*, eds. S.E. Ho & D.I. Groves, Geology Department and University Extension, The University of Western Australia, Publ. 11, pp 265-269.

Neall, F.B. & Phillips, G.N. 1987, Fluid-wall rock interaction in an Archean hydrothermal gold deposit: a thermodynamic model for the Hunt Mine, Kambalda. *Economic Geology*, 82, pp 1679-1694.

Phillips, G.N. & Groves, D.I. 1983, The nature of Archaean gold-bearing fluids as deduced from gold deposits of Western Australia. *Journal of the Geological Society of Australia*, 30, pp 25-39.

Ridley, J.R., Heinrich, C.A., & Mikucki, E.J. 1990, Chemical implications of imperfectly channelized fluid flow in hydrothermal systems. I. Fundamental aspects. II. Application to gold deposits. *Specialist Group in Economic Geology, Ore Fluids Conf.*, pp 31-32 and 70.

Turnbull, A.G. & Wadsley, M.W. 1986, The CSIRO-SGTE THERMODATA system, version V. *Div. Mineral Chemistry Commun.*, 7 v., 413p. CSIRO, Melbourne.

Inter-relationships and structural controls of gold and nickel mineralisation at the Mount Martin deposit, Western Australia

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The Mt Martin Au-Ni deposit is located 37 kms southeast of Kalgoorlie within the Norseman–Wiluna Belt of the Yilgarn Block, Western Australia. The deposit occurs in a number of ductile shear zones in altered ultramafic lithologies in a lower amphibolite facies metamorphic regime (Purvis, 1984; Perriam, 1985). The combined open pit and underground production to date is approximately 1.1 Mt at 3.6 g/t Au. The pre-mining gold resource to a depth of 250 m is estimated at 4.5 Mt at a similar grade.

An arsenical nickel sulphide resource (approx. 100 000 tonnes at 2.0% Ni and 2.3% As) occurs together with, or in close proximity to the gold mineralisation. The nickel mineralisation is effectively the "type example" of the rare and poorly understood "vein-type auriferous-arsenical" group of nickel deposits (Marston & others, 1981). Both late metamorphic-hydrothermal (Marston & others, 1981) and modified Kambalda-style origins (Kyin, 1989) have been proposed for the Mt Martin deposit.

The aim of this paper is to document an improved geological understanding of this deposit and more specifically to briefly examine the inter-relationships between structure, alteration and gold-nickel mineralisation.

Regional geology

The mine is situated within ultramafic rocks near the southern portion of the Boorara Domain of the Kalgoorlie Terrane (Swager & others, 1990). A "basin and dome" outcrop pattern (Fig.1) results from the interpreted interaction between D_1 recumbent folding and faulting about east-west axes and D_2 folding about north-northwest-trending axes (Perriam, 1985).

In the Mt Martin mine area lithological trends and foliation trajectories are dominated by the north-northwest-trending D_2 Kent's Dam Syncline (Fig.1). Thickening of the ultramafic pile appears likely as a result of folding and possibly D_2 thrust faulting (Perriam, 1985). A later phase of sinistral D_3 north-south shearing is mapped out by north-trending foliation domains which are clearly transgressive to the D_2 foliation trend (Fig. 2). A (D_2?) northwest-trending aeromagnetic lineament which breaks the pattern of foliation trajectories to the south west of the mine area is poorly exposed. The relationship between this structure and the north-south shearing is consequently unclear.

Mine geology

Structure

The immediate mine area has been subdivided into structural domains based on foliation trajectory and dip (Fig. 2). Foliations in the north-trending domains dip 25-40° west versus 40-50° west in the northwest-trending D_2 domains. The north-trending domains are ductile shear zones and are termed the Main and East shear zones (Fig. 2). These shears are transgressive to, and cause drag folding of, two northwest-trending foliation-parallel shear zones, termed the North Shaft and West shears (Fig 2), developed parallel to D_2 foliation trends. Gold and nickel mineralisation appear to be synchronous with D_3 movements on all four shear zones.

The sense of movement on both the Main, East, North Shaft and West shears is oblique with sinistral and normal components. This is indicated by:-

- tensional quartz vein arrays (300/65E),
- a consistent orientation of the "dilating" shear segments, and
- sinistral drag folding of the northwest shears into the north-trending shears (Fig. 3).

In the Main shear a second weaker foliation, thought to be a relict D_2 fabric, trends north-

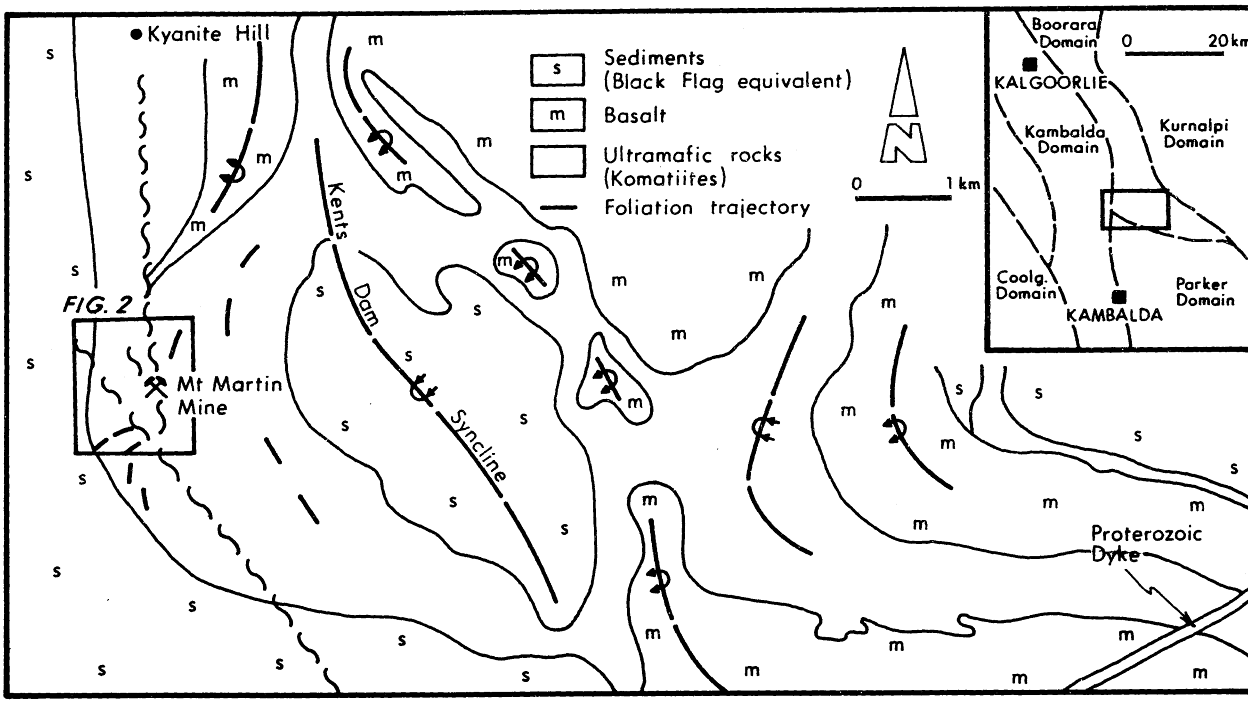

Fig. 1. Semi-regional geology Mt Martin Area.

west and dips more steeply at 45° west. The intersection of the D_2 and D_3 fabrics forms a prominent lineation that plunges at 30° towards 300°. A second weaker mineral lineation, which is best developed on the northwest-trending foliation surfaces plunges at 28° to the south parallel to the movement direction within the shear zone (Keele, 1989).

Structural controls on gold mineralisation

The gold mineralisation generally occurs as a series of sulphide lodes (mineralised faults) parallel to the dominant foliation along the Main, East, North Shaft and West shear zones (Figs. 2, 3). It is best developed where individual foliation-parallel faults, or complete shear zone segments, have been rotated anti-clockwise and steepened into dilational jogs. Dilational jogs affecting complete shear zone segments occur in five areas on the Main shear and at the northern end of the East shear (Fig. 2). The apparent "epicentre" of alteration and mineralisation appears to be the intersection of the North Shaft and West shears with a jogged portion of the Main Shear. Examples of dilational jogs affecting individual faults are shown on Fig. 3.

The dilational jogs, together with enhanced alteration, sulphide mineralisation plunge at 30° towards 300° at right angles to the apparent movement direction. In three dimensions the dilational jogs may display a "dilational kink" geometry resulting in a "stacking" of lodes in a vertical corridor parallel to the plunge direction. This direction is parallel to the fold axes of:-

- layer parallel, variably asymmetrically folded, late carbonate veins developed adjacent to zones of mineralisation and
- early generation carbonate veins which have been boudinaged and selectively replaced by sulphide (after quartz-cummingtonite-siderite) leaving rodded sulphide "hooks" and "eyes" which plunge at 30 to 300°.

Weak rodding of more competent domains in the host lithology is not uncommon.

Narrow late-stage subvertical cross-faults (Figs. 2, 3) which are transgressive across all foliation domains are present at attitudes of 60° and 100° and are noticeably more abundant within and at the margins of the dilational jogs. This distribution pattern indicates these faults to be relief structures associated with the dilational jogs and are observed to dislocate both the mineralisation and the late stage barren quartz veins associated with the gold mineralisation. Abrupt variations in alteration and mineralisation intensity are often evident across the cross faults/fractures, particularly at the boundaries of the dilational jogs. Sinistral, south-block-down displacements are evident but tend to be minimal (0-14 m). Rare dextral movements have also been observed.

Alteration/lithology

The mine sequence rock types are subdivided on the basis of alteration type. The "unaltered background" rocks in the mine sequence consist of highly strained, CO_2-altered pyroxenitic to peridotitic komatiitic ultramafic rocks (27-37%

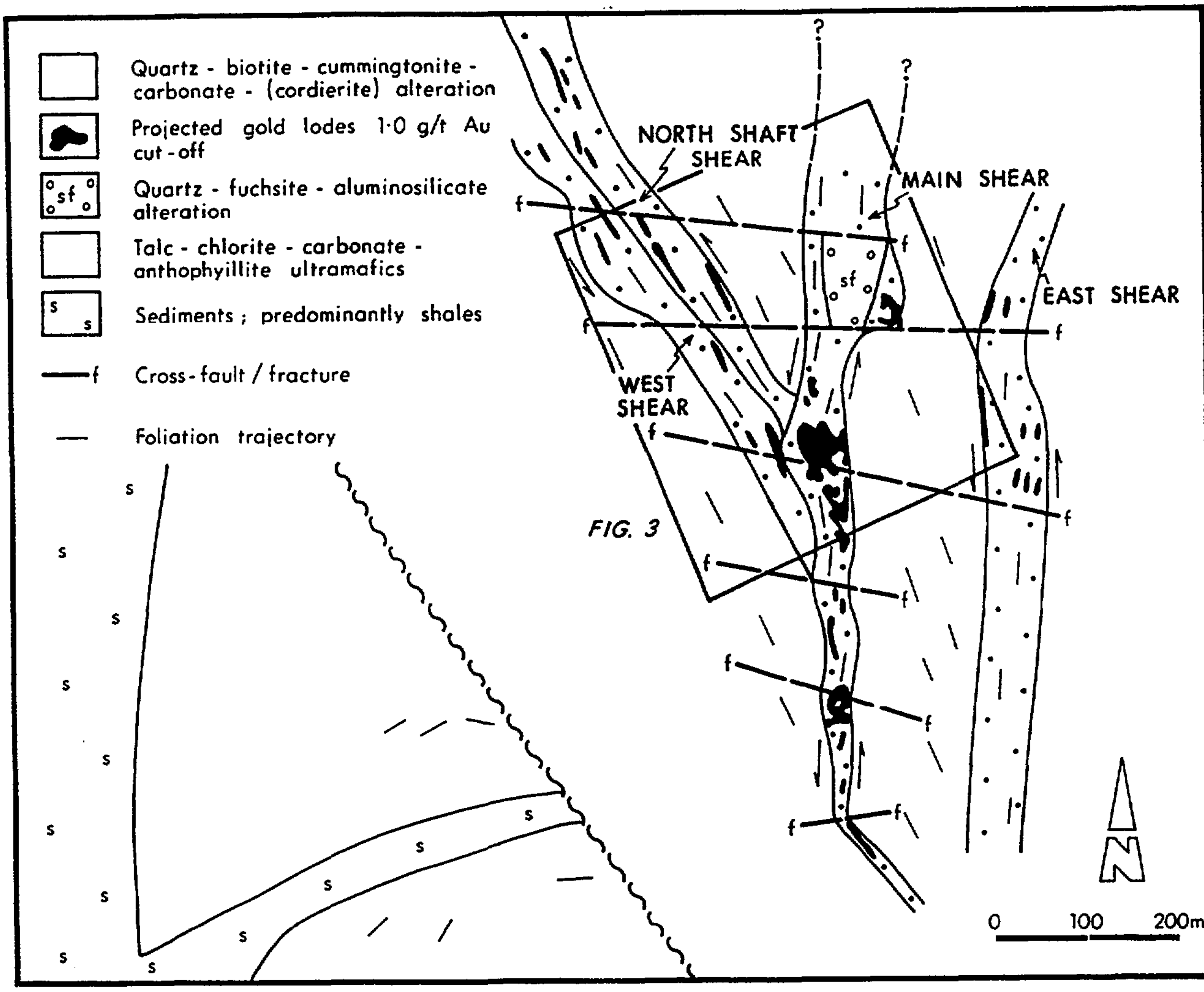

Fig. 2. Surface geology Mt Martin mine.

MgO). The more pyroxenitic variants have a anthophyllite-talc-chlorite-carbonate mineralogy while the more peridotitic variants consist of talc-carbonate-chlorite.

Previously the quartz-biotite-cummingtonite-siderite rocks at Mt Martin which host the bulk of the gold and nickel mineralisation have been described as sediments, mainly inferred from a variably banded and/or cherty appearance (Marston & others, 1981, Washausen, 1990). These 'sediments' are now considered to be altered komatiitic ultramafic rocks on the basis of geochemistry (Table 1) and the presence of sporadically preserved spinifex textures.

There are two phases of alteration overprinting the CO_2-altered ultramafic rocks at Mt Martin. The gold and nickel mineralisation is interpreted to be associated with the second alteration phase. Each phase has imparted distinctive geochemical trends which are briefly discussed below. Whole rock analyses and typical mineralogies of the various alteration assemblages are summarised in Table 1. Altered spinifex-textured rocks with primary MgO contents of 24-30% have been included in Table 1 to constrain primary igneous compositions.

The early phase one alteration, which is carbonate-replacive, is characterised by volume depletion, progressive stripping of Mg, Fe and Ca, addition of K_2O, relative enrichment in SiO_2 and residual enrichment of the immobile phases Al, Ti and Cr. Volume factor calculations (Gresens, 1967) indicate a range of volume factors of 0.6 to 0.9. This alteration results in, with increasing intensity,

- (i) cummingtonite-quartz-biotite-carbonate-(albite) schists, which form the dominant alteration lithology,
- (ii) quartz-cordierite-amphibole-chlorite-(biotite) schists and
- (iii) quartz-fuchsite-(andalusite-kyanite-sillimanite) schists.

The alteration assemblages generated by this style of alteration are similar in nature to that described by Purvis (1984), Martyn & Johnson (1986) and Halberg (1987), although at Mt Martin, partially stripped marginal phases, represented by assemblages (i) and (ii), are also developed. The

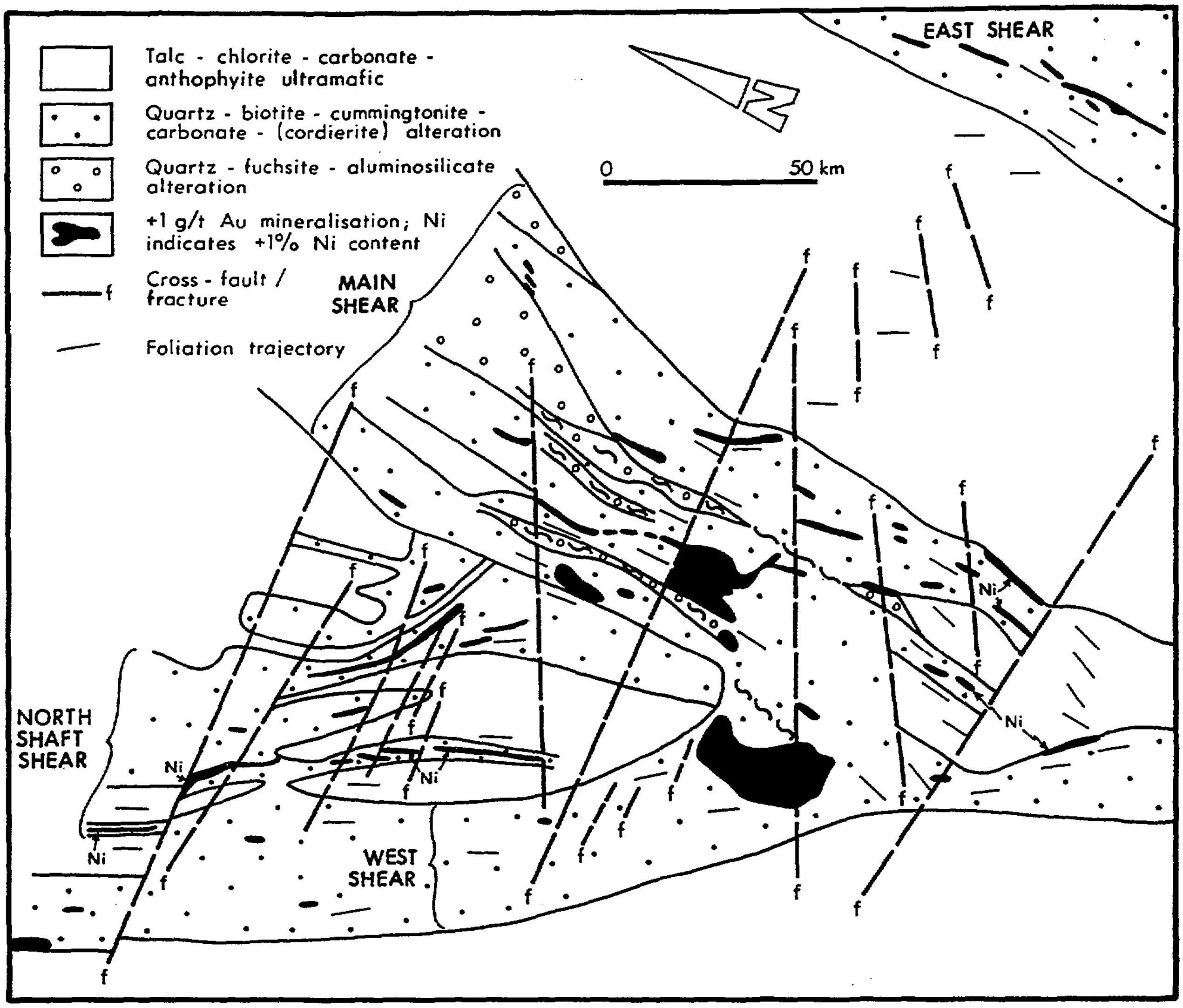

Fig. 3. 4 level geology Mt Martin mine.

quartz-fuchsite-aluminosilicate schists significantly *do not* form inner alteration cores to any of the gold lodes.

The later phase two alteration, associated with the Au-Ni mineralisation, is characterised by volume enhancement in structurally dilatant areas within the various shear zones. Volume factor calculations on variably mineralised rocks indicate volume factors of 1.7 to 5.6. This phase of alteration results in the 'dilution' of the immobile phases Al, Ti and Cr via the introduction of CO_2, Si, Fe, Mg, Ca, S, K, Au, As and Ni. This alteration is characterised by the development of biotite either along microfractures or replacing amphibole, commonly with accompanying fine granular quartz and sulphide together with vein quartz and carbonate. Cummingtonite can be abundant in highly altered and mineralised rocks and is interpreted to result from ferromagnesite + quartz reactions under lower amphibolite metamorphic conditions. Assemblages (i), (ii) and (iii) of the previous alteration phase can all be mineralised and overprinted although the cummingtonite-quartz-biotite carbonate rocks of assemblage (i) are volumetrically more abundant.

Mass balance calculations (Gresens, 1967) based on the Table 1 data indicate an approximate doubling of nickel content in the moderate to strongly leached phase one alteration products, and five to ten-fold increases in the nickel content of the weakly disseminated phase two alteration products. The variable degrees of nickel enrichment in the slightly altered, phase one alteration products (Table 1) are interpreted to be a result of weak overprinting by phase two alteration.

Gold mineralisation

The gold, which is slightly argentiferous, is generally associated with arsenopyrite, less commonly with siderite, occasionally in cummingtonite or quartz, and more rarely in pyrrhotite (or supergene pyrite), gersdorfite or chalcopyrite. Sulphide relationships are complex and both arsenopyrite after pyrrhotite and pyrrhotite after arsenopyrite replacement relationships are observed.

TABLE 1. Geochemistry of Mt Martin Alteration Assemblages

	ROCK TYPE	SIO2	MGO	AL2O3	FEO	CAO	NA2O	K2O	MNO	S	LOI	TI	CR	ZR	V	NI	AS	AU	AG	CU	CO	TOTAL	SG	fV
A	chtbc	39.57	28.19	6.55	10.03	3.22	0.16	0.36	0.14	0.24	12.27	1800	1650	15	135	1160	1500	0.01	0.30	52	<2	101.3	-	-
	tachcb	36.36	32.33	6.61	9.26	0.81	0.08	0.18	0.12	0.13	14.94	1850	1900	15	140	1020	1200	0.02	0.20	11	<2	101.4	-	-
	ctch	40.80	31.50	6.80	9.52	0.95	0.05	0.18	0.13	0.07	15.63	1850	2100	5	145	540	25	0.00	0.10	66	<2	106.0	-	-
B	anttchc	43.85	22.38	5.86	9.26	4.20	0.24	0.17	0.14	<0.01	9.34	1650	2150	14	120	470	100	<0.01	0.20	54	92	95.8	2.91	
	anttchc	37.43	25.70	5.19	8.23	4.90	0.20	<0.01	0.14	0.02	12.53	1450	1950	12	110	580	200	<0.01	0.20	47	84	94.7	2.88	
	anttchc	42.78	22.38	5.86	10.03	4.62	0.32	<0.01	0.17	0.14	8.66	1750	1700	12	115	860	1800	0.13	0.10	25	86	95.3	2.93	
	tchc*	40.64	24.04	7.37	10.55	3.08	0.81	<0.01	0.18	0.02	10.85	2100	2200	14	130	360	300	<0.01	0.10	70	76	98.0	2.91	1.00
	tchcb*	43.85	23.21	7.56	11.06	1.54	0.23	2.11	0.09	0.02	6.33	2100	2350	16	150	440	300	<0.01	0.10	130	80	96.4	2.88	0.98
C	cumqtzc(b)	51.34	13.26	9.07	10.55	3.99	3.24	0.42	0.18	0.15	5.21	2350	2150	15	160	1000	1080	0.02	0.40	66	<2	98.1	-	-
	cumbcqtz	44.92	14.92	11.33	16.72	1.65	1.21	2.71	0.34	0.19	1.90	3200	2600	20	225	2500	3100	0.10	0.20	6	<2	97.0	-	-
	cumbqtz*	53.47	12.60	10.96	10.55	1.20	0.70	1.99	0.21	0.15	2.66	3200	3900	18	210	2550	3400	0.12	<0.10	120	175	95.8	2.90	0.68
	qtzbcum*	55.61	9.28	11.33	13.12	1.12	0.63	2.53	0.28	0.12	1.24	3200	3600	18	220	1450	1900	0.24	0.10	112	145	96.3	2.95	0.64
D	cumbcqtz*	59.89	6.13	12.47	9.52	1.26	1.11	0.24	0.12	0.40	3.40	3500	3700	6	265	1350	200	0.02	<0.10	66	150	95.4	2.79	0.62
E	qtzfand*	70.59	0.86	11.71	1.16	0.13	1.40	0.72	0.01	0.31	1.45	3100	2400	4	190	1200	300	0.03	<0.10	96	155	89.0	2.75	0.67
	qtzf	72.73	0.90	9.07	1.13	0.06	0.19	3.01	0.01	0.47	2.02	2500	2850	16	160	760	300	0.04	0.10	52	140	90.2	2.63	0.90
	qtzf	71.87	0.25	13.60	0.50	0.01	0.38	4.22	0.00	0.24	1.98	4000	2950	30	420	1180	560	0.00	0.10	108	<2	93.9	-	-
F	qtzcumbc	63.10	9.62	3.87	6.94	4.76	0.36	1.35	0.12	0.37	7.14	1050	1400	10	85	1140	2700	0.12	0.10	18	78	98.3	2.89	1.92
	qtzbcumcs#	68.45	3.15	4.53	14.15	0.67	0.61	1.69	0.26	2.50	2.27	1300	1950	12	105	2500	2600	0.66	0.50	60	130	99.1	2.82	1.68
	qtzbcums#*	62.03	5.64	3.40	18.65	1.54	0.11	0.87	0.43	2.80	2.66	950	1250	10	90	2300	24500	2.65	0.90	66	104	101.1	3.03	2.08
	cumqtzcbs#	42.78	7.79	2.27	28.29	0.82	0.22	0.54	0.77	3.50	6.60	450	860	10	85	8600	9600	0.92	1.00	92	<2	95.5	-	-
	bcqtzs#	31.02	7.96	3.68	28.29	0.66	1.27	0.78	0.72	3.70	13.01	850	1400	10	155	2200	6600	0.20	1.20	70	<2	92.2	-	-
G	cchbQC	18.82	20.72	8.50	12.60	10.07	0.42	1.87	0.22	3.10	19.00	2200	2300	15	195	600	1300	0.02	0.80	86	<2	96.0	-	-
	ccumqtzabchC	25.24	15.59	2.08	12.09	16.51	0.55	0.30	0.27	1.75	25.60	250	210	10	30	680	390	1.10	1.30	46	<2	100.1	-	-
	cumbcqtzQC	33.15	18.90	3.12	12.09	12.59	0.20	0.84	0.28	0.27	19.61	700	920	5	65	980	920	0.03	0.10	28	<2	100.4	-	-
H	cs#(cumqtz)	5.56	9.95	1.21	26.36	12.31	0.55	0.22	0.45	13.50	14.65	50	74	12	15	41000	68000	9.70	3.40	180	520	95.7	3.52	5.03
	cumcqtzs#	23.96	11.27	1.10	37.29	0.70	0.15	0.18	0.90	13.50	14.02	150	155	18	20	13000	8800	15.00	3.90	185	102	104.4	3.49	5.59
I	s#qtzccum	5.99	4.97	1.44	45.01	1.48	0.36	0.30	0.62	25.50	25.80	400	360	20	75	4800	1400	0.41	1.30	74	280	112.1	4.17	3.57
	s#cumqtzc	32.08	9.28	3.78	30.22	0.24	0.92	0.70	0.90	13.00	10.83	850	1000	14	110	980	86000	0.72	3.90	800	155	110.8	3.33	1.70

Notes (1) *= spinifex textured; '-'= not determined
(2) A= CO2-altered peridotite; B= CO2-altered pyroxenite; C= slightly leached alteration phase 1 (+/- alteration phase 2?) D= moderately leached alteration phase 1; E= strongly leached alteration phase 1; F= disseminated gold/nickel mineralisation alteration phase 2; G= variably altered ultramafic with abundant carbonate veining; H= nickel/gold mineralisation; I= gold mineralisation
(3) ab= albite, and= andalusite, b= biotite, c= carbonate, cum= cummingtonite, f= fuchsite, qtz= quartz, s#= sulphide, t= talc
(4) fV= volume factor (Gresens 1966) assuming Al2O3 immobility = (a.Al2O3 x aspecific gravity)/(b.Al2O3 x bspecific gravity)
(5) Total Fe calculated as FeO
(6) Trace elements in ppm; major element oxides and S in %

The arsenopyrite is typically micro-fractured. The Au mineralisation occurs in three morphologies:-

- as highly disseminated through semi-massive to massive sulphide concentrations with a carbonate-cummingtonite-quartz gangue. This material constitutes the majority of the high grade underground material mined to date. These high grade shoots have a lensoidal geometry orientated parallel to the prevailing foliation with a pronounced plunge of 30° towards 295-300°. These sulphide enrichments develop preferentially in dilational bends in conjunction with enhanced alteration and barren white quartz veining. Three dimensional 'stacking' of the high grade shoots within the dilational bends is a common occurence and is best observed in detailed open pit grade control plans. At a 5 ppm Au gold cut-off these shoots are typically 15-20 m in strike length. At a 1 ppm Au cut-off, the high grade shoots may link up along strike. The East Lode and South Lodes (Fig. 2) have a more tabular geometry with strike lengths of approximately 40 m.
- attenuated veins with a variable sulphide-siderite-cummingtonite mineralogy; remobilised sulphide concentrations around quartz veins; fracture fillings and disseminations (termed "pseudostockwork" mineralisation). This form of mineralisation is typical in the hanging wall portion of the Main shear and in the H/W West shear. Although the better developed zones of this mineralisation can be traced from level to level, continuity of high grade (+5 ppm Au) ore within these zones is typically poor. Where well developed, this form of mineralisation is accompanied by abundant quartz veining and more abundant cross faulting and fracturing.
- weakly disseminated, bleb and fracture sulphide in the quartz-biotite-cummingtonite-carbonate wall rocks. Sulphides in these rocks are typically associated with biotite foliae and micro-fracture fillings. Background gold values of 0.1-0.3 ppm Au are common in conjunction with elevated Ni and As values.

Nickel mineralisation

The Ni mineralisation is considered to be epigenetic and closely related to the Au mineralisation, on the basis of comparable characteristics such as morphology, distribution, geochemistry and plunging geometry. This latter characteristic is interpreted to be related to relatively late stage structural features. A high MgO ultramafic host to much of the nickel mineralisation is not obvious. In the case of the "Ni lode" (Fig .3), which hosts the bulk of the more continuous Ni mineralisation, the weakly altered anthophyllite-talc-chlorite-carbonate ultramafic rocks on either side of the relatively narrow (5 m) quartz-biotite-cummingtonite-carbonate alteration halo have MgO contents of only 24-29%.

The more nickel-rich pyrrhotite-gersdorfite-arsenopyrite-pentlandite mineralisation has a similar gangue mineralogy and appearance to the gold mineralisation and occurs in both lode and 'pseudostockwork' morphologies. Like Au mineralisation, Ni mineralisation is not "vein-associated", but rather occurs in sulphide-rich dilatant zones in association with enhanced carbonate and quartz veining. Gold grades vary from 0.3-30 ppm Au and where economic have been mined as gold lodes. Nickel mineralisation assaying greater than 1% Ni is always strongly arsenical (0.5-7.0% As), although as with the gold mineralisation, high arsenic values do not necessarily coincide with high Ni values.

The dominant Ni phase is gersdorfite which is generally fractured and occurs variously as:-

- a replacement of pyrrhotite (remnant pyrrhotite preserved as thin plates); as inclusions within pyrrhotite;
- as larger grains with silicate inclusions; as cross-cutting veinlets and as replacement rims and fracture fillings of supergene pyrite after pyrrhotite (Kyin, 1989).

Pentlandite, where present occurs as inclusions within pyrrhotite.

Ni values in excess of 1% (Fig. 3) occur:-

- Along the "Ni Lode" in the North Shaft shear in conjunction with high grade gold values (10-30 ppm Au)
- In two stacked parallel lodes in the Main shear in conjunction with relatively low Au values (0.3-2 ppm Au) and
- As "pseudostockwork" mineralisation in three areas along the West Shear with variable gold values. Nickel mineralisation in these areas is typically discontinuous and has been left out of resource calculations

Anomalous Ni values in the 0.3-0.8% Ni range are more widespread and have a distribution more closely related to high arsenic grades. This often corresponds to areas of gold mineralisation.

Conclusions

An early alteration phase (unrelated to the gold and nickel mineralisation) resulted in strong cation leaching and volume depletion. A synmetamorphic, early D_3 timing of this alteration is interpreted on the basis of the prograde metamorphic nature of the alteration assemblages and the presence of the alteration in the D_3 north-trending shear zones.

The gold-nickel mineralisation is localised in dilatant zones associated with late D_3 ductile shearing. A later alteration phase associated with the mineralisation is characterised by volume enhancement and enrichment in Si, Fe, Mg, Ca, K, S, Au, As and Ni. The mechanism of nickel transport is unclear. The abundance of amphibole in strongly mineralised alteration assemblages is consistent with a timing close to conditions of peak metamorphism.

References

Gresens R.L. 1967, Composition-volume relationships of metasomatism, *Chemical Geology*, 22, pp47-65.

Hallberg J.J. 1987, The nature and origin of some aluminous alteration assemblages of the Eastern Goldfields, in Geological Society of Australia-Western Australian Division, (compilers), *The Second Eastern Goldfields Geological Field Conference, Kalgoorlie, Western Australia, Abstract and Excursion Guide*, pp 11-12

Keele R.A. 1989, Progress report on mapping in the Mount Martin open pit: a report to AUR Ltd., Unpublished internal report.

Kyin A. 1989, A mineralogical investigation of the Mount Martin gold-nickel sulphide mineralisation, Postgraduate Diploma in Mining and Mineral Technology thesis, Western Australian School of Mines, (unpublished).

Marston R.J., Groves D.I., Hudson D.R., & Ross J.R. 1981, Nickel sulphide deposits in Western Australia: a review, *Economic Geology*, 76, pp 1330-1363.

Martyn J.E., & Johnson G.I. 1986, Geological setting and origin of fuchsite-bearing rocks near Menzies, Western Australia, *Australian Journal of Earth Sciences*, 33, pp 1-18.

Perriam R.P.A. 1985, The tectonic evolution of the Mount Martin-Carnilya Hill district of the Eastern Goldfields, Western Australia. M.Sc. thesis, The University of Western Australia, (unpublished).

Purvis A.C. 1984, Metamorphosed altered komatiites at Mount Martin, Western Australia-Archaean weathering products metamorphosed at the aluminosilicate triple point, *Australian Journal of Earth Sciences*, 31, pp 25-40

Supergene mineralisation in the Eastern Goldfields Province, Western Australia

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Research into supergene mineralisation in recent years has been driven largely by the metals exploration industry. These investigations have been based on the knowledge that geochemical dispersion haloes within the regolith greatly enlarge the target size in the search for concealed and deeply weathered ore deposits, and that these same supergene processes may also result in supergene enrichment of primary mineralisation.

The Eastern Goldfields Province has been the centre of much of this exploration activity, being not only historically the largest producer of gold in Western Australia, but also hosting the major komatiite-associated nickel deposits of the Yilgarn Block. Other metal deposit discoveries, such as base metals and platinum, have been less common, and the behaviour of these commodities in the regolith is less well understood. Exploration is complicated by deeply weathered, complex regolith situations, where multiple erosional and depositional events have resulted in truncation and burial of profiles, which have been continuously weathered under changing climates from seasonally humid, tropical to arid, at least since the early Tertiary.

Although surface physical transport from an exposed source may result in placer deposits, chemical mobilisation from the weathering of primary mineralisation is the dominant form of supergene enrichment. The mobilisation and concentration of any particular element in the supergene environment depends on its individual chemistry. Whilst gold is much more freely mobile in the supergene environment than once thought, its mobility is restricted to certain zones within the regolith. Other metals have broader stability fields in supergene solutions and, therefore, are more freely mobile. A detailed discussion of the chemical mobility and transport of elements in the weathering environment is given by Thornber (1992).

This paper reviews the major geochemical constraints which result in the formation of supergene mineralisation, and compares the behaviour of the major supergene ore-forming metals of the Eastern Goldfields Province. Importantly, this paper demonstrates that supergene geochemistry, itself controlled by climate, topography and rock type, particularly primary mineralisation type, controls supergene mineralisation.

Geochemistry of the supergene environment

Intensive weathering in the Eastern Goldfields Province has resulted in strong chemical fractionation. Although the overall supergene processes are integrated and complex, specific chemical environments (or zones) are produced within the regolith as a result of the combined effects of climate, topography and rock type. Distinctive weathered horizons are developed and subsequently overprinted by the accumulation of redox and mobile weathering products in specific horizons with continuous physical and chemical modification. Some of these are coincident with weathering horizons and relate to mineralogy, others are largely independent of weathering horizon but are controlled by the prevailing oxidation potential (Eh) and hydrogen ion activity (pH) within the profile.

The deposition of redox products, dominantly iron oxides, in the profile is the most significant indicator of past and present geochemical environments. The lower part of the weathered profile is generally reducing and the upper part oxidising. Where the profile becomes sufficiently oxidising, red, brown and yellow iron oxides are precipitated by ferrolysis. This iron oxidation front is referred to as the redox front (Lawrance, 1991).

Reducing Environment   Oxidising Environment

$$2\,Fe^{2+} + 0.5\,O_2 + 3\,H_2O \Rightarrow 2\,FeOOH + 4\,H^+$$

mobile ferrous ion   goethite

This reaction produces acid and is irreversible in the supergene environment, except by specialized organic processes. Hence, the iron oxide is insoluble and, therefore, represents a permanent, highly visible record of the position of the redox front within the regolith. Only one active redox front exists in the profile at any given time, and its location (depth) depends on climate.

Humid Climates

High watertables and large volumes of water during profile formation, under a seasonally humid, tropical climate, leached mobile components with the resultant residual accumulation of stable primary and secondary minerals, and the precipitation and accumulation of iron oxides above a high watertable in the near-surface. This iron oxide accumulation resulted in the formation of laterite at the surface. Thus, the laterite can be regarded as the uppermost palaeo-redox front in the complete weathering profile. Acid conditions produced by ferrolysis probably enhanced weathering in the laterite and mottled clay horizons.

Arid Climates

Subsequently, under increasingly arid conditions, an excess of evaporation over precipitation lowered the watertable and decreased groundwater flow, which resulted in decreased weathering and an increase in the accumulation of weathering products and groundwater salinity, and permitted iron oxide precipitation lower in the profile. The most abundant deposition of iron oxides occurred as near-horizontal enrichment zones as the redox front remained static, corresponding to a still-stand in the watertable. Acid conditions, produced by ferrolysis above the descending redox front, probably caused further intensive leaching of the upper saprolite and formation of the leached upper saprolite. With progressive lowering and further still-stands in the watertable, under periods of constant climate, a series of palaeo-redox fronts (or iron oxide accumulations) were formed in the profile. The positions of these palaeo-redox fronts generally indicate that there was not just a continuous downward progression of the redox front but that, in some situations, it also rose in the profile, with perhaps a reversal of climate or change in topography, such as with tectonic uplift. During the decline of the watertable, oxygen is readily available and the deposition of iron oxides and intense weathering are uninhibited. However, when the watertable becomes static, redox processes are slowed, because eventually the reaction front will descend to a level of anoxic conditions. With a rising watertable, redox processes are limited by the decline in oxygen access and weathering is greatly reduced. However, redox processes can continue higher in the profile at a new redox front associated with the watertable.

Topographically low, partly water-saturated profiles generally have the sharpest redox fronts compared to topographically high profiles. In topographically low areas, such as lake environments, permanent water-saturation of the lower profile maintains a reducing environment and the present redox front is generally preserved in the saprolite. In topographically high profiles, a watertable may no longer exist and the present redox front is generally not well-defined and approximates the weathering front.

The intensity of iron oxide accumulation at the redox front depends on the length of time of the still-stand and the availability of iron in the profile. Iron oxides may also move as colloids and, hence, precipitate on fracture surfaces, indicating fluid movement within the profile. It is the deposition of these iron oxides at the redox front and on fracture surfaces that indirectly controls most element mobility and deposition and, hence, supergene mineralisation.

Element mobility

On dissolution at the weathering front, the solubility of an element will depend on the oxidation state permitted in the groundwater. The groundwater chemistry is strongly controlled by the weathering mineralogy and soluble secondary products. However, the primary control on element mobility is the development of acid and alkaline environments. Generally, acid conditions enhance the mobility of metal elements and alkaline conditions inhibit mobility. If the zone of inhibition occurs close enough to the primary source, where the concentration of elements in solution is likely to be greatest, then secondary enrichment of the element is likely. Due to the individual chemistries of the metal elements in solution, their sites of inhibition are slightly different. Hence, elements tend to separate in the weathered profile in a manner analogous to that in a chromatographic column.

The weathering (oxidation) of most mineralised zones is, at least locally, an acid forming process due to redox processes, described above, and the weathering of sulphides; the most common being pyrite:

$$\underset{\text{pyrite}}{4\,FeS_2} + 8\,H_2O + 15\,O_2 \Rightarrow \underset{\text{hematite}}{2\,Fe_2O_3} + 8\,SO_4^{2-} + 16\,H^+$$

This reaction involves the simultaneous oxidation of Fe^{2+} and S^{2-}, and results in a strongly acid environment surrounding the weather-

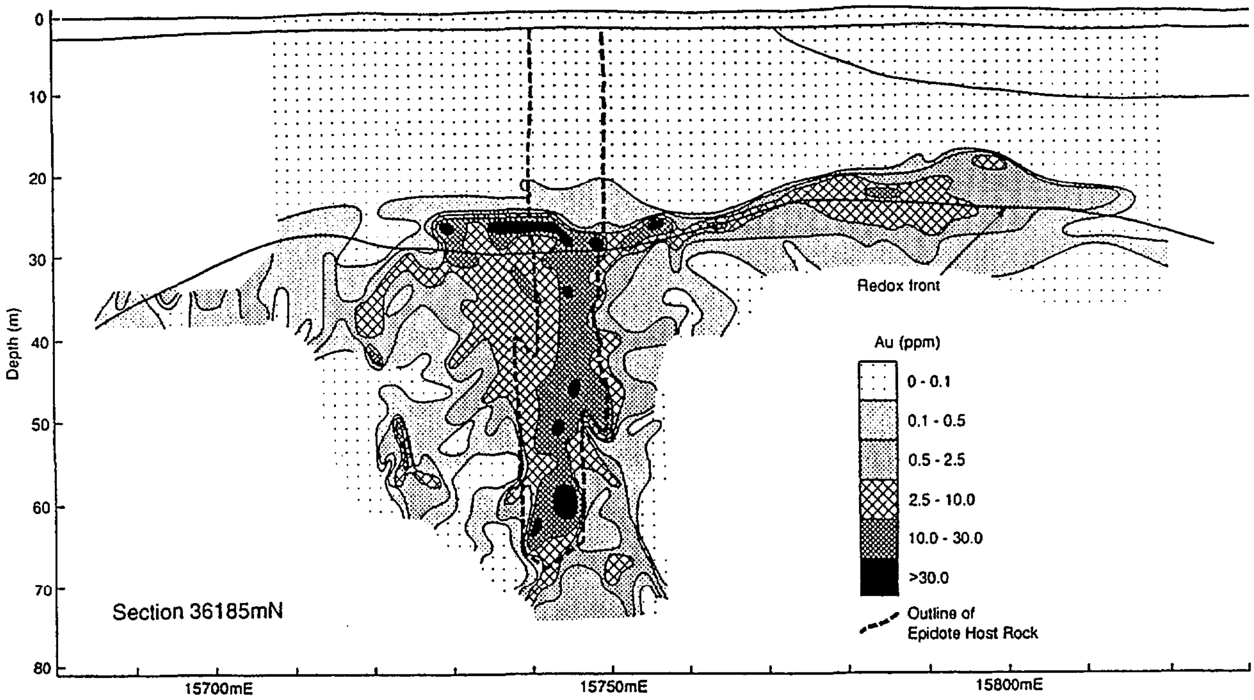

Fig. 1. Section through the Hannan South mineralization showing location of secondary saprolitic gold enrichment zone above the redox front (modified from Lawrance, 1991).

ing pyrite grains. This acidity promotes further weathering. Similar acid conditions are produced by the weathering of the accessory sulphides, but, in addition, these reactions involve the oxidation and release of other elements, such as As, Cu, Pb, Zn, Bi and Co, and, therefore, the formation of metal cations. Under acid oxidising conditions, these metals adopt a low oxidation state. In this state, the metals are far more soluble than the larger sized ions that typify the higher oxidation state of the element. Therefore, under acid conditions their mobility is enhanced. With the exception of the noble metals, most metal elements are mobile as the free ion over a wide range of Eh-pH conditions in the supergene environment. Hence, they are widely dispersed, and are only precipitated by their adsorption on to iron oxides and are unlikely to form supergene mineralisation.

Gold mobility

Gold mobility is strongly control by the geochemical environment. Gold solubility is dependent on the availability of water, suitable Eh-pH conditions and the presence of suitable ligands. Its unique chemistry is demonstrated in numerous deposits of the Yilgarn Block. In these deposits, the major factor affecting the distribution of gold in the regolith is the position of palaeo- and present iron redox fronts, controlled by climate and topography.

This geochemical control on supergene gold mineralisation is best illustrated in wetter profiles (topographic lows) where the redox front is sharp. An example of this style of supergene mineralisation is the Hannan South deposit, which occurs beneath an ephemeral salt-lake system. At Hannan South, supergene gold-enrichment occurs just above a redox front in the saprolite at 25-30 m depth (Fig. 1). The geochemical control on the mobility and enrichment of gold in the profile is demonstrated by the site of deposition and the morphology and composition of the secondary gold. Two types of secondary gold occur in the profile. Small rounded grains (commonly <1μm) of moderate fineness (970) occur *below the redox front* around partly weathered sulphide grains, confined to the host unit. Large crystals (commonly >0.5mm), predominantly trigonal and hexagonal plates and octahedra of very high fineness (999), occur *above the redox front* within a lateral saprolitic enrichment zone. Gold is depleted above this enrichment zone. Two processes, involving dissolution and mobilisation of gold; as a thiosulphate complex under alkaline, reducing conditions below the redox front, and as a chloride complex under acid, oxidizing conditions, above the redox front, account for this gold distribution.

During lateritisation, under a seasonally humid, tropical climate, gold was probably leached above a redox front, high in the profile, as gold-organic complexes. This process is interpreted to have produced low residual concentrations of gold in wide dispersion haloes (several hundreds of meters) in the laterite. Below this redox front, under less oxidizing conditions, minor mobilisation of the gold may have occurred as a thiosulphate complex, particularly where sulphides were being weathered. Exposure of the upper profile to saline, acid, oxidizing conditions under an arid climate, with a lowering of the redox front, has leached gold from the upper saprolite, probably as a chloride complex, resulting in a depleted zone. With a still-stand in the watertable, gold probably accumulated above the redox front in a near-horizontal saprolitic enrichment zone. Under a sustained arid climate, a salt-lake system has over-printed the profile and the lower profile has remained partly water-saturated. Lowering of the watertable below this palaeo-redox front has mobilized gold and accumulated it as high-purity crystals in a new saprolitic enrichment zone, that extends into the weathered wall rocks (several tens of metres), just above the present redox front. The preservation of pyrite and carbonate minerals under reducing conditions below this redox front, indicates that alkaline conditions are preserved. In this environment, gold may continue to be mobilized as a thiosulphate complex.

In topographically high profiles, similar processes resulted in the formation of supergene gold-enrichment zones, but the progression of oxidizing conditions to the weathering front, during extended arid phase weathering, has exposed gold throughout the regolith to acid oxidizing conditions. However, due to limited groundwater, gold mobility has been restricted to almost *in situ* reworking of the grains, and enrichment zones are largely preserved above palaeo-redox fronts in the upper profile.

Mobility of other elements

The behaviour of the platinoid group elements in the supergene environment is perhaps the least well understood. No large economic occurrence of supergene platinum has been discovered in the Yilgarn Block to date. However, platinum mobility and precipitation appear to be strongly controlled by solution chemistry, similarly to gold. Other less noble elements are more soluble in a wide range of supergene solutions and, therefore, are more widely dispersed above the redox front. The relative concentrations of these elements depends on their primary concentrations and their relative mobilities. However, due to the high adsorption capacity of iron oxides, concentrations of these elements are enhanced in the laterite and ferruginous horizons, associated with palaeo-redox fronts. A single or stacked mushroom-shaped dispersion pattern may result. Therefore, these ore elements are generally not enriched in the supergene environment, but are depleted compared to the primary mineralisation. However, concentrations of ore elements within these zones are, thus, easily accessible guides to mineralisation. In addition, under recent conditions of sustained aridity, vertical hydromorphic processes have resulted in the accumulation of low concentrations of ore elements and soluble weathering products, particularly Ca^{2+}, HCO_3^- and SO_4^{2-}, as carbonate and gypsum in the near-surface, independent of the near-surface horizon. This accumulation is low and does not result in supergene mineralisation, but may enhance lateritic mineralisation or anomalies, and is particularly valuable as an exploration aid in truncated and shallowly buried profiles.

Influence of primary rock type

Regional and local geology control the location and type of primary mineralisation. However, mineralisation is generally hosted within quartz veins and/or sulphides and has associated alteration assemblages. Most metals are developed in both primary mineralisation styles. However, the base metal elements and nickel generally only reach economic concentration in sulphide bodies. Precious metals, which are at low concentration in the Earth's crust, can reach economic concentrations in both styles of mineralisation.

With weathering, the profile geochemistry is most strongly affected by the oxidation of sulphides and carbonate minerals. As outlined above, the weathering of sulphides produces acid conditions which enhance metal element mobility. The more concentrated the sulphides, the greater the effect, and in massive sulphide bodies this reaction becomes polarised as an electrochemical system develops (Thornber & Taylor, 1992). In contrast, the weathering of carbonate zones tend to buffer the profile or cause alkaline conditions which inhibit element mobility, with the exception of some ligand complexes under reducing conditions. In these profiles, acid conditions produced at the redox front are neutralised in the upper profile, restricting element mobility. Element dispersion from these systems is, therefore, limited and substantial supergene mineralisation rarely occurs.

Massive sulphide bodies

During weathering, massive sulphide bodies oxidise to a porous ferruginous material, gossan, which extends from surface to the redox front and generally retains the geometrical form of the original sulphide body. The mechanisms by which gossans form from the parent sulphides are given by Thornber & Taylor (1992).

The oxidation of sulphides within a massive sulphide body results in electrochemical

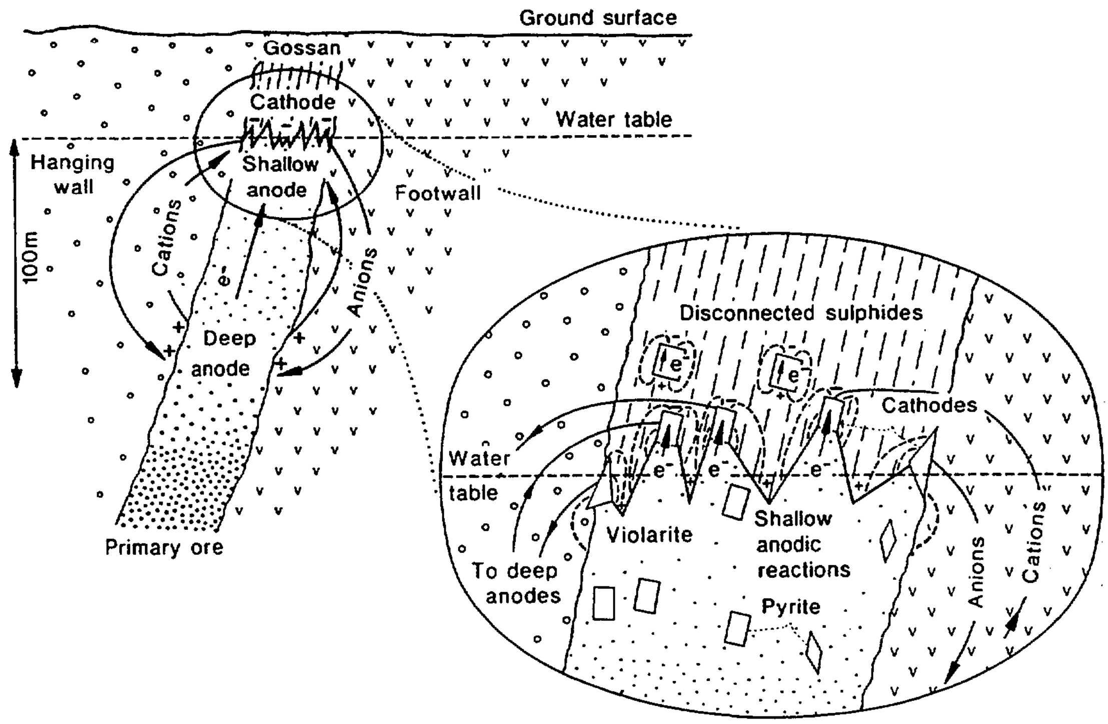

Fig. 2. Cross sectional representation of the deep weathering reactions and the reactions at the watertable for Kambalda-type massive nickel sulphides (from Thornber & Taylor, 1992).

weathering, where the more reactive sulphide behaves as an anode undergoing oxidation while an adjacent more noble sulphide behaves as a cathode undergoing reduction. In most base-metal sulphide ores, pyrite, covellite and chalcocite are more noble and less reactive than pentlandite, violarite, chalcopyrite, sphalerite and galena and, consequently, can remain unaltered higher in the oxidised profiles (Nickel & others, 1974). The oxidation processes at the anode result in acid solutions, and the reduction processes at the cathode result in alkaline solutions. Generally, acid conditions predominate due to subsequent acid-forming reactions, such as the hydrolysis of the metal cations produced at the anode:

$$M^{2+} + 2\,H_2O \Rightarrow M(OH)_2 + 2\,H^+$$

(where M is a divalent base metal)

Metal cations released by the anodic reaction interact with alkaline solutions produced by the cathodic reaction which causes them to precipitate as metal hydroxides. The precipitates develop a fabric that accentuates the solution channels and replicates the morphologies of the minerals being weathered. This results in the box-work fabrics, dominantly goethite and hematite, that are characteristic of gossans. In the near-surface, the gossan becomes indurated on exposure to oxidising conditions and may outcrop as a resistant unit.

Acids produced by the anodic reaction and cation hydrolysis reactions are buffered by alkaline conditions of the cathodic reactions, resulting in further metal hydrolysis. These acid solutions also attack the gangue minerals that are commonly rich in silica which are dissolved and redeposited in the surrounding profile under more alkaline conditions. Hence, this often causes silicification of the ferruginous box-work fabric in solution channels, and silicification of the surrounding rock. In this acid environment, metals may be initially precipitated as complex hydroxides with other anions such as carbonate and sulphate.

The nature of the resultant gossan is strongly controlled by the separation of the anodic and cathodic reactions. In massive Ni-sulphide ores, such as those at Kambalda, (Nickel & others, 1974), the anodic supergene weathering can be 100 m or more beneath the cathodic oxygen reduction at the watertable. Below the anodic front, a zone of supergene sulphides develops above the primary sulphides.

Element mobility is restricted to the host gossan due to adsorption on to iron oxides. This is demonstrated by Travis, Keays & Davison (1976) who showed that a positive correlation between Pd-Ir and nickel in primary sulphides persisted through to the surface gossans, often at enriched levels which are little affected by strong leaching and silicification which deplete most metals to very low levels. However, some element mobilisation may occur, particularly if redox processes have overprinted the profile since gossan formation. Evidence for this is Ni-enrichment in clays in joints and fractures, where nickel concentrations increase upward in the saprolite and may reach 1-2 percent (Elias & others, 1981). However, these enrichments rarely reach economic concentrations.

Disseminated sulphide bodies

In disseminated sulphide deposits, silicates insulate the weathering sulphide and, although electrochemical processes are active within individual grains, acid conditions predominate. A major control on the nature and mineral assemblage of the resulting gossan is the separation of the cathodic, oxygen-consuming, alkali-producing reactions from the anodic, oxidizing, dissolution, acid-producing reactions (Thornber & Taylor, 1992). Within these profiles, normal redox processes tend to control element mobilisation and enrichment.

Summary

The development of acid and alkaline zones, in response to Eh and pH conditions, controlled by climate, topography and rock type, including primary mineralisation type, within the profile, strongly controls the mobility of individual elements. Metal elements are mobilised and precipitated in the profile as a function of their individual chemical behaviour in response to these geochemical environments. Acid conditions enhance element mobility, and are produced at redox fronts and with the weathering of primary sulphide mineralisation. The precipitation of iron oxides is an inherent and unequivocal diagnostic feature of iron redox processes within the profile. Because the redox process produces acid conditions, these ferruginous zones are indicators of past and present zones of low pH.

Elements which form supergene deposits are generally those elements with limited mobility fields, namely the noble metals, such as gold and platinum. The enrichment of gold in the supergene environment is due to its restricted mobility above redox fronts within the profile. The less noble metals have greater stability over a wide range of Eh and pH conditions and are, therefore, widely dispersed in the supergene environment and are, thus, less likely to form supergene deposits.

From an exploration viewpoint, whether dispersed or enriched in particular horizons of the profile, these element concentrations in the supergene environment are easily accessible guides to the underlying source mineralisation.

References

Elias, M., Donaldson M.J. & Giorgetta, N. 1981, Geology, mineralogy and chemistry of lateritic nickel-cobalt deposits near Kalgoorlie, Western Australia, *Economic Geology*, 76, pp 1775-1783.

Lawrance, L.M. 1991, *Distribution of gold and ore-associated elements within lateritic weathering profiles of the Yilgarn Block, Western Australia*, Unpublished Ph.D. Thesis, University of Western Australia.

Nickel, E.H., Ross, J.R. & Thornber, M.R. 1974, The supergene alteration of pyrrhotite- pentlandite ore at Kambalda, Western Australia, *Economic Geology*, 69, pp 93-107.

Thornber, M.R. 1992, The chemical mobility and transport of elements in the weathered environment, in *Regolith Exploration Geochemistry in Tropical and Subtropical Terrains*, eds. C.R.M. Butt & H. Zeegers, Handbook of Exploration Geochemistry, 4, pp 79-96.

Thornber, M.R. & Taylor, G.F. 1992, The mechanisms of sulphide oxidation and gossan formation, in *Regolith Exploration Geochemistry in Tropical and Subtropical Terrains*, eds. C.R.M. Butt & H. Zeegers, Handbook of Exploration Geochemistry, 4, pp 119-137.

Travis, G.A., Keays, R.R. & Davison, R.M. 1976, Palladium and iridium in the evaluation of nickel gossans in Western Australia, *Economic Geology*, 71, pp 1229-1243.

The classification and volcanological setting of komatiite-hosted nickel sulphide deposits

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The nickel exploration boom of the late 1960s and early 1970s led to the discovery of numerous komatiite-hosted nickel sulphide deposits, associated with variably serpentinised bodies of olivine-rich cumulates. Subsequent research has shown the importance of volcanological processes to understanding the genesis of these deposits. Crucial developments have come through consideration of the fluid dynamics of magmas and magma-crystal mixtures, through observation of the dynamics and geometry of modern day basaltic lava flows, through application of theory and experimentation on the kinetics of crystal growth from magmas, and most importantly from extensive detailed field mapping of komatiitic sequences in the Eastern Goldfields and elsewhere. From these studies has emerged a new integrated view of the volcanological setting of komatiite hosted deposits, and a recognition that a complete continuum of deposit types exists. Crucial to this interpretation has been the recognition that the large dunite lenses of the Agnew–Wiluna greenstone belt are integral parts of the extrusive komatiite stratigraphy (Hill & others, 1989, 1990).

Prior to this development, komatiite-hosted nickel sulphide deposits had been divided into two distinct categories: "Intrusive Dunite Associated" and "Volcanic Peridotite Associated" deposits. This classification has since been modified by Hill & Gole (1990) and Lesher (1989) into "Komatiite peridotite-hosted deposits" (Type 1) and "Komatiite dunite-hosted deposits" (Type 2). Lesher (1989) further subdivided this classification into a four-fold division, comprising two lithological groups and two ore distribution types.

Type 1. (Thin flow or peridotite-hosted). A) Stratiform deposits: small (0.5 to 5 million tonnes) high grade (2-4% Ni) deposits of massive, matrix and disseminated sulphides at the base of flow units, typically less than 100 m thick, composed mainly of olivine orthocumulates and mesocumulates. The Kambalda deposits are the type example. B) medium sized (3 to 30 million tonnes) low grade (<1% Ni) deposits of disseminated sulphides within thin (<100 m) orthocumulate-dominated flow units. Type 1B is relatively uncommon.

Type 2. (Dunite-hosted). A) Stratiform small to medium sized deposits of massive, matrix and disseminated sulphides at the base of thick komatiitic units composed mainly of olivine adcumulates, for example the Digger Rocks and New Morning deposits in the Forrestania Greenstone Belt (Porter & McKay, 1981; Perring & others, in prep). B) Large (up to hundreds of millions of tonnes) low grade (<1% Ni) deposits of fine disseminated sulphides within olivine adcumulates, for example Mt. Keith, Six Mile (Yakabindie).

This classification is essentially a matrix of two variables: the geometry and rock type of the host flow unit (Type 1 vs. type 2), and the grade and nature of sulphide mineralisation (A vs. B). While the first variable forms a continuum, the second reflects two distinct mechanisms of sulphide liquid segregation.

Volcanological setting of Type 1 deposits at Kambalda

Nickel mineralisation at Kambalda occurs within the Silver Lake Member, the lower of the two Members of the Kambalda Komatiite Formation. The Silver Lake Member consists of one or more 25 m to 100 m thick high-Mg komatiite flows with thick lower cumulate B-zones and thin upper spinifex A-zones. Lateral variations in internal structure and differentiation of flows, and distribution of interflow sediments and Ni-sulphide bodies, define two time-equivalent volcanic facies. These were originally defined empirically as "Ore Environment" and "Non-Ore Environment" (Gresham & Loftus Hills, 1981) depending on the presence or absence of thick basal Fe-Ni sulphide accumulations, and have since been referred to in genetic terms as "channel" and "sheet flow" facies (see fig. 1 of Hill & others, this volume).

The channel facies is characterised by thick units of up to 100 m of olivine orthocumulates with minor olivine harrisite layers, thin intervening spinifex zones and an absence of interflow sediments (Hill & others, this volume). The thickest flow unit is at the bottom, and typically hosts the major thickness of Fe-Ni sulphides. Up to three subsequent flow units occur above it. Channel Facies units occupy linear belts at least 10 km long but no more than 500 m wide (Cowden & Roberts, 1990). In some cases "Hanging Wall" ore zones occur stratigraphically vertically above the major "Contact Ore" zones and consist of massive sulphide bodies directly overlying spinifex zones of the underlying flow. The basal "Contact Ore" zone at the base of the thick lower flow is usually in direct contact with the footwall Lunnon Basalt. Interflow sediments, which occur along the basalt–komatiite contact in the flanking sheet flow environment, are absent below contact massive ore in all cases except for the Foster and Mount Edwards orebodies (Cowden, 1988). There is some controversy as to whether the Contact Ore and its host komatiite flow occupy primary topographic troughs or channels within the basalt substrate. There is no question that many of the Kambalda ore bodies occupy physical troughs in the footwall surface, but the controversy centres on the extent to which these are artefacts of subsequent low-angle faulting. It is clear that thermal erosion of thin footwall sediment layers has occurred in some if not all cases.

Sheet Facies komatiites occur gradational with and flanking the Channel Facies units. They are thinner (10-20 m) and poorer in cumulus olivine than the laterally equivalent Channel Facies flows, and are well differentiated into A and B zones. Thinner flows correlate laterally over hundreds of metres, and can in some cases be correlated with flow units of the Channel Facies. Thin interflow sediment units are common, but pinch out in the transitional zones between Sheet Flow and Channel environments. The volcanic stratigraphy of central Channel Facies with flanking Sheet Flow facies is now generally accepted as the result of flow of komatiite lava down primary central feeder channels, with episodic overflow to form thin "overbank" sheet flows (Lesher & others, 1984). Precisely the same geometry and process is seen in modern day basaltic lava flows on Hawaii. The open nature of the central channels is recorded by the high proportion of cumulus olivine to spinifex zones. Lava was continuously flushed through the channel, spilling periodically over the side, and leaving behind an olivine-rich residue formed by crystallisation at the temporary channel floor. Flow down the channel occurred beneath a floating quenched skin, which was periodically absorbed into the flowing lava and remelted as observed in modern day basalt flows. During periods of particularly rapid extrusion, komatiite lava overflowed levee banks on either side of the main channel to form thin sheet flows, which differentiated in situ to form typical thin layered flows with well developed spinifex zones.

Volcanological setting of dunite-hosted Type 2B disseminated deposits

Type 2B deposits occur within several of the numerous lenticular dunite deposits within the Agnew–Wiluna greenstone belt. The essential features of the host units are typified by the Perseverance Ultramafic Complex (fig. 1; Barnes & others, 1988a) which hosts type 2B mineralisation immediately overlying a major type 1A deposit hosted by underlying thin flows. The central dunite lens occupies a substantially thickened part of a laterally extensive komatiite unit, most of which consists of sheet-like accumulations of olivine orthocumulate with minor spinifex textured material. The base of the dunite lens occupies a transgressive channel, which cuts down through more than 100 m of underlying felsic volcanic stratigraphy. This feature is interpreted as a thermal erosion channel developed at the base of a major komatiite lava river. Within the dunite lens, olivine compositions become progressively more magnesian upward, indicating that progressively hotter, more primitive lavas were flowing down the channel with time. Prolonged flow of lava and heating of the floor of the channel to the komatiite liquidus temperature, coupled with highly turbulent flow of the extremely fluid lava, resulted in accretion of coarse-grained olivine adcumulates on the floor and wall of the channel. The whole sequence grades up through orthocumulates to a sequence of thin differentiated spinifex-textured flows. These general features are common to all the major dunite lenses of the Agnew–Wiluna belt, including the Mount Keith body which hosts the largest known Type 2B deposit.

The difference between this environment and that seen at Kambalda is essentially one of scale, or more specifically the rate and size of the eruptive event. Dunite channel morphologies are developed during huge cataclysmic eruptions, of comparable scale to major eruptions in continental flood basalt traps provinces in more recent times. The dunite-filled channels represent major central feeder channels filled with turbulent lava rivers, flanked laterally by thinner, slower-flowing, laminar sheet flows giving rise to the extensive bodies of orthocumulate which link the lenses, a situation analogous to a large river breaching its banks and flooding over a wide area. The Kambalda situation represents a substantially smaller rate of eruption and flow, such that episodic overflow occurs from a smaller central flow channel.

Dunite-hosted type 2A deposits

Occurrence of high-grade sulphide-rich accumulations at the base of major dunite lenses is relatively uncommon. The highly turbulent, dynamic environment within these major channels probably results in early-formed sulphide accumulations being re-melted and dispersed in most cases. The Perseverance (formerly Agnew) deposit was previously held to be such a deposit, but has subsequently been re-interpreted as discussed below. However, the Digger Rocks deposit in the Forrestania Greenstone Belt in the Southern Cross Province does belong in this category, although the bulk of the disseminated mineralisation is hosted within olivine orthocumulates forming a basal zone to the dunite body rather than being directly hosted by the olivine adcumulates themselves. Massive sulphides occur immediately below these olivine-sulphide orthocumulates, and may pre-date the major eruptive event from which the overlying cumulate sequence developed. Detailed rock-type relationships indicate that the Digger Rocks deposit formed within a thermal erosion channel. It appears that there may have been multiple eruptive episodes causing erosion and infilling of the channel, and that sulphide accumulation happened during the initial phase of a major eruption which postdated the major episode of thermal erosion, and which eventually led to the channel being filled with olivine cumulates. The processes involved in generating the massive and matrix sulphides at Digger Rocks were essentially the same as those responsible for type 1A deposits such as the Kambalda shoots.

The Perseverance deposit

Detailed pre-deformation geological reconstruction of the Perseverance deposit (Barnes & others, 1988b) (Fig. 2) resulted in revision of the previous interpretation of the Perseverance deposit as being directly hosted by the dunite lens. The bulk of the mineralisation is hosted by a relatively thin (50-70 m) contaminated komatiite flow, underlain by 1-5 m thick weakly mineralised flow units and overlain by further thin (<10 m) flows with basal massive sulphide segregations. Much of this massive

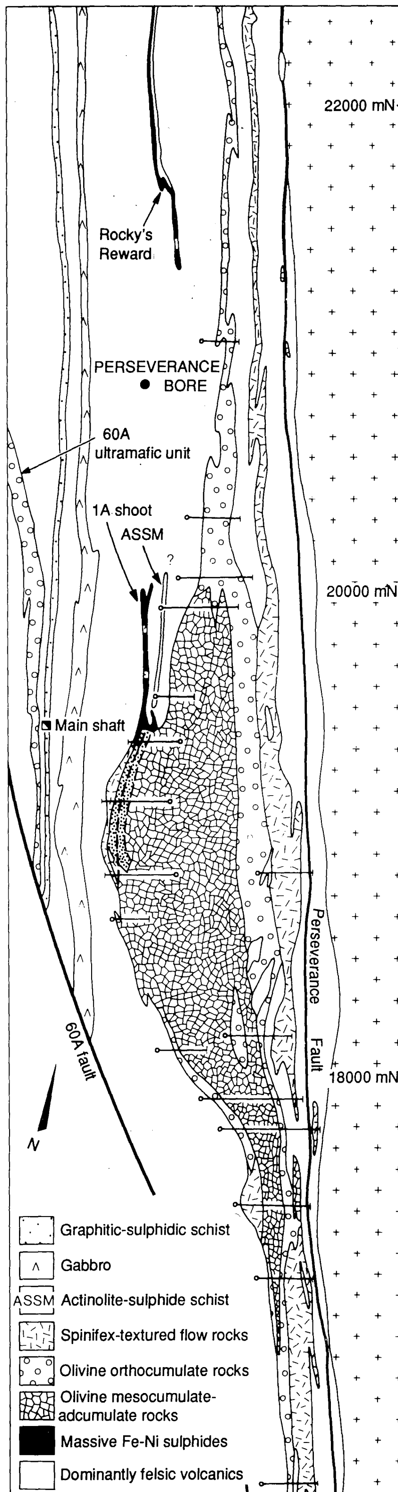

Fig. 1. Geological map of the Perseverance Ultramafic Complex.

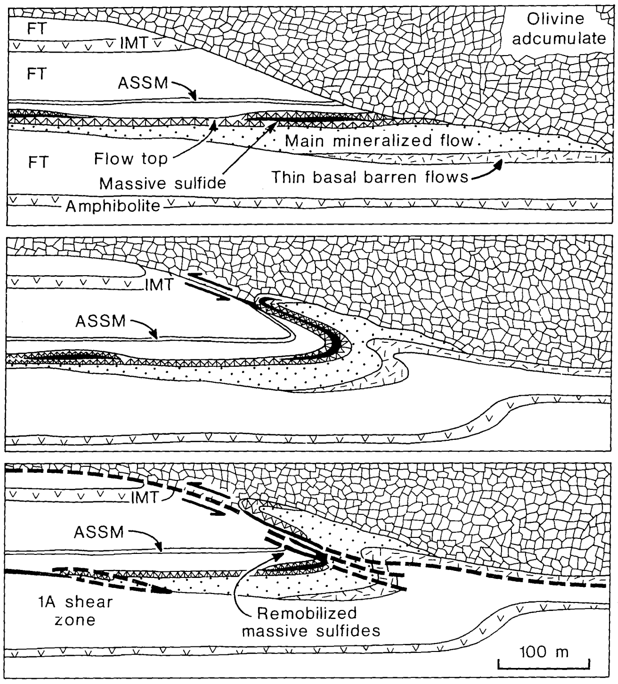

Fig. 2. Geological interpretation and pre-deformation stratigraphic reconstruction of relationships exposed on no. 6 level of the Perseverance nickel mine.

sulphide has been structurally remobilised into shear zones and fold hinges at the margin of the dunite body, while rare primary contacts are indicated by the presence of primary chromite concentrations. The mineralised flow sequence is in part directly overlain by the central dunite lens and in part, to the north of the mine is separated from the base of the lens by over 100 m of intervening felsic volcanic rocks. This relationship is attributed to extensive thermal erosion of low-melting felsic volcanic rocks at the base of the komatiite lava river which formed the dunite lens. Stratigraphic and geochemical evidence suggest that the mineralised flow at Perseverance is correlative with the flow which hosts the Rocky's Reward deposit 2 km to the north. The high grade mineralisation at Perseverance should therefore be classified as a type 1A deposit.

Sulphide segregation mechanisms in disseminated and massive deposits

The basis for the subdivision between types 1A and 1B, and between 2A and 2B, is the proportion of sulphide to silicate (usually olivine or its alteration products) in the orebody in question. In type 1A and 2A deposits this ranges up to 100% sulphide in massive segregations, and the bulk of the tonnage is typically in the form of "matrix ore" ("net-textured ore" in North American terminology), consisting of olivine grains in a continuous network or matrix of sulphide which makes up between 30% and 70% by volume. In contrast, the proportion of sulphide in type 2B deposits is remarkably consistent within and between deposits at a value of around 2% by volume.

The consistency of the proportion of sulphide and the Ni grade in disseminated (types 1B and 2B) deposits is a function of segregation of cotectic proportions of sulphide liquid and olivine from a lava precisely at sulphur saturation (Duke, 1986). A given incremental temperature drop causes crystallisation of certain amount of olivine, an instantaneous slight enrichment of the melt in sulphur and a slight decrease in the solubility of sulphur in the melt. Sulphide liquid therefore exsolves to maintain the lava composition on the sulphur saturation surface, resulting in segregation of a roughly constant ratio of sulphide to olivine. The critical point is that all the sulphur in the deposit was initially dissolved in the parent komatiite melt.

In most of the Kambalda shoots and in other type 1A deposits the mass of sulphide is so high that it is unlikely that all the sulphur in the deposit could have been completely dissolved in the host komatiite. Recent models for genesis of the Kambalda deposits (Huppert & others, 1984; Lesher & others, 1984; Frost & Groves, 1988) involve local partial melting of sulphidic sediments in the immediate substrate to the flow. Lesher & Campbell (1993) suggest that much of the molten sulphide so generated never dissolves in the host flow but rather is carried along beneath it as a dense basal layer, with varying degrees of entrainment into the komatiite lava depending upon the flow regime. This mechanism accounts for the wide variation in sulphide abundance and grade in this type of deposit.

Conclusions

The fourfold classification scheme of Lesher (1989) is based on a matrix of two variables: the scale and effusion rate of the komatiite eruption which hosts the mineralisation, and the relative proportion of sulphide and olivine segregating from the host magma.

The first variable spans a complete continuum, from relatively small overflowing channels to large regional sheet flows fed by turbulent lava rivers. A complete gradation exists between type 1A and type 2A deposits, both of which form by essentially the same mechanisms at the base of lava flow channels. In the case of type 2A deposits, extensive lava rivers develop in the same channel subsequent to the main mineralisation, giving rise to overlying dunitic units. The distinction between type 1 and 2 deposits is one of scale rather than of process.

The second variable reflects distinctly

different segregation mechanisms, depending on whether or not all the sulphur in the deposit was originally dissolved in the host lava. The distinction between type A and B deposits is a genetic one.

Recognition of volcanological environments, particularly major flow channels, and identification of thermally erodable substrate lithologies which could provide the necessary sulphur, are important guides in exploration for komatiite-hosted deposits.

References

Barnes, S. J., Gole, M. J., & Hill, R. E. T. 1988, The Agnew nickel deposit, Western Australia. I. Stratigraphy and structure. *Economic Geology,* 83, pp 524-536.

Barnes, S. J., Hill, R. E. T., & Gole, M. J. 1988, The Perseverance ultramafic complex, Western Australia: product of a komatiite lava river. *Journal of Petrology,* 29, pp 305-331.

Cowden, A. 1988, Emplacement of komatiite lava flows and associated nickel sulphides at Kambalda, Western Australia. *Economic Geology,* 83, pp 436-442.

Cowden, A., & Roberts, D. E. 1990, Komatiite hosted nickel sulphide deposits, Kambalda, in F. E. Hughes ed. *Geology of mineral deposits of Australia and Papua New Guinea.* (Australian Institute of Mining and Metallurgy Monograph 14). Melbourne: Australian Institute of Mining and Metallurgy, pp 557-559

Duke, J. M. 1986, The Dumont nickel deposit: a genetic model for disseminated magmatic sulphide deposits of komatiitic affinity, in M. J. Gallacher, R. A. Ixer, C. R. Neary, & H. M. Prichard, eds. *Metallogeny of Basic and Ultrabasic Rocks.* London: The Institute of Mining and Metallurgy, pp. 151-160.

Frost, K. M., & Groves, D. I. 1989, Ocellar units at Kambalda: evidence for sediment assimilation by komatiite lavas, in M. D. Prendergast, & M. J. Jones, eds. *Magmatic sulphides - the Zimbabwe Volume.* London: Institute of Mining and Metallurgy, pp 207-214.

Gresham, J. J., & Loftus-Hills, G. D. 1981, The geology of the Kambalda nickel field. *Economic Geology,* 76, pp 1373-1416.

Hill, R. E. T., Barnes, S. J., Gole, M. J., & Dowling, S. E. 1990, The physical volcanology of komatiites in the Norseman-Wiluna belt, Western Australia. *Geological Society of Australia, Western Australian Division, Excursion Guide 1.* 100 pp.

Hill, R. E. T., & Gole, M. J. 1990, Nickel sulphide deposits of the Yilgarn Block, in F. E. Hughes ed. *Geology of the Mineral Deposits of Australia and Papua New Guinea.* (Australian Institute of Mining and Metallurgy Monograph 14). Melbourne: Australian Institute of Mining and Metallurgy, pp 557-559.

Hill, R. E. T., Gole, M. J., & Barnes, S. J. 1988, Olivine adcumulates in the Norseman-Wiluna greenstone belt Western Australia: implications for the volcanology of komatiites, in M. D. Prendergast, & M. J. Jones, eds. *Magmatic sulphides - the Zimbabwe Volume.* London: Institute of Mining and Metallurgy, pp 189-206.

Huppert, H. E., Sparks, R. S. J., Turner, J. S., & Arndt, N. T. 1984, Emplacement and cooling of komatiitic lavas. *Nature,* 309, 19-22.

Lesher, C. M. 1989, Komatiite-associated nickel sulfide deposits, in J. A. Whitney, & A. J. Naldrett, eds. *Ore Deposition Associated with Magmas.* (Reviews in Economic Geology 4). El Paso: Economic Geology Publishing Company, pp 44-101.

Lesher, C. M., Arndt, N. T., & Groves, D. I. 1984, Genesis of komatiite-associated nickel sulphide deposits at Kambalda Western Australia: a distal volcanic model, in D. L. Buchanan, & M. J. Jones, eds. *Sulphide deposits in mafic and ultramafic rocks.* London: Institute of Mining and Metallurgy, pp 70-80.

Lesher, C. M., & Campbell, I. H. 1993, Geochemical and fluid dynamic modelling of compositional variations in Archean komatiite-hosted nickel sulfide ores in Western Australia. *Economic Geology,* in press,

Porter, D. J., & McKay, K. G. 1981, The nickel sulphide mineralization and metamorphic setting of the Forrestania area, Western Australia. *Economic Geology,* 76, pp 1524-1549.

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A critical evaluation of the thermal erosion model for Archaean and Proterozoic komatiite-associated Fe-Ni-Cu sulphide deposits

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Our understanding of the genesis of Archaean and Proterozoic komatiite-associated Fe-Ni-Cu sulphide deposits has changed significantly over the past 10 years, reflecting a better understanding of the physical volcanology of komatiites and their influence on ore genesis. There is a growing consensus that the host rocks of these deposits represent dynamic lava channels, that the lavas in the channels thermally-eroded their floor rocks, that the sulphur in the deposits was derived from floor rocks upstream from the present site of the ore deposits, and that the geochemistry and textures of the ores were controlled by the composition of the hybridized lava and the fluid dynamics during emplacement. The objective of this paper is to summarize the evidence that Archaean and Proterozoic komatiite-associated Fe-Ni-Cu sulphide deposits formed by thermal erosion of sulphur-rich floor rocks and to identify the most fundamental elements of the model as they relate to mineral exploration in Archaean, Proterozoic, and Phanerozoic terrains.

Host units

The geologic settings of komatiitic-associated Fe-Ni-Cu sulphide deposits have been reviewed by Lesher (1989), and the type-examples at Kambalda have been described by Gresham & Loftus-Hills (1981) and Cowden & Roberts (1990). Within a given district, the ore deposits may be associated with *komatiites* (for example Kambalda, Perseverance) or *komatiitic basalts* (for example Katinniq), but are hosted exclusively by thick *komatiitic peridotites* or *komatiitic dunites* that occur at or near the base of the komatiite sequences. Deposits hosted by intrusions associated with Proterozoic and Phanerozoic picrites and flood basalts (for example Duluth, Noril'sk-Talnakh, Pechenga) are not considered to be of this type, but probably represent intrusive analogs. Although the host units of these deposits have been interpreted previously as sills, phenocryst-enriched lava flows, and lava ponds, all grade laterally into less magnesian komatiitic peridotites, komatiites, or komatiitic basalts, most exhibit olivine habits and matrix textures indicative of rapid crystallisation, many exhibit rhythmic variations in olivine textures and cryptic variations in olivine compositions indicating crystallisation *in situ*, and some exhibit flow top breccias. As such, all of the host units, including the komatiitic dunites, are now considered to be integral parts of the host komatiite sequences and are interpreted as a *lava channels* or *lava tubes* in which olivine fractionally accumulated during lava flow and crystallisation (Lesher & others, 1984; Donaldson & others, 1986; Cowden, 1988; Barnes & others, 1988; Lesher, 1989; Cowden & Roberts, 1990; Lesher & others, 1991).

Lava channelisation

The relationship between the lava channel facies and the adjacent flows appears to vary depending on the physical properties of the lava and the fluid dynamics of the system. For example, the host units at Kambalda are derived from a high-Mg komatiitic magma (ca. 30% MgO), comprise one or more reactivated lava channels characterized by mesocumulate and crescumulate textures, and grade laterally into a contemporaneous flanking *sheet flow facies* characterized by less magnesian komatiitic peridotites with orthocumulate and crescumulate textures (Lesher & others, 1984; Cowden & Roberts, 1990). In contrast, the host units at Katinniq are derived from a low-Mg komatiitic magma (ca. 20% MgO), form multiple overlapping lava channels characterized by mesocumulate and orthocumulate textures, and grade laterally into komatiitic basalts and sediment-basalt breccias representing a contemporaneous *levee/overbank facies* (Gillies & Lesher, 1992). The breccias contain fragments of hornfelsed sediment, implying that sediments were deposited onto lava tubes, hornfelsed, sloughed off, and redeposited with overbank basalt flows.

Thermal erosion

Komatiites are interpreted to have had very high liquidus temperatures (up to 1650°C) and very low viscosities (down to 1 g cm^{-1} sec^{-1}), to have flowed turbulently during at least the initial stages of emplacement, and to have been capable of thermally-eroding floor rocks (Huppert & others, 1984; Lesher & others, 1984). This is important for two reasons:

- most deposits of this type are localized in footwall embayments which may have been modified or generated by thermal erosion, and
- most deposits are associated with sulphidic footwall rocks which may be thermally-eroded and incorporated into the lava.

There is a wide variety of direct (field, petrographic) and indirect (stratigraphic, geochemical, and isotopic) evidence for partial melting and thermal erosion of floor rocks by komatiites. There is direct evidence of partial melting of komatiites at Kambalda (Groves & others, 1986) and Honeymoon Well (Gole & others, 1990), direct evidence of melting of basalts at Kambalda (Evans & others, 1989), indirect evidence of melting of cherty sulphidic sediments at Kambalda (Lesher & others, 1984; Frost & Groves, 1989) and Windarra (Lesher, 1989), indirect evidence of melting of felsic volcaniclastic rocks at Perseverance (Barnes & others, 1989), direct evidence of melting of pelitic sediments and gabbros at Katinniq (Dufresne & Lesher, 1991), and direct evidence of melting of felsic volcanics at Munro-Manville (Davis & Lesher, in prep.). Thermal erosion appears to have occurred only beneath lava channels and appears to have been influenced by the thermal properties of the substrate and the size and thermal/fluid dynamic properties of the channel, all of which varied from area to area.

Hybridization

Geochemical and Nd isotopic data relevant to identifying contamination by thermal erosion of floor rocks are only available at Kambalda (Lesher & Arndt, 1990; Arndt & Lesher, 1992), Perseverance (Barnes & Lesher, in prep.), and Katinniq (Lesher, unpubl. data). All three areas contain komatiites with normal, Al-undepleted, LREE-depleted geochemical signatures, which are interpreted to represent uncontaminated parental magmas derived from a depleted mantle source. All three areas also contain komatiites with LREE-enriched geochemical signatures, which are interpreted to represent lavas contaminated by granitic crust and/or sediments (Kambalda and Katinniq) or granitic crust and/or felsic volcanics (Perseverance). The degree of contamination and the locations of the uncontaminated and contaminated lavas within the volcanic facies systems differ in the three areas, reflecting differences in their physical volcanological development.

Note that contamination alone does not appear to be enough to induce sulphide saturation under normal circumstances. Although the solubility of sulphur in a sulphide-undersaturated magma decreases with decreasing T, aFeO, and fS_2, and increasing aSiO$_2$ and fO_2 (see review by Naldrett, 1989), all of which are expected consequences of crustal contamination, komatiitic basalts derived by up to 25% crustal contamination of komatiites (for example Arndt & Jenner, 1986; Compston & others, 1986) do not contain any magmatic sulphide deposits. The amount of sulphide produced was too small and/or the sulphides were too dense to be erupted (see discussion by Lesher & Groves, 1986). The most effective mechanism of generating a magmatic sulphide deposit is to thermally-erode a sulphur-bearing wall or floor rock.

Chalcophile element depletion

Most komatiites at Kambalda, including unmineralized units high in the sequence, are depleted in Ni and Co relative to komatiites in unmineralized areas (Lesher & others, 1981). However, the komatiites do not appear to be depleted in PGE, which have even higher sulphide/silicate melt partition coefficients (for example Peach & others, 1989), and relict olivines in the host units are not depleted in Ni or PGE (Keays, 1982; Lesher, 1989). The olivines have crystallized from replenished lavas (Lesher & Arndt, 1990; Arndt & Lesher, 1992) and indicate, despite previous conclusions to the contrary, that the *parental* magmas did not equilibrate with sulphides prior to eruption. Systematic analysis of whole-rock samples and corresponding olivine separates for Ni, Co, and PGE from a variety of least-altered mineralized and unmineralized komatiites are required to resolve this conflict.

Zn-rich chromites

Chromites in mineralized komatiite sequences in Western Australia are enriched in Zn relative to chromites in mineralized komatiitic dunites in Western Australia and unmineralized komatiite sequences (Groves & others, 1977; Lesher & Groves, 1984). This was originally interpreted to reflect differences in the sulphide saturation state of the magmas, but is probably better interpreted to reflect contamination by Zn-rich sediments (for example Lesher, 1989; Cowden & Roberts, 1990). Mineralized komatiites associated with Zn-poor sulphidic sediments (for example Katinniq, some parts of the Abitibi belt) contain Zn-poor chromites (Gillies, Davis, unpubl. data).

Sulphur isotopes and S/Se ratios

The $\delta^{34}S$ values of ores and footwall rocks at individual deposits vary from deposit to deposit within a range of -8‰ to +6‰ (see summary by Lesher, 1989; Lesher & Ripley, 1992). These values are systematically different from primitive mantle values (0 ± 1‰) and isotopic fractionation should have been negligible at such high temperatures. The similarity of $\delta^{34}S$ values of ores and country rocks at individual deposits and the differences between deposits are consistent with derivation of S by melting/assimilation of the country rocks, presumably upstream from the site of mineralisation. It might be argued that the similarity of S isotopic values for the ores and footwall rocks may simply reflect a common source; i.e. that the S in the sediments may have been derived from volcanic exhalations accompanying the volcanism, but in that case the variations in S isotopes would reflect isotopic heterogeneities in the mantle, produced for example by subduction of oceanic crust. There is no evidence that the Al-undepleted, LREE-depleted, +ve ε_{Nd} komatiites which host most of these deposits were derived from such a source. Fractionation of S isotopes in the seafloor environment and melting of sedimentary sulphides by komatiites is the best interpretation for the systematic variations in the S isotopic data. S/Se ratios have also been used to distinguish between magmatic and crustal S sources, but like any other element with a high sulphide/silicate melt partition coefficient (ca. 1770: Peach & others, 1989), the amount of Se in the sulphide melt will be influenced by the relative masses of silicate and sulphide in the system (R factor).

Ore tenor variations

Numerical modelling of Western Australian and Cape Smith deposits (Lesher & Campbell, in press; Gillies, Coutts, Barnes & Lesher, in prep.) indicates that the observed ranges of ore compositions within each region can be accounted for primarily by variations in the effective sulphide:silicate ratio (R); low tenor ores represent equilibration at lower R and high tenor ores represent equilibration at higher R. Modelled R factors for Cape Smith deposits (300-1100) are higher than those for Western Australian deposits (100-500), consistent with the greater abundance of net-textured and disseminated sulphides in the former area. The ranges of calculated R values are relatively low, suggesting that low tenor sulphides were not entrained into the komatiite lava, but remained as a segregated layer at the base of the flow, and that high tenor sulphides were not transported long distances in suspension, but settled rapidly to the base of the flow. Magma compositions vary only slightly from the inferred parental komatiites and komatiitic basalts, respectively; low tenor ores appear to have equilibrated with only slightly more evolved (contaminated and fractionated) lavas.

Sulphide saturation state of the host magmas and timing of mineralisation

Many shoots at Kambalda contain stratiform mineralisation that rests directly on the footwall contact, without any intervening basal chilled margin, and the overlying host units are essentially barren of sulphides. These sulphides must have been present as a segregated layer during emplacement, but the overlying lava could not have equilibrated with the sulphides; once saturated, the lava should have continued to exsolve sulphides during cooling and crystallisation. This is independent evidence that the host units at Kambalda were replenished during lava emplacement and crystallisation. Other deposits such as Alexo and Katinniq contain stratiform mineralisation that overlies a basal chilled margin and the overlying host unit contains ubiquitous fine disseminated sulphides. These sulphides were deposited after initial emplacement of the host unit but before crystallisation of the overlying host rocks, and the host lavas remained saturated in sulphide during cooling and crystallisation. Still other deposits (for example Mt. Keith, Dumont) contain primarily strata-bound disseminated mineralisation. These sulphides formed relatively late in the crystallisation history of the host rock.

Lesher & Campbell (in press) have pointed out that stratiform sulphide ores will not necessarily be in equilibrium with overlying komatiites, but will record equilibration with variably contaminated lavas during the initial stages of emplacement and crystallisation. The solubility of sulphur in komatiite is relatively low, so most of the sulphide in eroded sediments will be melted and remain as a dense layer at the base of the flow or be incorporated into the turbulently flowing komatiite as immiscible sulphide droplets. The size of immiscible droplets and the interface between two immiscible layers are affected by inertial forces during turbulent flow. Turbulence causes coalescence of small droplets and breakup of large droplets, leading to an equilibrium droplet size. If the average size of the droplets is small and/or the discharge rate is high, they may be carried in suspension in the flowing komatiite; droplets have a large surface area to volume ratio and will be effective in scavenging chalcophile elements as they are carried by the turbulent motion of the flowing komatiite. If the average size of the droplets is large or if the discharge rate is low, they will settle and collect at the base of the komatiite; komatiite and sulphide liquids may continue to flow, but the sulphide layer will have a low surface area to volume ratio and will be ineffective in extracting chalcophile elements from the overlying komatiite layer. Thus, it is during the initial stages of emplacement, when sulphides are initially melted and are most likely to be in suspension (if at all), that controls the effective R factor and therefore the tenor of the sulphide ores.

Discussion

There is strong albeit indirect stratigraphic evidence that the host units of komatiite-associated Fe-Ni-Cu sulphide deposits are dynamic lava channels. There are sound theoretical arguments that komatiites should have flowed turbulently, at least during the initial stages of eruption, and there is unequivocal field evidence that these channels thermally-eroded floor rocks during emplacement (and indirect but equally convincing evidence that they thermally-eroded crustal rocks during ascent). Lava channels provide a relatively continuous (although not unlimited) source of heat and metals. The geochemical and isotopic compositions of the sulphide ores are consistent with derivation of sulphur from floor rocks and equilibration with restricted volumes of the komatiitic lava. It is not possible to completely rule out derivation of sulphides directly from the mantle, but this seems unlikely and unnecessary.

The type of deposit formed appears to depend on the fluid dynamics, the relative volumes of lava and assimilant, the sulphur content of the assimilant, and the sulphide saturation state of the lava. The silicate components of the floor rocks appear to have been dissolved and diluted by lava replenishment, and only rarely preserved as xenomelts. The sulphur melted from floor rocks may i) dissolve completely in the lava, ii) dissolve partially and induce sulphide saturation in a sulphide-undersaturated lava, or iii) melt and remain as an immiscible sulphide liquid. Thus, large lava channels may assimilate considerable amounts of sulphur without achieving sulphide saturation, resulting in sulphide saturation at a late stage in the crystallisation of the host rock, forming disseminated sulphides. Small lava channels may assimilate little sulphur, melting sulphides which accumulate as a separate sulphide layer at the base of the flow. The compositions of the ores depend on the composition of the hybridized lava, the sulphide/silicate melt partition coefficients under the prevailing T, fO_2, and fS_2, and the degree of equilibration between the sulphide and silicate melts (R factor).

Magma channelisation and thermal erosion are not, in principle, restricted to lava channels; similar processes may occur in magma conduits or sills that feed lavas. All known deposits of this type are restricted to the Archaean and Proterozoic, however, deposits hosted by intrusions associated with Proterozoic and Phanerozoic picrites and flood basalts (for example Duluth, Noril'sk-Talnakh, Pechenga) may represent intrusive analogs. The predominantly extrusive nature of Archaean deposits and the predominantly intrusive nature of Phanerozoic deposits probably reflects a fundamental change in the maximum MgO content, and therefore temperature and viscosity, of mantle-derived melts (for example Campbell & Griffiths, 1992) and therefore their ability to penetrate the crust (for example Lister & others, 1991).

Summary

A general thermal erosion model for magmatic sulphide deposits involves the juxtaposition in time and space of:

- a komatiitic (or picritic) magma to provide heat and metals (Ni, Cu, PGE),
- a suitable magmatic or volcanic plumbing system to facilitate thermal erosion of wall or floor rocks, and
- a sulphur-rich wall rock to incorporate and form sulphides that extract and concentrate the metals from the silicate magma.

Although komatiites occur primarily in the Archaean, high magnesium magmas occur through geologic time and represent potential host rocks. Exploration should focus on cumulate rocks (peridotites, pyroxenites, and gabbros) that may represent magma conduits/lava channels associated with voluminous mafic-ultramafic volcanism (komatiites, picrites, and flood basalts), in areas where they occur with sulphidic country rocks (magmatic, hydrothermal, or sedimentary).

References

Arndt, N.T. & Jenner, G.A. 1986, Crustally contaminated komatiites and basalts from Kambalda, Western Australia, *Chemical Geology*, 56, pp 229-255.

Arndt, N.T. & Lesher, C.M. 1992, Fractionation of REEs by olivine and the origin of Kambalda komatiites, Western Australia, *Geochimica et Cosmochimica Acta*, 56, pp 4191-4204.

Barnes, Stephen J., Hill, R.E.T. & Gole, M.J. 1988, The Perseverance ultramafic complex, Western Australia: The product of a komatiite lava river, *Journal of Petrology*, 29, pp 305-331.

Campbell, I.H. & Griffiths, R.W. 1992, The changing nature of mantle hotspots through time: Implications for the chemical evolution of the mantle, *Journal of Geology*, 92, pp 497-523.

Compston, W., Williams, I.S., Campbell, I.H. & Gresham, J.J. 1986, Zircon xenocrysts from the Kambalda volcanics: age constraints and direct evidence for older continental crust below the Kambalda-Norseman greenstones, *Earth and Planetary Science Letters*, 76, pp 299-312.

Cowden, A. & Roberts, D.E. 1990, Komatiite-hosted nickel sulphide deposits, Kambalda, in *Geology of the Mineral Deposits of Australia and Papua New Guinea*, ed. F.E. Hughes, Australasian Institute of Mining and Metallurgy Melbourne, pp 567-581.

Cowden, A. 1988, Emplacement of komatiite lava flows and associated nickel sulfides at Kambalda, Western Australia, *Economic Geology*, 83, pp 436-442.

Donaldson, M.J., Lesher, C.M., Groves, D.I. & Gresham, J.J. 1986, A comparison between Archaean dunites and komatiites associated with nickel mineralisation in Western Australia, *Mineralium Deposita*, 21, pp 296-305.

Dufresne, M.W. & Lesher, C.M. 1991, Localization of komatiite-associated nickel sulfide mineralisation at the Katinniq deposit, Cape Smith Belt, New Québec. Geological Association of Canada - *Mineralogical Association of Canada Annual Meeting, Program with Abstracts*, p 32.

Evans, D. M., Cowden, A. & Barratt, R. M. 1988, Deformation and thermal erosion at the Foster nickel deposit, Kambalda-St. Ives, Western Australia, in *Magmatic Sulphides - the Zimbabwe Volume*, eds. M.D. Prendergast & M.J. Jones, Institution of Mining and Metallurgy London, pp

Frost, K.M. & Groves, D.I. 1989. Ocellar units at Kambalda: Evidence for sediment assimilation by komatiite lavas, in *Magmatic Sulphides - the Zimbabwe Volume*, eds. M.D. Prendergast & M.J. Jones, Institution of Mining and Metallurgy London, pp 207-214.

Gillies, S.L. & Lesher, C.M. 1992, Lava channelisation in the Katinniq Peridotite Complex, Cape Smith belt, New Quebec, *Geological Society of America Annual Meeting, Abstracts with Programs*, 24(7), p A267.

Gole, M.J., Barnes, S.J. & Hill, R.E.T. 1990, Partial melting and recrystallisation of Archaean komatiites by residual heat from rapidly accumulated flows, *Contributions to Mineralogy and Petrology*, 105, pp 704-714.

Gresham, J. J. & Loftus-Hills, G. D. 1981, The geology of the Kambalda nickel field, Western Australia, *Economic Geology*, 76, pp 1373-1416.

Groves, D. I., Barrett, F. M., Binns, R. A. & McQueen, K. G. 1977, Spinel phases associated with metamorphosed volcanic-type iron-nickel sulfide ores from Western Australia, *Economic Geology*, 72, pp 1224-1244.

Groves, D. I., Korkiakoski, E. A., McNaughton, N. J., Lesher, C. M. & Cowden, A. 1986, Thermal erosion by komatiites at Kambalda and genesis of nickel ores, *Nature*, 319, pp 136-139.

Huppert, H.E., Sparks, R.S.J., Turner, J.S. & Arndt, N.T. 1984, Emplacement and cooling of komatiite lavas, *Nature*, 309, pp 19-22.

Keays, R. R. 1982, Palladium and iridium in komatiites and associated rocks: Application to petrogenetic problems, in *Komatiites*, eds. N. T. Arndt & E. G. Nisbet, Allen and Unwin London, pp 435-457.

Lesher, C. M. 1989, Komatiite-associated nickel sulphide deposits, in, *Ore deposition associated with magmas*, eds. J.A. Whitney & A.J. Naldrett, Reviews in Economic Geology 4, pp 45-101.

Lesher, C.M. & Arndt, N.T. 1990, Geochemistry of komatiites at Kambalda, Western Australia: Assimilation, fractional crystallisation, and replenishment, *Third International Archaean Symposium, Extended Abstracts Volume*, Perth, pp 149-151.

Lesher, C.M. & Campbell, I.H., in press, Geochemical and fluid dynamic modelling of compositional variations in Archean komatiite-hosted nickel sulfide ores in Western Australia. *Economic Geology*, 88(4).

Lesher, C.M. & Groves, D.I. 1984, Geochemical and mineralogical criteria for the identification of mineralized komatiites in Archaean greenstone belts of Australia, in *Petrology: Igneous and Metamorphic Rocks*, Proceedings of the 27th International Geological Congress, Volume 9. VNU Science Press Utrecht, pp 283-302.

Lesher, C.M. & Groves, D.I. 1986, Controls on the formation of komatiite-associated nickel-copper sulphide deposits, in *Geology and Metallogeny of Copper Deposits*, in eds. G. Friedrich, A.D. Genkin, A.J. Naldrett, J.D. Ridge, R.H. Sillitoe & F.M. Vokes, Springer-Verlag Heidelberg, pp 43-62.

Lesher, C.M. & Ripley, E.M. 1992, Stable isotope geochemistry of Proterozoic komatiitic peridotite-associated Fe-Ni-Cu sulfide deposits, Raglan block, Cape Smith belt, New Quebec. *Geological Society of America Annual Meeting, Abstracts with Programs*, 24(7), p A62.

Lesher, C.M., Arndt, N.T. & Groves, D.I. 1984, Genesis of komatiite-associated nickel sulphide deposits at Kambalda, Western Australia: A distal volcanic model, in *Sulphide Deposits in Mafic and Ultramafic Rocks*, eds. D.L. Buchanan & M.J. Jones, Institution of Mining and Metallurgy London, pp 70-80.

Lesher, C.M., Lee, R.F., Groves, D.I., Bickle, M.J. & Donaldson, M.J. 1981, Geochemistry of komatiites from Kambalda, Western Australia: Chalcophile element depletion - a consequence of sulphide liquid separation from komatiitic magmas, *Economic Geology*, 76, pp 1714-1728.

Lesher, C.M., Thacker, J.L., Thibert, F., Tremblay, C. & Dufresne, M.W. 1991, Physical volcanology of Proterozoic komatiitic peridotites in the Chukotat Group, Cape Smith Belt, New Québec. Geological Association of Canada - *Mineralogical Association of Canada Annual Meeting, Program with Abstracts*, p 74.

Lister, J.R., Campbell, I.H. & Kerr, R.C. 1991, The eruption of komatiites and picrites in preference to primitive basalts, *Earth and Planetary Science Letters*, 105, pp 343-352.

Naldrett, A.J. 1989, Sulfide melts: crystallisation temperatures, solubilities in silicate melts, and Fe, Ni, and Cu partitioning between basaltic magmas and olivine. in, *Ore deposition associated with magmas*, eds. J.A. Whitney & A.J. Naldrett, Reviews in Economic Geology 4, pp 5-20.

Peach, C.L., Mathez, E.A. & Keays, R.R. 1989, Sulfide melt-silicate melt distribution coefficients for noble metals and other chalcophile elements as deduced from MORB: Implications for partial melting in the mantle, *Geochimica et Cosmochimica Acta, 54, pp 3379-3389.*

The Mount Keith ultramafic complex and the Mount Keith nickel deposit

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The Mt. Keith region occupies the most attenuated part of the Agnew–Wiluna greenstone belt, in the north-western extremity of the Norseman–Wiluna greenstone belt. The region is structurally complex with a pronounced NNW trending linearity and vertical to steep dips to the west. The stratigraphic succession at Mt. Keith has been placed within the Upper Greenstones Sequence by Naldrett & Turner (1977) and can be correlated with the Yakabindie Sequence to the south.

The komatiites are of the Al-undepleted variety, and occur within an Archaean layered succession of tholeiitic basalts, layered gabbros, high-Mg basalts, felsic to intermediate volcaniclastic and clastic sediments, acid volcanics, with minor carbonaceous shales and cherts. The boundaries of the greenstone belt are defined by the Eastern and Western Granites. An east-facing sequence of arkosic arenites and boulder conglomerates, the Jones Creek Conglomerate, lies unconformably on the margins of the Western Granite, and defines the Perseverance Fault. The eastern margin of the belt consists of a sequence of felsic volcaniclastic sediments, basalts, and folded, banded-quartz-magnetite rocks which has been extensively invaded by granite. The Keith–Kilkenny Lineament is expressed as a wide zone of shearing along the eastern margin.

The ultramafic rocks have been metamorphosed in the presence of H_2O and CO_2 bearing fluids to mid-upper greenschist facies. Igneous olivine, pyroxene, amphibole and chromite are occasionally preserved. Typical assemblages consist of tremolite, actinolite, chlorite, antigorite, lizardite, brucite, pyroaurite, talc, magnesite, dolomite, stichtite and magnetite. Primary igneous textures in the ultramafic rocks are usually well pseudomorphed and vary from adcumulate through mesocumulate, orthocumulate and harrisite to spinifex types. In zones of shearing and fluid access extreme talc-carbonate-chlorite alteration has resulted in a massive or schistose fabric.

Distribution of komatiite units

Three major separate komatiite units, the Eastern, Central and Western Ultramafic Units, have been mapped in the stratigraphy between Kingston and Betheno (Fig. 1; see also fig. 2 of Hill & others, this volume). They vary in thickness and continuity along strike and they face and dip steeply towards the west. In places they are structurally juxtaposed. The existence of complex regional faulting and folding is recognised and the potential for some equivalence of the various komatiite units is understood; however the present geological data base supports the interpretation that the Eastern Ultramafic, which contains the Mt. Keith Ultramafic Complex (MKUC), is the oldest of the three units.

The Mt. Keith Ultramafic Complex

The Eastern Ultramafic Unit (Fig. 2) is dominated by olivine orthocumulates, but is characterised by lenticular bodies of olivine adcumulate-mesocumulate with gradational contacts with laterally equivalent sequences of olivine orthocumulate and spinifex-textured flows. Low-grade disseminated nickel-sulfide mineralisation occurs in layered olivine adcumulates-mesocumulates occupying several of these zones of thickening. The MKUC hosts the MKD5 Mt. Keith disseminated nickel-sulfide deposit (270 Mt of 0.6 wt% Ni), and is the most significant zone of thickening in the Eastern Ultramafic Unit.

The MKUC (Fig. 3, 4) consists of a basal zone of olivine orthocumulate overlain by a thick zone of unmineralised coarse-grained olivine adcumulate and a thick zone of layered, mineralised olivine mesocumulate which forms the MKD5 ore body. This sequence grades laterally and vertically into an upper zone of predominantly olivine orthocumulate, but which is characterised by fractionated sequences which contain branching olivine harrisite, layered olivine-pyroxene cumulates, pyroxene cumulates, gabbros and plagioclase cumulates. Primary kaersutitic amphibole is present as oikocrysts

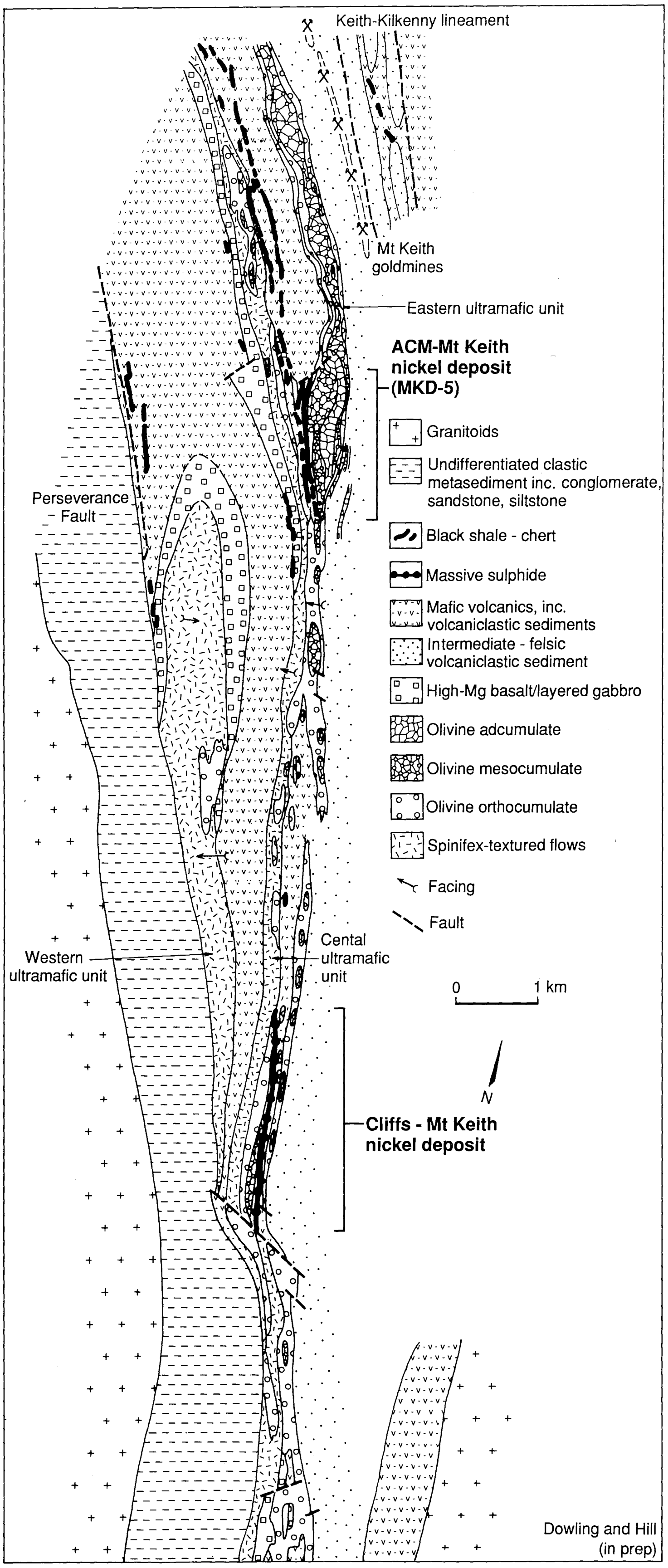

Fig. 1. Geological map of the Mt. Keith area, showing distribution of the Eastern, Central and Western Ultramafic units, and the Mt. Keith MKD5 and Cliff–Mt. Keith nickel deposits.

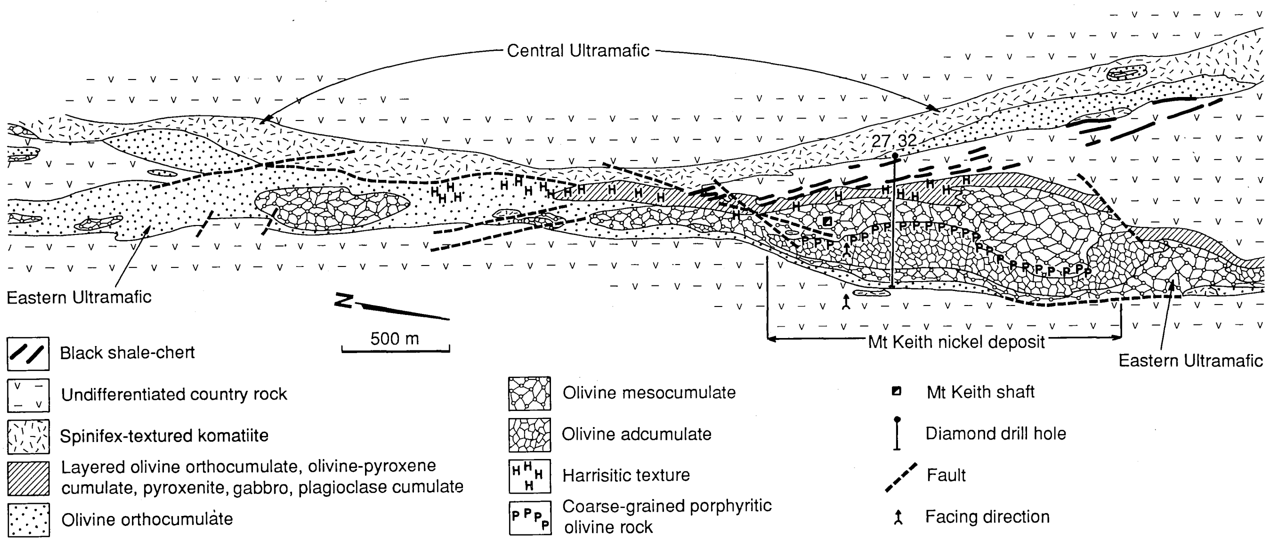

Fig. 2. Detailed geological map of the Eastern and Central Ultramafic Units in the are of the Mt. Keith MKD5.

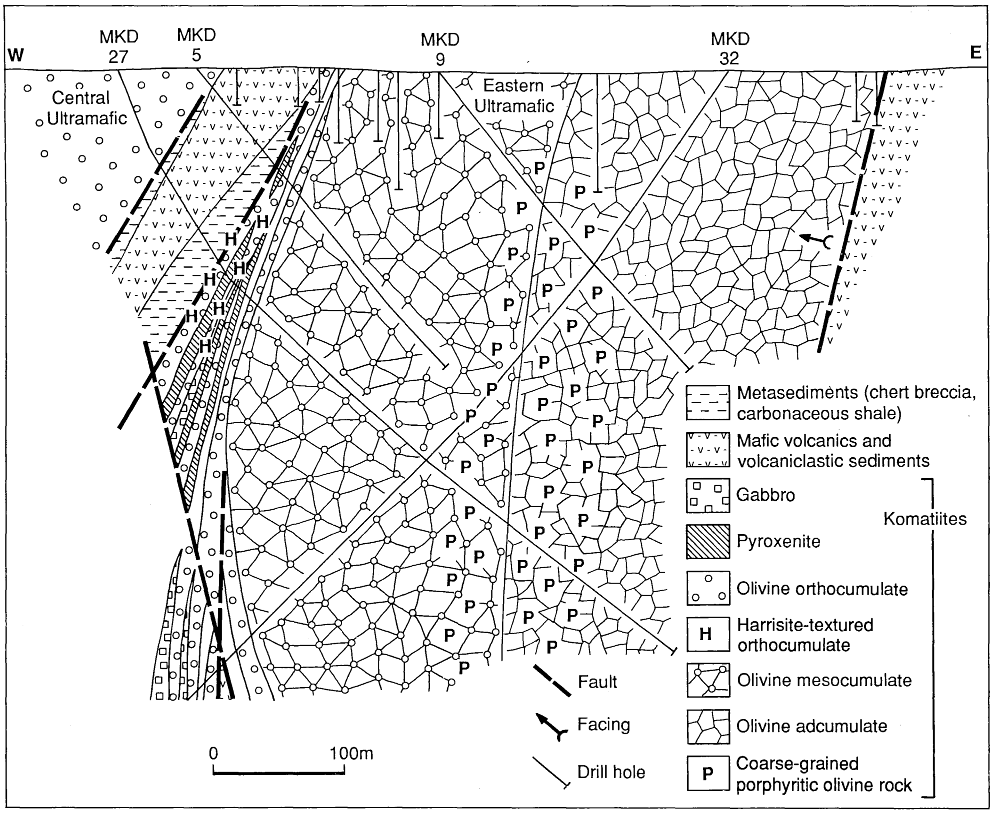

Fig. 3. Geological cross section through the Mt. Keith MKD5 orebody.

in the olivine orthocumulate in this upper zone. Zones of olivine-sulfide orthocumulate are variably developed within this upper zone. Coarse-grained mesocratic hornblende-plagioclase rocks and metasomatically altered (rodingitised) gabbro/dolerite dykelets transgress the ultramafic stratigraphy. Anastomosing zones of talc-carbonate alteration are prevalent in the central portion of the mesocumulate, and the margins of the MKUC exhibit extreme hydrothermal alteration.

Mineralisation

The mineralisation within the MKD5 nickel-sulfide deposit is disseminated and characteristically layered. It is generally confined to the olivine mesocumulate, although minor thin mineralised layers are present in the olivine adcumulate. The distribution of nickel tenor within the MKUC on a vertical section through MKD 27, 32 is portrayed in Fig. 4. The nickel content of the mineralised olivine mesocumulate is generally within the range 0.5-

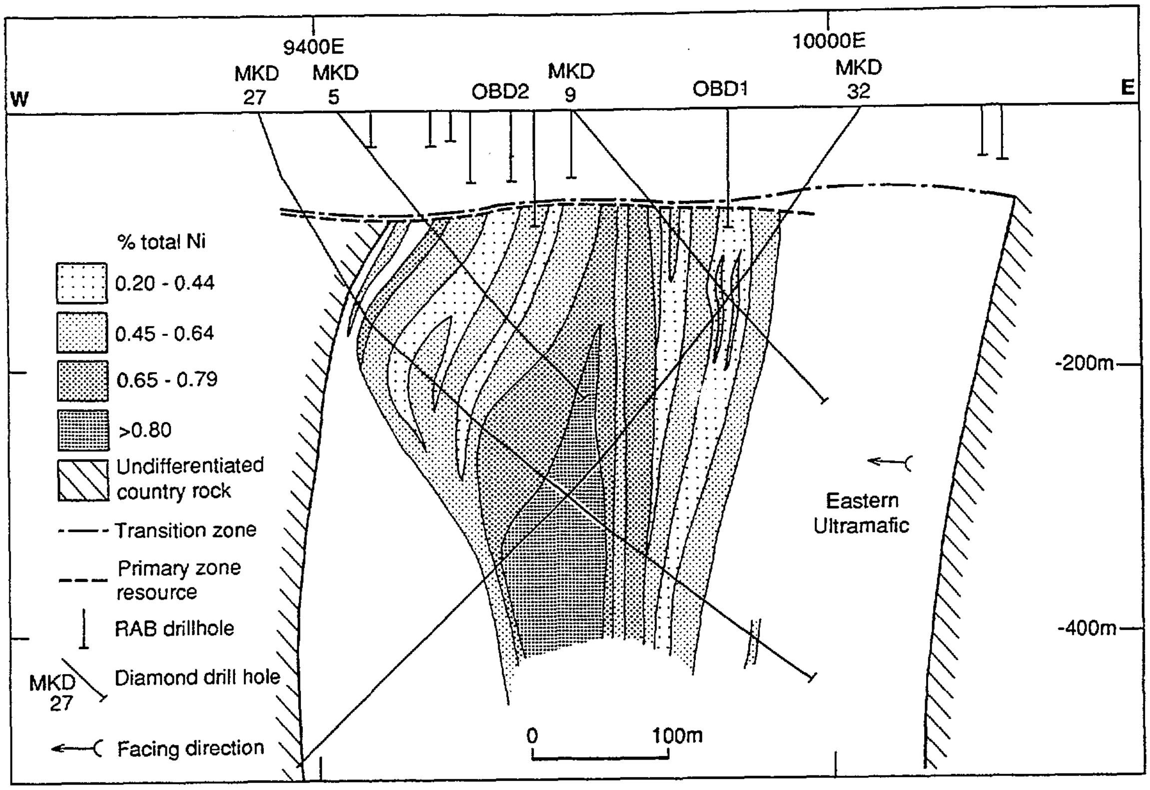

Fig. 4. Cross section through the MKD5 orebody, corresponding to that shown in Fig. 3, showing the distribution of nickel grade.

1.0%, and is characterised by a Ni/S ratio of 1.02 and a high Ni/Cu ratio of 52 (Keays & Davidson, 1976).

The present sulfide mineralogy of the MKD5 deposit is the result of primary magmatic, secondary hydrothermal and weathering processes. Pentlandite is the dominant sulfide with subordinate pyrrhotite, millerite and heazlewoodite, minor chalcopyrite, violarite and gersdorffite. Supergene violarite, pyrite and marcasite replacing pentlandite and pyrrhotite are common in the upper zone of oxidation, and throughout the deposit in zones which have permitted high fluid access during weathering.

The sulphides occur as medium to coarse-grained lobate patches interstitial to olivine pseudomorphs, as very fine-grained dust (515 μm) disseminated throughout olivine pseudomorphs, as fine-grained (50 μm) aggregates concentrated in intracrystal partings, intercrystal margins and cross-cutting veinlets, and as fine-grained disseminated crystals intergrown with carbonate, usually in marginal talc-carbonate altered rocks. In most of the mineralised rocks, intergranular lobate patches are rimmed, veined and replaced by magnetite. Some are intergrown with carbonate and antigorite laths.

The olivine-sulfide cumulates are believed to have formed by the cotectic accumulation of olivine and sulfide liquid of mono-sulfide-solid-solution (MSS) composition from sulfur-saturated komatiite liquid. The original sulfide would have been similar in composition and mineralogy to most magmatic massive ores, solidifying and exsolving the assemblages of varying proportions of pyrrhotite, pentlandite, pyrite and chalcopyrite. The disseminated low modal distribution of the sulfide, and its association with a preponderance of olivine have been responsible for significant chemical and mineralogical reconstitution. Sub-solidus re-equilibration of olivine and subordinate sulfide during initial cooling, has involved nickel enrichment of the sulfide. Subsequent redistribution of nickel from olivine to sulfide has accompanied the process of serpentinisation during metamorphism.

Platinum group metal distribution

Preliminary whole-rock PGM analyses for twenty samples of diamond drill core from MKD 27 and 32 have been obtained by ICPMS. There is a consistent positive correlation between platinum and palladium which suggests a relatively constant sulfide composition during the crystallisation of the olivine-sulfide mesocumulate. The Ni/Pd ratios of olivine-sulfide mesocumulates fall on the mixing curve of Keays & others (1981) which indicates that these rocks are physical mixtures of olivine and nickel sulfide of constant composition. Pt/Pt+Pd ratios upwards throughout the mineralised zone are cyclic, but fall within a very restricted range. This constancy in ratio is indicative of precipitation from a continuously replenished supply of sulfur saturated lava, such as envisaged from flow-channel dynamics.

Interpretation of the MKUC

The nature and distribution of lithologies, igneous textures and the whole-rock major and trace element patterns are indicative of the MKUC having formed as part of an infilled large flow channel during a period of voluminous continuous eruption and flow of komatiite lava.

Textural variation in the olivine adcumulate-mesocumulate reflects variations in the extent of supercooling at the crystal-liquid interface as a result of fluctuations in flow rate. Variations in chromite and sulfide abundance and olivine compositions have arisen from changes in the composition of the flowing lava—which are products of the fractionation of the parent komatiite magmas either en route to the surface from the mantle or as it flowed over the surface. The formation of lobate chromite in olivine adcumulates-mesocumulates is thought to be the result of simultaneous crystallisation of chromite and olivine at high temperatures.

Harrisitic textured orthocumulates are believed to have formed by directional cooling through the top of the lava flow. An episodic flow rate and local damming of the flow due to solidification of lava downstream would produce small lava lakes which would undergo in-situ fractionation resulting in differentiated sequences of cyclically layered olivine, pyroxene and plagioclase cumulates.

References

Keays, R. R., and Davidson, R. M. 1976, Palladium, iridium and gold in the ores and host rocks of nickel sulphide deposits in Western Australia. *Economic Geology*, 71, pp 214-228.

Keays, R. R., Ross, J. R., and Woolrich, P. 1981, Precious metals in volcanic peridotite-associated nickel sulfide deposits in Western Australia, II. Distribution within ores and host rocks at Kambalda. *Economic Geology*, 76, pp 1645-1674.

Naldrett, A. J., and Turner, A. R. 1977, The geology and petrogenesis of a greenstone belt and related nickel sulfide mineralisation at Yakabindie, Western Australia. *Precambrian Research*, 3, pp 43-103.

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Nickel sulphide deposits of the Kambalda Dome—a 3-dimensional perspective

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The Kambalda dome, located approximately 60 kilometres south of Kalgoorlie, lies within the south-central portion of the NNW-trending Archaean Norseman–Wiluna Greenstone Belt (Gee & others, 1981). Nickel sulphides were discovered on the Kambalda dome in January 1966, following drill testing down-dip of surface gossans in the Red Hill area. The first hole KD1, intersected 2.75 metres @ 8.30% Ni, heralding the discovery of Lunnon Shoot. Production of nickel concentrates commenced shortly afterwards in mid-1967 and increased dramatically to 30,000 tonnes of contained Ni by 1970/71 following the discovery of other shoots around the Kambalda dome. To January 1992, the pre-mined geological ore reserve for the Kambalda dome deposits was 33.3 Mt @ 3.2% Ni for 1.08 Mt Ni metal.

The Kambalda nickel deposits occur at the base of the Kambalda Komatiite and predominantly on the contact with the underlying tholeiitic Lunnon Basalt. The Kambalda Komatiite varies between 250 metres and 1000 metres thick and is divided into the Lower Silver Lake Member hosting the nickel sulphides and the less magnesium-rich upper Tripod Hill Member (Gresham & Loftus Hills, 1981; Archibald, 1985). A high magnesium basalt, the Devon Consols Basalt, overlies the Komatiite and in turn, is overlain by a regionally persistent sedimentary marker horizon, the Kapai Slate. Dating of zircons from the Kapai Slate have yielded an age of 2692 ± 2Ma (Claoué-Long & others, 1988). Conformably overlying the Kapai Slate is a suite of evolved mafic and ultramafic rocks that constitute the Paringa Basalt. It is likely the Devon Consols Basalt and the Paringa Basalt are of komatiitic parentage. These rocks are conformably overlain by a suite of felsic volcanic and turbidite facies sedimentary rocks of the Black Flag Group (Cowden & Archibald ms). The youngest rocks in the Kambalda dome area are a sequence of high-energy clastic sedimentary rocks of the Merougil Sandstones which unconformably overlie the Black Flag Group.

Precise dating utilising the established stratigraphic framework of the Kambalda dome stratigraphy indicates accumulation of the volcano-sedimentary successions occurred within a 47 Ma time period between 2709 Ma and 2662 Ma (Claoué-Long & others, 1988; Claoué-Long, 1990)

The Kambalda area has undergone polyphase deformation with up to four major deformation events recognised (Gresham & Loftus-Hills, 1981; Archibald, 1990; 1985). The deformation is dominated by two events of thrusting (D_1 and D_2). According to Archibald (1990), the D_2 deformation formed dislocated reclined to recumbent folds and thrust ramps which stack stratigraphy, with southern blocks of older stratigraphy being ramped over northern blocks of younger rocks. The third phase of deformation (D_3), is characterised by open upright, shallow to steep, commonly doubly plunging folds, as typified by the Kambalda dome, which have a variably developed axial surface foliation. The D_4 deformation is represented by NNW-oriented normal and reverse faults and associated splays. Major suites of felsic porphyry and felsic to intermediate lamprophyre dykes were emplaced along the thrust surfaces or along D_4 faults. Talc-carbonate alteration overprinted serpentisation and is predominantly controlled by syn-post D_2.

Regional metamorphism was synchronous with thrusting and the subsequent D_3 upright folding. It reached upper greenschist facies (500°C; 200MPa–300MPa). A contact metamorphic aureole surrounding the Durkin Granodiorite which cored the Kambalda dome, overprints a low-amphibolite facies on the regional metamorphism (Wong, 1986).

The nickel sulphide deposits occur predominantly at the base of the basal komatiite flow of the Silver Lake Member with subordinate occurrences located at the base of succeeding flows. Considerable controversy exists regarding the genesis of the ore-confining features ('troughs') located at the footwall basalt-ultramafic interface. Various theories include a primary palaeo-topography of the basaltic sea floor (Lesher, 1989); thermally eroded channels created by hot turbulently flowing komatiites (Huppert & others, 1984) and growth faults contemporaneous with komatiitic volcanism (Ross & Hopkins, 1975; Gresham & Loftus-Hills, 1981). All mechanisms potentially allow for the channelisation of subsequent Komatiite flows. Other authors (Cowden & Archibald 1991) have highlighted the strongly deformed nature of the nickel sulphide ores and have pointed out that some of the terminations to troughs observable in underground workings, appear to result from fold-thrust couples produced during the D_2 deformation.

During the period 1991-93, a re-evaluation of the Kambalda dome was completed, specifically aimed at better understanding the nature of the footwall basalt/ultramafic contact. This involved interrogating the entire Kambalda dome drillhole database using specifically written software. The data were loaded into three-dimensional modelling package (VULCAN, AVS and EXPLORER) as a means of visually portraying in three dimensions, a large amount of data from a geometrically complex environment. To contrast, structures on a mine scale were visualised from the well-documented Lunnon Shoot (Gresham & Loftus Hills, 1981; Middleton, 1980). Some seventy-one, 1:500 scale digitised mine cross sections were modelled using the three-dimensional interactive graphics packages.

The contrast between the gross geometry of the Kambalda dome and the more detailed complexities in a mine environment provides some significant insights into the nature of troughs controlling the localisation of nickel sulphide mineralisation. The three dimensional images of the Kambalda dome highlight a number of significant features. These include the long linear nature of mineralised flows (in excess of 5 kms at Lunnon Shoot; 9 kms from Fisher to Fletcher to Beta Shoot), and ore-bearing flows (channel-flow facies of Cowden & Roberts, 1990) that appear to anastomose and merge with one and other, as seen at Fisher and Fletcher. The images from Lunnon Shoot highlight the more local structural overprint on the ore-confining troughs. The geometry and size of individual ore surfaces within a shoot clearly shows the finer scale complexities associated with Kambalda nickel ore bodies. It is apparent from these comparisons that trough development has resulted from a combination of primary topographical features and overprinting structural effects.

References

Archibald, N.J. 1985, The stratigraphy and tectonic-metamorphic history of the Kambalda-Tramways area. Unpub. internal WMC Report, 66pp

Archibald, N.J. 1990, Tectonic - metamorphic history of the Lake Lefroy area: Implications for greenstone belt evolution in the Kambalda-Norseman region, Western Australia, in, *Third International Archean Symposium, Perth, 1990* eds J.E. Glover and S.E. Ho. Extended Abstracts Volume, Geoconferences (W.A.) inc., pp 457 - 458

Claoué-Long, J.C., Compton, W., & Cowden, A. 1988, The age of the Kambalda greenstones resolved by ion-microprobe: Implications for Archaean dating methods, *Earth Planetary Science Letters*, 89 (2): 239-259

Claoué-Long, J.C. 1990, High resolution timing constraints on the evolution of the Kalgoorlie-Kambalda mineral belt, in, *Third International Archaean Symposium, Perth, 1990*, eds J.E. Glover and S.E Ho, Extended Abstracts Volume, Geoconferences (W.A.) Inc., pp 355 - 357

Cowden, A., & Archibald, N.J. 1991, Massive sulphide fabrics at Kambalda - sensitive records of deformation history in *Structural Geology in Mining and Exploration*, Extended Abstracts Volume, University of Western Australia, Publication No. 25, 99 - 102

Cowden, A., & Roberts, D.E. 1990, Komatiite hosted nickel sulphide deposits, Kambalda, in *Geology of the Mineral Deposits of Australia and Papua New Guinea*, ed F.E. Hughes, The Australasian Institute of Mining and Metallurgy: Melbourne, pp 567 - 581

Cowden, A., & Archibald, N.J., Manuscript. Stratigraphy of the Kambalda-Kalgoorlie Archaean greenstone terrain

Gee, R.D., Baxter, J.L., Wilde, S.A., & Williams, I.R. 1981, Crustal development in the Archaean Yilgarn Block, Western Australia, in *Archaean Geology*, Second International Symposium, Perth 1980, eds J.E. Glover and D.I. Groves, Geological Society of Australia. special Publication, 7/43 - 56

Gresham, J.J., & Loftus-Hills, G.D., 1981. The geology of the Kambalda nickel field, *Economic Geology*, 76:1373-1416

Huppert, H.E., Sparks, R.S.J., Turner, J.S., & Arndt, N.T. 1984, Emplacement and cooling of Komatiite lavas, *Nature*, 309: 19-22

Lesher, C.M. 1989, Komatiite associated nickel sulphide deposits, in, *Reviews in Economic Geology*, 4, 45 - 101

Middleton, C.N. 1980, Lunnon Shoot. Unpub. internal WMC report, 41 pp

Ross, J.R., & Hopkins, G.M.F. 1975, Kambalda nickel sulphide deposits, *Economic Geology of Australia and Papua New Guinea*, Volume 1, Metals, ed C.L. Knights, The Australasian Institute of Mining and Metallurgy : Melbourne, pp 100 -121

Wong, T. 1986, Metamorphic patterns in the Kambalda area and their significance to Archaean greenstone belts of the Kambalda-Widgiemooltha area. Unpub. BSc (Hons) thesis, University of Western Australia, 153 pp

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Volcanogenic base metal sulphides on the modern sea floor: implications for future exploration in the Eastern Goldfields Province of Western Australia

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Despite considerable exploration in the past, the Eastern Goldfields Province (EGP) of Western Australia has an unimpressive inventory of volcanic-exhalative base metal deposits when compared to broadly equivalent greenstone-granite terrain in the Abitibi Province of Canada. Occurrences of volcanogenic massive sulphide (VMS) ore bodies such as Murrin and Teutonic Bore indicate that appropriate genetic processes operated at least locally in the EGP. Whether they were sufficiently widespread to justify mounting further exploration, and whether in places they were developed on a sufficiently large scale to create sizeable resources, are burning questions of the moment. The poor discovery record in Western Australia may relate more to problems caused by deep weathering and transported overburden than to any fundamental differences in tectonic style or rock assemblage between the EGP and the Abitibi Province. Alteration commonly associated with VMS mineralisation is one reason to expect that the more prospective ground for such deposits might lie concealed in poorly exposed sectors of the EGP where they are less detectable by conventional technology.

From selecting tenements to evaluating the results of drilling, future base metal exploration under such difficult conditions must benefit from any increase in the confidence level with which geologists can assess the limited amount of stratigraphic, volcanological, structural and lithogeochemical data that will be available, either directly from samples or indirectly from interpreting the output of increasingly sensitive or novel geophysical and geochemical survey techniques. This increased confidence will rely on careful documentation and iterative research at ancient VMS sites and also at their modern analogues where metamorphism and deformation pose no problems to genetic evaluations.

Studies of ore-forming environments on the modern sea floor that might be considered closely analogous with Archaean VMS settings are in a state of distinct infancy. Controversies surrounding plate-tectonic reconstructions of EGP greenstone sequences further confuse the issue. Accepting that EGP greenstones formed on a sialic basement and that most Archaean VMS deposits are associated with relatively siliceous volcanic rocks, the essential requirements of a modern analogue on purely "look alike" grounds are, firstly, a continental crust or continental margin setting, and secondly a predominance of submarine felsic volcanism. Exploration of present-day sea floor with these characteristics commenced less than a decade ago.

The closest modern analogue on this simplistic basis is the PACMANUS deposit, discovered in 1991 at the far eastern end of the Manus back-arc basin between the islands of New Britain and New Ireland, Papua New Guinea (Binns & Scott, 1993). Massive sulphide chimneys and mounds, rich in copper and associated with low-temperature Fe-Mn-Si oxide deposits, here extend discontinuously for 3 km along the crest of a ridge formed by dacite lava domes with subordinate andesite and rhyolite. The largest sulphide deposit is some 200 m across. Intense alteration of dacite hyaloclastite occurs below the oxide deposits, but fractured lavas underlying the sulphide deposits are relatively unaffected. Focussed discharge of high-temperature hydrothermal fluids, governed by cross-faulting parallel to regional transform structures, evidently controls the location of "ore". The dacite ridge lies within an *en-echelon* series of neovolcanic edifices, predominantly of basaltic andesite and dacite, which are coeval with arc volcanics related to active subduction along the New Britain Trench to the south but which are built upon a basement of

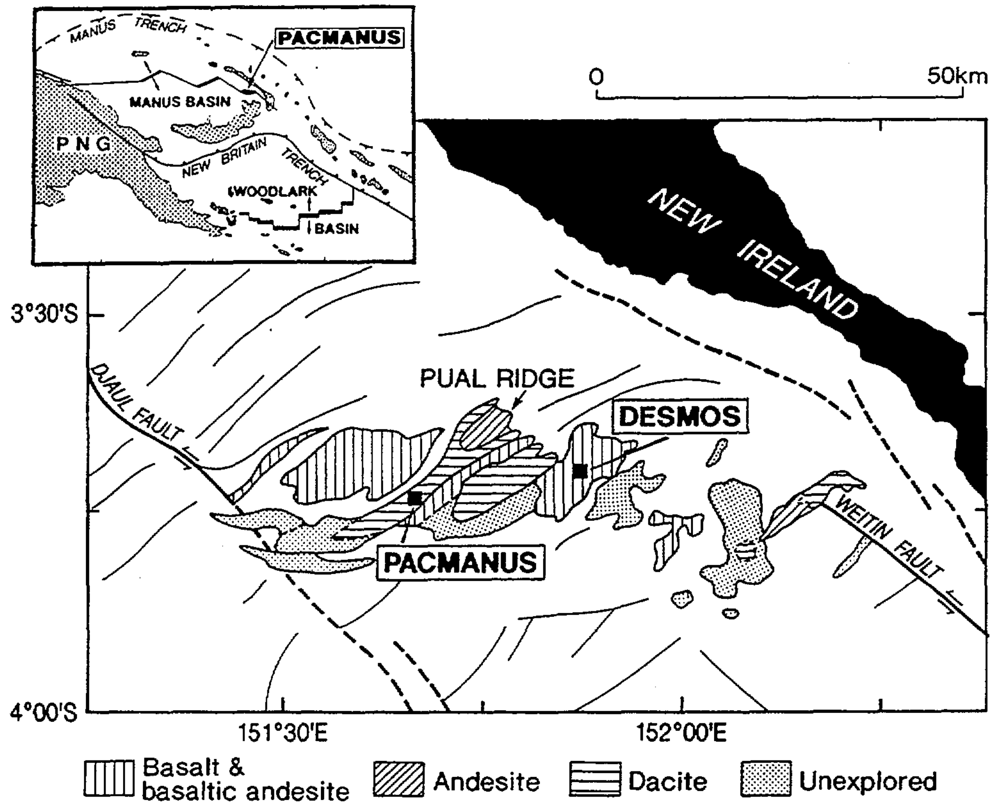

Fig. 1. Seafloor geology and neovolcanic edifices of the eastern Manus Basin, based on dredge results and interpretation of bathymetric, sidescan sonar and seismic data. Thin lines denote extensional fault scarps within thickly sedimented deeps, which expose a basement of older arc crust equivalent to outcrops on New Britain and formed by earlier subduction along the inactive Manus Trench. Heavy dashed lines denote (early?) faults parallel to the Djaul and Weitin Faults, members of an oblique transform set in the Manus back-arc basin behind the active New Britain arc (inset shows the regional tectonic setting). The PACMANUS hydrothermal field occurs near the bathymetric culmination of dacitic Y-shaped Pual Ridge. DESMOS is a site of low-temperature hydrothermal activity in a basaltic andesite caldera.

basalts and volcaniclastic sediments formed during earlier subduction on the Manus Trench to the north (Fig. 1). The neovolcanic edifices are aligned normal to the direction of back-arc extension that thins the island arc crust, and are thought to lie above subjacent intrusions. With further evolution, they will probably develop into a zone of back-arc sea-floor spreading. Rapid sedimentation including large components of debris from the modern arc is burying the deposit even as it forms. A future cross-section through the vicinity of the PACMANUS deposit would greatly resemble geological maps of some Archaean VMS deposits, for example the Millenbach deposit at Noranda which lies on the flank of a domal construction of rhyolitic lavas in a milieu of andesite and basalt (Knuckey & others, 1982).

The Jade Deposit (Halbach & others, 1989) in the Okinawa Trough, a back-arc rift with bimodal basalt-rhyolite volcanism in extended continental crust lying behind the Ryuku arc-trench system between Japan and Taiwan, is another example of active sulphide formation associated with felsic volcanics regarded as a close analogue of Kuroko-type VMS ores and their Archaean equivalents. Hydrothermal venting occurs at intervals along a 900 m long fissure on the sloping wall of a sedimented 5 km-diameter caldera in rhyolitic volcanics. The deposits have variable Cu and are rich in Zn and, unusually, Pb. Some chimneys have grown above unconsolidated sediments at least 10-20 m thick. Altered rhyolite with stockwork Zn-Pb-Cu mineralisation has been dredged, and a 10-15 cm layer of probable mass-wasted sulphides is buried about 80 cm below the sediment surface.

Most other hydrothermal deposits known in back-arc basins (including the more mature, western part of the Manus Basin; Both & others, 1986; Tufar, 1990) are associated with basaltic seafloor spreading ridges, and have characteristics generally similar to mid-ocean ridge deposits (Rona, 1988) whose tectonic relevance to Archaean greenstone settings is more dubious. An exception is the Valu Fa Ridge at the southern end of the Lau Basin spreading axis near Tonga, which is propagating into and separating the remnant Lau Ridge arc and the active Tofua volcanic arc (Fouquet & others, 1991).

Vesicular basaltic andesites, andesites and dacites (with a preponderance of breccia and hyaloclastic deposits) are overlain by extensive massive sulphide deposits and low-temperature Mn oxide crusts, the former containing significant Ba, As and Au as well as Zn, Cu and Pb. Normal faulting appears to control the mineralisation sites, and has exposed sections through the deposits including underlying stockworks and alteration zones. Barite-silica chimneys in this setting are similar to those associated with extensive low-temperature Fe-Mn-Si oxide deposits on a basaltic andesite seamount at the tip of the Woodlark spreading zone southeast of Papua New Guinea (Fig. 1), where it is propagating directly into continental crust in what is not strictly a back-arc environment but rather a consequence of microplate rotation (Binns & others, 1993). The latter are exceptionally rich in Au and Ag but have no known massive sulphide associates: they suggest a possible mafic volcanic-ironstone-barite-gold target for land-based exploration of Archaean greenstones.

While detailed descriptions and genetic interpretations of the above occurrences and others yet to be discovered will help interpret their metamophosed Archaean equivalents, particularly at the advanced stages of exploration, and while they provide tantalising hints as to the importance of substrate lithologies in governing metal contents and ratios, it is less clear at this early stage whether they suggest new concepts regarding selection of prospective ground in the EGP. Rather than concentrate on presumed analogues of Archaean tectonic settings, it is perhaps more useful for the present to consider generalised genetic models emerging from studies of all modern seafloor hydrothermal deposits, including those which might not have Archaean equivalents.

The essential elements of these models are volcanic activity as a heat engine to drive circulating fluids (seawater in particular, but possibly including a magmatic component) that leach metals from the heated crustal rocks they traverse, extensional tectonism to fracture the substrate and facilitate circulation of those fluids, and precipitation of metals when the hydrothermal fluids remix with cold seawater at or near the sea floor at depths where pressure precludes boiling or phase separation as a major depositional process. Since the first discovery of "black smokers" in 1979, modern hydrothermal deposits (though not necessarily massive sulphides) have now been found in a wide range of tectono-magmatic environments satisfying these requirements: mid-ocean spreading axes, back-arc spreading ridges with both oceanic and continental substrates, on- and off-axis seamounts, "hot-spot" seamounts, and rifted continental margins. About the only significant potential settings for VMS formation (as assessed from ancient deposits) missing from the list are submarine volcanic arcs and intra-arc rifts, where high sedimentation rates discourage conventional sea-floor exploration.

The common feature of these occurrences is their location at centres of intense igneous activity, generally reflected by positioning at local or regional bathymetric high points within which, however, there may be a secondary structural control such as an axial valley or collapse caldera. Much previous land-based VMS exploration focussed on troughs or palaeo-topographic lows, guided by models derived from the Red Sea brine pool setting (Degens & Ross, 1969), but this is now recognised as an exceptional situation requiring an evaporite-bearing substrate (unlikely in greenstone belts). The recent sea-floor research instead opens up a wide range of formerly high-standing targets which may have been neglected.

A second important deduction from the modern sea-floor data is that, certainly insofar as Zn and Cu are concerned, the distinction between mafic and felsic volcanism is not important to the chemical requirements of VMS ore formation according to models invoking seawater as the main source of hydrothermal fluids. If appropriate extensional settings and eruptive centres can be identified within the plethora of basaltic and even komatiitic volcanism in greenstone belts, the amount of prospective ground for base metal massive sulphide deposits within the EGP becomes greatly expanded and concentration on felsic sequences may be unwise. In this context, inter-flow sulphidic metasediments in komatiite sequences (Bavinton, 1981) warrant renewed attention. The volcanological setting must be such as to suggest the presence or former presence of subvolcanic intrusions that were the essentially contemporary heat engine. A caveat here is that if igneous fluids are more important than seawater for deriving and transporting metals, then the preference among known ancient VMS deposits for felsic hosts becomes explicable as a consequence of fractional crystallisation in magmas (Stanton, 1990). This vital question will soon be tested when manned or robot submersibles sample actual vent fluids at sites like PACMANUS and isotopic investigations of their sources are conducted.

Conditions favourable to efficient exhalative precipitation of sulphides and to their subsequent preservation are other requirements for the accumulation of viable VMS ore deposits which relate basically to submarine vulcanology. Blanketing by sedimentary or volcaniclastic rocks before redissolution of the ores by submarine "weathering" appears the common way of satisfying the second -the process by which most submarine volcanoes grow probably precludes sufficiently rapid covering by later lava flows. Although spectacular in the modern environment, the construction of "chimneys" at hydrothermal-exhalative sites is a most inefficient process of sulphide deposition since most of the precipitate is dispersed as "smoke" into the seawater column (Scott, 1992). Development of mounds at advanced stages of venting allows more efficient precipitation both by cavity filling and replacive growth under sustained high temperatures within a protective envelope.

A significant result of the few successful attempts so far made to sample vent fluids at active low-temperature sites suggests that their "hydrothermal end member" chemistries are basically similar to those of high-temperature sulphide-depositing "black smokers" in terms of metal contents, but that reduced sulphur is lacking (Binns & others, 1993; see also Fouquet & others, 1991). These low-temperature vents tend to overlie porous flow breccias and hyaloclastite banks, and the implication is that subsurface mixing with cold seawater has allowed very efficient precipitation of sulphides deeper within the volcanic pile. Various physical and chemical processes that would focus such "sub-exhalative" deposition at a particular level are conceivable. Many ancient VMS deposits hosted by volcaniclastic rocks may have formed in this way, which would explain a tendency for their "exhalative" cherts and ironstones to occur as stratigraphically higher horizons rather than as lateral fringes to massive sulphide bodies, and any developments of hanging wall alteration.

Although attempts to compile a set of guidelines would be premature at present, the data (much as yet unpublished) arising from careful studies of modern VMS environments include many hints for interpreting exploration tenements, assessing their prospectivity, and predicting potential ore sites. The challenge facing industry geologists during the next phase of exploring poorly exposed areas of the EGP for base metals will be to apply these hints under conditions where samples are few in number and where the evidence must be detected through a veil of metamorphic and deformational phenomena, so that more confident placement of the necessary deep drill holes becomes possible. The major challenge for marine geologists, as indicated above, will be to find and survey appropriate analogue sites where the vent fluids associated with mineralisation hosted by felsic volcanic rocks can be sampled for laboratory examination.

References

Bavinton, O.V. 1981, The nature of sulfidic metasediments at Kambalda and their broad relationships with associated ultramafic rocks and nickel ores, *Economic Geology*, 76, pp. 1606-1628.

Binns, R.A. & Scott, S.D. 1993, Actively-forming polymetallic sulphide deposits associated with felsic volcanic rocks in the eastern Manus back-arc basin, Papua New Guinea, *Economic Geology Special Issue* "Seafloor Hydrothermal Mineralization: New Developments" (in press).

Binns, R.A., Scott, S.D., Bogdanov, Yu.A., Lisitzin, A.P., Gordeev, V.V., Gurvitch, E.G., Finlayson, E.J., Boyd, T., Dotter, L.E., Wheller, G.E., & Muravyev, K.G. 1993, Hydrothermal oxide and gold-rich sulfate deposits of Franklin Seamount, western Woodlark Basin, Papua New Guinea, *Economic Geology Special Issue* "Seafloor Hydrothermal Mineralization: New Developments" (in press).

Both, R., Crook, K., Taylor, B., Brogan, S., Chappell, B., Frankel, E., Liu, L., Sinton, J., & Tiffin, D. 1986, Hydrothermal chimneys and associated fauna in the Manus Back-arc basin, Papua New Guinea. *EOS, Transactions American Geophysical Union*, 67, pp.489-490.

Degens, E.T. & Ross, D.A., eds., *Hot brines and recent heavy metal deposits in the Red Sea*, Springer-Verlag, New York.

Fouquet, Y., Von Stackelberg, U., Charlou, J.L., Donval, J.P., Erzinger, J., Foucher, J.P., Herzig, P., Muhe, R., Soakai, S., Weidicke, M, & Whitechurch, H. 1991, Hydrothermal activity and metallogenesis in the Lau back-arc basin. *Nature*, 349, pp. 778-781.

Halbach, P., Nakamura, K., Wahsner, M., Lange,J., Sakai, H., Kaselitz, L., Hansen, R.-D., Yamano, Y., Post, J., Prause, B., Seifert, R., Michaelis, W., Teichmann, F., Kinoshita, M., Marten, A., Ishibashi, J., Czerwinski, C., & Blum, N. 1989, Probable modern analogue of Kuroko-type massive sulphide deposits in the Okinawa Trough back-arc basin, *Nature*, 338, pp. 496-499.

Knuckey, M.J., Comba, C.D.A., & Riverin, G. 1982, The Millenbach deposit, Noranda district, Quebec - an update on structure, metal zoning and wall rock alteration. *Geological Association of Canada Special Paper*, 25, pp. 297-318.

Rona, P. 1988, Hydrothermal mineralization at oceanic ridges. *Canadian Mineralogist*, 26, pp. 431-465.

Scott, S.D. 1992, Polymetallic sulphide riches from the deep: fact or fallacy?, in *Use and misuse of* *the seafloor*, eds. K.J. Hsu and J. Theide, John Wiley, New York , pp. 85-113.

Stanton, R.L. 1990, Magmatic evolution and the ore type-lava type affiliations of volcanic exhalative ores. *Australasian Intitute Mining and Metallurgy, Monograph*, 15, pp. 101-107.

Tufar, W. 1990, Modern hydrothermal activity, formation of complex massive sulphide deposits and associated vent communities in the Manus back-arc basin (Bismarck Sea, Papua New Guinea). *Mitteilungen Osterreichischen Geologischen Gesellschaft*, 82, pp. 183-210.

Follows p. 179

Introduction to Session 5: Regolith evolution and exploration significance

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Regolith is used as a general term for the weathered mantle (soils, weathered rock or saprolite), the accumulated residua (such as laterite, silcrete), as well as associated sedimentary cover (colluvium, alluvium and salt lake deposits etc). Although Bates & Jackson (1987) refer to regolith as unconsolidated overburden, in the Yilgarn Craton and commonly in other lateritic terrains, some of the abundant regolith materials are quite consolidated. Besides lateritic duricrust, another common example is hardpan formed by siliceous cementation, in particular, of thick surficial sediments to form sandstones.

The common presence of a thick and variable regolith is well recognised as a major impediment to mineral exploration in the Yilgarn Craton (Butt & Smith, 1992) as well as in other important mineral provinces of Australia. The processes of deep weathering, residual accumulation, erosion and sedimentation have resulted in widespread concealment of bedrock sequences and included ore deposits. Commonly, the geological, geochemical and geophysical expression of ore deposits in the regolith is altered, weakened or buried. Regolith processes have led also to the formation of important secondary mineral deposits including lateritic and supergene gold, lateritic bauxite, nickel and cobalt deposits.

Besides tending to mask the appearance of most bedrock hosted mineral deposits, regolith processes can give rise to large, though often weak, dispersion patterns. Use of these dispersion patterns can provide great advantages in exploration for concealed ore deposits in regolith-dominated terrains by increasing the likelihood of success and, at the same time, substantially reducing exploration costs (Smith, 1989).

One of the characteristics of regolith environments in the Yilgarn Craton is their variability. Ridges and hills can be characterised by exposures of saprolitic or fresh bedrock, with thin soil cover and, in such cases, geological mapping is straight forward. This can also hold for areas of partly dissected saprolite. In other cases extensive areas of lateritic residuum (gravels, duricrust and associated sands) and depositional sediments can blanket the landscape essentially obscuring all bedrock relationships. This regolith variability, in many places closely coupled with landform and vegetation variation, is well seen on airphotos, photomosaics and satellite imagery. Probably in as much as 75% of the Yilgarn Craton bedrock relationships are obscured by a substantial regolith.

Session 5 looks at the present state of knowledge of regolith evolution in the Yilgarn Craton and presents some of the most important implications in exploration geology, geochemistry and geophysics.

Historical perspective

Over the last two decades, major advances have been made in exploration practice as applied in the Yilgarn Craton. Some advances have resulted from the base knowledge arising from geological mapping (Geological Survey of Western Australia, 1990), the understanding of ore genesis (Ho & others, 1990; Hill & others, 1988; Keays & Skinner, 1989) and the use of airborne geophysics, particularly high resolution airborne magnetics and radiometrics (Isles & others, 1989). Complementing these advances, a growth in the knowledge of regolith environments integrated with geochemical dispersion studies has made valuable inroads in the

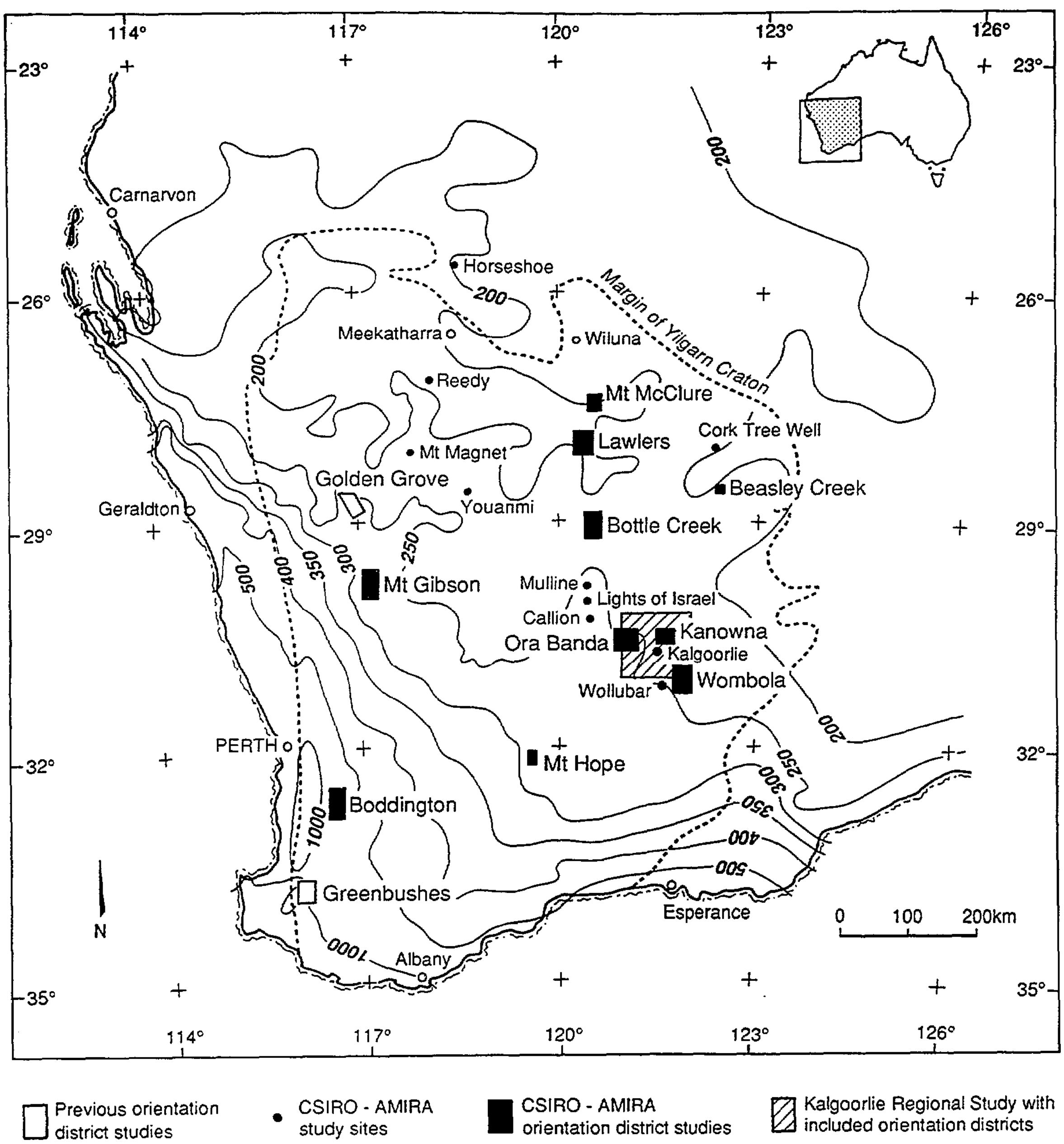

Fig. 1. Location map showing orientation areas, sites and districts within CSIRO exploration geochemical research studies. In addition, study sites within the Kalgoorlie Region include Panglo, Bardoc and Mt. Percy. Isohyets show average annual rainfall in millimetres.

search for concealed ore deposits. Marked improvements in our understanding of regolith and geochemical processes have had greatest impact in gold exploration (Butt & others, 1991; Davy & El Ansary 1986; Griffin & Harris in Elliot & Towsey, 1989; Smith & others, 1992). However, it provides a framework in exploration for a wide range of commodities, including base metals (Cu, Pb, Zn and Ni) and rare metals (Sn, Nb, Ta). These latter developments are fundamentally important, particularly, as exploration increasingly moves away from the outcropping areas into regolith-dominated terrain, comprising areas of deep weathering, soil or laterite cover, and areas of transported overburden.

Whilst much remains to be learnt as we enter the mid 1990s, explorationists can draw from a substantial knowledge and experience base. Thus many feel increasingly comfortable with the regolith settings that they are exploring. This comfort arises in part from an understanding of some of the fundamental dispersion mechanisms, of important element associations with ore deposits types, and of element abundances in a range of regolith, geomorphic and climatic settings (Butt & others, 1991; Smith & others, 1992).

For more than two decades, CSIRO, more recently in collaboration with universities, the Geological Survey of Western Australia and the

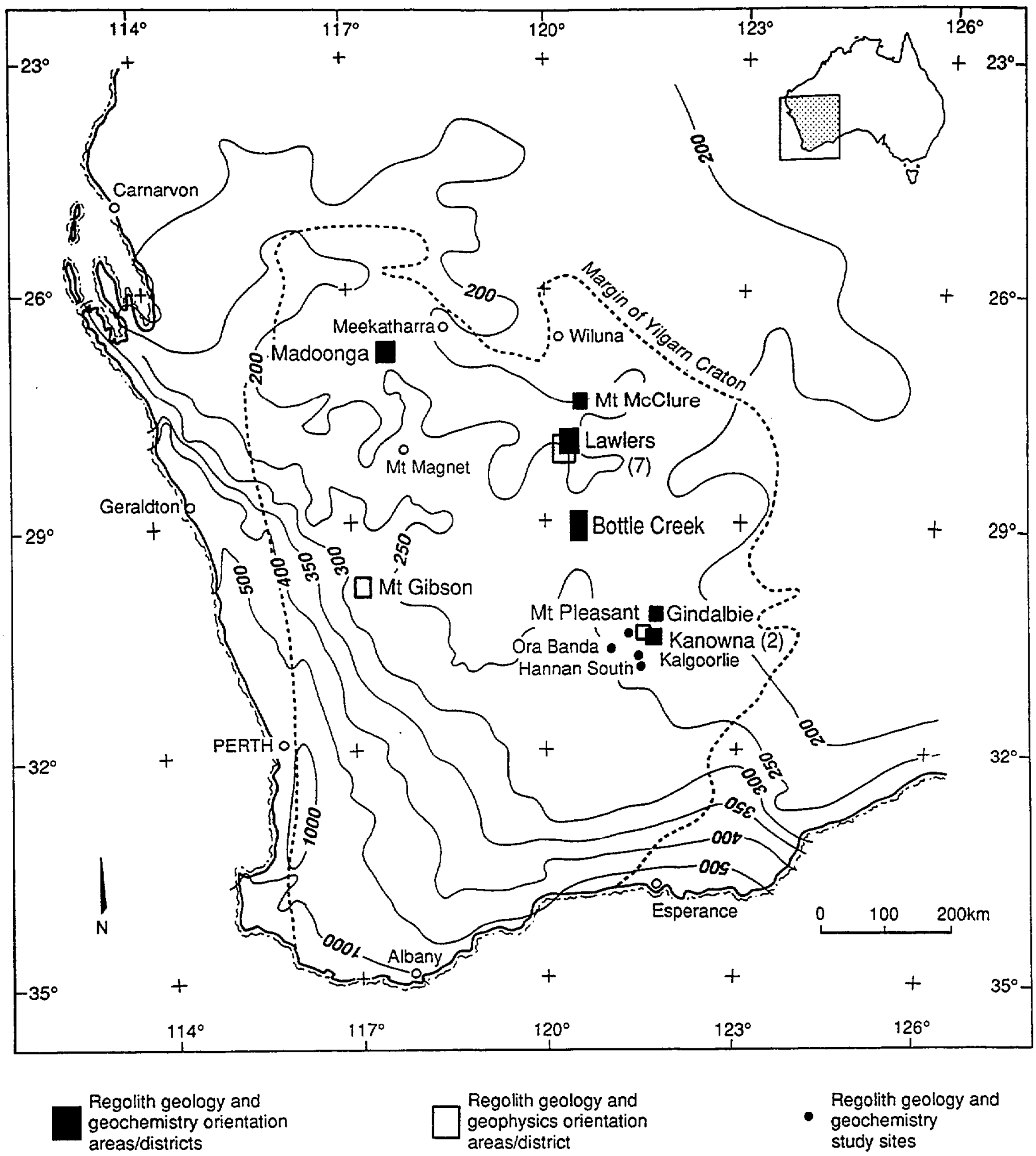

Fig. 2. Map showing the location of university theses carried out in conjunction with the CSIRO regolith geochemistry or geophysics research. All are Bachelors degree Honours theses except for the PhD thesis of L.M. Lawrance (University of WA, 1992) on Mt. Pleasant, Ora Banda and Hannans South. Seven studies have been carried out to date at Lawlers and 2 in the Kanowna district.

Australian Geological Survey Organisation, has provided the core for this regolith-geochemical research, with a focus on generating new or improved concepts and methods for locating concealed mineral deposits. Since 1987, several substantial projects funded through AMIRA have made fundamental contributions in lifting the level of knowledge and, in turn, the level of exploration expertise. These projects have been funded by more than 35 mining and exploration companies, in addition to funding from CSIRO. Several of the authors in Session 5 have drawn from the research findings of these projects. Short titles for the main projects (with their AMIRA project numbers) are: *Laterite Geochemistry P240, Weathering Processes P241, Remote Sensing for Gold P243, Lateritic Environments P240A, and Dispersion Processes P241A.* Figure 1 shows the distribution of key orientation studies which have been part of the focus of this research. Besides the study of individual sites, several districts (ranging in area from 100 to 500 square km) were carefully chosen to be distributed across the present-day rainfall gradient and representing a range of geomorphic and bedrock settings. Several research themes have been carried across the study areas and sites, including: regolith mapping methods (using both air photography and remote sensing), the classification of laterite types and associated ferruginous materials, saprolite textures, dispersion processes, and multi-element data interpretational methods. Recently, a new AMIRA project, *Yilgarn Transported Overburden* P409, fully focussed on exploring in areas of sedimentary cover, commenced and will run until mid 1996 (Butt & Smith, 1992).

Besides the high level of expertise of Australian exploration companies, important developments are also seen in the private service companies, such as World Geoscience Corporation/Aerodata, Chemtronics, Geochemex Australia and Geoscan, which are providing increasing capabilities in exploration in regolith terrains.

As a result of a successful competitive grant application, the Co-operative Research Centre in Australian Mineral Exploration Technologies (CRCAMET) commenced July 1992, with funding for seven years. The purpose of the Centre is to develop core technologies, particularly airborne methods, for the discovery of orebodies concealed beneath the unique Australian regolith. Emphasis is on geophysical exploration methods, notably electromagnetic (EM) technologies, coming together with the regolith and regolith studies. Part of the initial activities are in the Yilgarn, with some in the Kalgoorlie region.

Attention has also been given to the training of explorationists in regolith and geochemical skills. This has been achieved by linking industry funded research closely with teaching and training at several levels. Research findings have been incorporated into teaching 3rd year undergraduate courses; Honours studies have become an integral part of the research; and Master of Science and industry short courses, including those within the CRCAMET, have been established to provide continuing career training.

Integration of exploration methods is increasingly important both in research and in application. For example, processed satellite imagery (Landsat TM, SPOT), airborne radiometrics, airborne scanner imagery and air photography are common starting media for regolith mapping. In addition, airborne electromagnetics (AEM) is beginning to be seen as a possible tool (over and above its role in defining exploration targets) for mapping bedrock and regolith relationships. Environmental applications of AEM have demonstrated its use in mapping groundwater salinity in some of the grazing and farming areas of the Yilgarn (Street, 1992). The SALTMAP airborne EM system (Roberts & others, 1992) has been specifically designed to map shallow conductivity structures, particularly groundwater salinity, not possible before. Salinity of groundwater is also a fundamental aspect of geochemical environments and is therefore pertinent to geochemical dispersion. We are likely to see increasing use of AEM for that purpose as these technologies become more available and interpretation more definitive.

The purpose of session 5

The purpose of this session is to provide an integrated overview of topics fundamental to exploration of regolith-dominated terrain of the Eastern Goldfields Province and generally throughout the Yilgarn Craton. The session is also designed to link with Session 6, *The Search for Blind Orebodies*.

Scope and format

An overview of regolith variation, regolith stratigraphy, geomorphology and regolith evolution is provided by R.R. Anand and R.E. Smith. These authors provide comparisons between three contrasting regolith-landform settings in the Yilgarn Craton and include particular points of view on the implications of regolith relationships in mineral exploration. Their contribution provides a setting for topics which are developed in the other papers.

Next follows the presentation by C.R.M. Butt and others in which concepts and methods of exploration geochemistry for the Eastern Goldfields Province are developed. Dispersion processes are integral to regolith evolution as testified by two decades of research and exploration applications.

Effective exploration of regolith-dominated terrain generally requires mapping of regolith relationships as a first step. This control is important for sensible choice of exploration methods, particularly because the cost of applying different methods can vary by several orders of magnitude. Control by regolith mapping (and derived syntheses) is generally essential for designing geochemical exploration programs, control of sampling and interpretation of results. It is also important in the choice and interpretation of relevant geophysical methods of exploration. M.A. Craig and others discuss recent advances in regolith mapping methods and regolith mapping technologies. As mentioned above, an emerging issue is the integration of regolith stratigraphy, geochemistry and geology with geophysics. Particularly important are geophysical methods which provide information on the distribution, characteristics and stratigraphy of the regolith units. An overview is presented by V.C. Wilson.

The session is designed to be participatory, both through discussions after each of the four chosen topics and particularly, in the substantial closing Panel Discussion.

Some questions and comments

Critical questions are commonly raised amongst explorationists: Are volcanogenic massive sulphide deposits likely to be generally as abundant in the Yilgarn as they are in the Canadian Archaean terrains and are not being recognised here? If so, are we yet to grasp the secrets of finding them?

One wonders whether this is due to the impost of deep weathering and/or cover sequences. The appearance and geochemical signatures of volcanogenic massive sulphide gossans are distinctive in the few known Western Australian locations, that is Golden Grove (Smith & Perdrix, 1983), Teutonic Bore (Nickel, 1984) and Whim Creek (Nickel, 1982). Are there more subtle expressions which are being missed, perhaps soft iron-oxyhydroxide products forming depressions rather than prominent gossanous outcrops?

What would be expected in areas of transported cover? Recognising soft ferruginous zones in drill spoil in areas of cover could face the problem of being swamped by the abundance of ferruginous materials of common weathering profiles.

A great deal has been learnt about regolith evolution and the ferruginous materials in weathered environments. Considerable data and information on multi-element geochemistry of these ferruginous materials has been generated. Furthermore, besides Au being a very effective trace element in geochemical exploration for Au deposits, it is also a minor commodity of many VMS deposits, e.g. at Golden Grove. This knowledge needs to be specifically applied to base metals exploration. In addition, classical ore deposit models need to be translated into specific regolith settings.

A point already touched upon is worth developing. Mineral exploration is a three-dimensional geological problem spanning a wide range of scales. (More strictly, it is four-dimensional as geological time must be taken into account, which is particularly relevant to regolith evolution). Efficient and effective exploration more than ever requires integration of exploration concepts and methods. We have seen successful integration of regolith geology and exploration geochemistry. All would accept that airborne magnetics and bedrock geology go hand in hand with magnetics providing an unbiased view of bedrock relationships (Isles & others, 1989). In research, education and applications it is vital that interaction between minerals geologists and geophysicists be substantially enhanced. We need to see far more interaction from the planning stage, through operations, and interpretation, both in the field and in the laboratory.

Rapid developments in technologies of Geographical/Geological Information Systems (GIS) and two-/three-dimensional visualisation enable the merging and viewing of geological and geophysical data sets of disparate origin with increasing ease. These developments facilitate the critical examination and interpretation of these data, with the potential to provide new insight into complex regolith settings.

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References

Bates, R.L., & Jackson, J.A. 1987, *Glossary of Geology.* American Geological Institute, Alexandria, Virginia, 788pp.

Butt, C.R.M., & Smith, R.E. 1980, *Conceptual models in exploration geochemistry,* 4 - Australia. Elsevier Scientific Publishing Co., Amsterdam. 275pp.

Butt, C.R.M., & Smith, R.E. 1992, Geochemical exploration in areas of transported overburden, Yilgarn Craton and Environs, W.A. *Australian Mineral Industries Research Association, Proposal,* 22pp.

Butt, C.R.M., Gray, D.J., Lintern, M.J., Robertson, I.D.M., Taylor, G.F., & Scott, K.M. 1991, Gold and associated elements in the regolith–Dispersion processes and implications for exploration. *CSIRO Division of Exploration Geoscience, Report* 167R, 114pp.

Butt, C.R.M., & Zeegers, H., eds. 1992, Regolith exploration geochemistry in tropical and subtropical terrains. Volume 4 (607pp) in *Handbook of Exploration Geochemistry,* G.J.S. Govett, Series Editor, Elsevier, Amsterdam..

Davy, R., & El Ansary, M. 1986, Geochemical patterns in the laterite profile at the Boddington gold deposit, Western Australia. *Journal of Geochemical Exploration* 26, p119-144.

Elliott, S.M., & Towsey, C.A. 1989, Regional drainage geochemical gold techniques used in Queensland, Australia, in *Ninth Queensland Gold '89 Conference, Townsville,* Australasian Institute of Mining and Metallurgy, p51-61.

Geological Survey of Western Australia, 1990, Geology and Mineral Resources of Western Australia: *Western Australia Geological Survey, Memoir* 3, 827pp.

Ho, S.E., Groves, D.I., & Bennett, J.M. 1990, Eds.

Gold deposits of the Archaean Yilgarn Block, Western Australia: Nature, genesis and exploration guides. Geology Department (Key Centre) and University Extension, *University of Western Australia, Publication No.* 20, 407pp.

Hill, R.E.T., Gole, M.J., & Barnes, S.J. Physical volcanology of Komatiites: *Geological Society Australia, WA Division, Excursion Guidebook* No.1.

Keays, R.R., & Skinner, B.J. 1989, Introduction, in *Economic Geology Monograph 6: The Geology of Gold Deposits: The Perspective in 1988,* eds. R.R. Keays, W.R.H. Ramsay, and D.I. Groves, pp 1-8.

Isles, D.J., Harman, P.G., & Cunneen, J.P. 1989, The contribution of high resolution aeromagnetics to Archaean gold exploration in the Kalgoorlie region, Western Australia, *in Economic Geology Monograph 6: The Geology of Gold Deposits: The Perspective in 1988,* eds R.R. Keays, W.R.H. Ramsay and D.I. Groves, pp 389-397.

Nickel, E.H. 1982, The mineralogy and geochemistry of the Whim Creek Gossan. Proc. *Australasian Institute of Mining and Metallurgy,* 282.

Nickel, E.H. 1984, The mineralogy and geochemistry of the weathering profile of the Teutonic Bore Cu-Pb-Zn-As sulphide deposit. *Journal of Geochemical Exploration* 22, pp 239-264.

Roberts, G.P., Duncan, A.C., Anderson, A., & Roocke, P.A. 1992, SALTMAP - A new airborne electromagnetic system for salinity studies. *7th ISCO Conference Procedings, Helping people and their lands* 5.3, p745-750.

Smith, R.E. 1989, Using Lateritic Surfaces to Advantage in Exploration, in G.D. Garland, Editor, *Proceedings of Exploration '87, Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater, Ontario Ministry of Northern Development and Mines.* Ontario Geological Survey. Special Volume 3, 312-322, 960pp.

Smith, R.E., & Perdrix, J.L. 1983, Pisolitic Laterite geochemistry in the Golden Grove massive sulphide district, Western Australia. *Journal of Geochemical Exploration* 18: 131-164.

Smith, R.E., Anand, R.R., Churchward, H.M., Robertson, I.D.M.R., Grunsky, E.C., Gray, D.J., Wildman, J.E., & Perdrix, J.L. 1992, Laterite geochemistry for detecting concealed minerals deposits. *CSIRO Division of Exploration Geoscience, Report* 236R, 171pp.

Street, G.J. 1992, Airborne geophysical surveys - applications in land management. *Bulletin Australian Society of Exploration Geophysicists,* 23, No.1/2, 333-338.

Regolith distribution, stratigraphy and evolution in the Yilgarn Craton—implications for exploration

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Weathering under prolonged conditions, which are interpreted to have been warm, humid and stable, has resulted in widespread, deep weathering profiles over the Yilgarn Craton. Subsequent differential erosion and chemical modification, particularly under semi-arid to arid conditions inland, has added to the complexity. As a result we now commonly see a great variety of regolith materials exposed on the land surface with intricate regolith landform relationships. An understanding of these relationships and knowledge of the geochemical and mineralogical characteristics of regolith are key ingredients in effective exploration in lateritic terrains. These factors govern the nature of the geochemical and geophysical expressions of weathered or otherwise concealed ore deposits in these terrains. An understanding of regolith-landform relationships allows:

- choice of appropriate exploration methods;
- design and execution of optimal geochemical programmes;
- sensible data interpretation, and
- soundly-based integration of exploration findings.

Three major contrasting geographical regions (the Darling Range, Kalgoorlie, and Leonora–Wiluna regions) have been identified based on their regolith-landform characteristics (Table 1). For selected districts within these regions, regolith-landform relationships were mapped, the regolith stratigraphy established, regolith units characterized, regolith models erected, and the regolith evolution interpreted. These are briefly discussed below.

Weathering

The Yilgarn Craton has been exposed to long periods of lateritic weathering, involving leaching of alkali and alkaline earth elements and silica, leading to deep kaolinization of bedrocks. During lateritic weathering, much of the ferrous iron, released into the groundwaters by breakdown of the primary minerals can, particularly where the water table is near the ground surface, be oxidized and precipitated. As a result a ferruginous horizon (lateritic residuum) typically develops in the upper part of the deeply weathered profile (Fig. 1). The left hand side of the Fig. shows a profile commonly developed through lateritic weathering of mafic and ultramafic rocks, with a characteristic ferruginous saprolite. In contrast, a profile with a strongly developed mottled zone commonly formed on felsic bedrocks, is shown on the right. Rocks rich in Fe however, may weather directly to Fe-rich duricrusts without forming deep saprolites. Furthermore, it seems that thick, widespread red clay soils may form instead of well developed laterite. Such is the case in the Kalgoorlie region where red soils probably once blanketed the land surface.

The chemical composition (major, minor and trace elements) of lateritic residuum is largely lithodependent at a landscape scale. However, there is evidence to suggest that some Fe-rich black duricrusts may have been produced by the absolute accumulation of Fe in valley floors followed by the processes of relief inversion in response to drainage incision. Detailed work has shown that lateritic nodules and pisoliths in lateritic residuum are formed by a combination of several processes, including ferruginization, fragmentation, and multiple of phases of leaching, migration and deposition of Fe-oxides. Biological processes also contribute to this re-organization. Thus, formation of lateritic residuum is complex, consisting of numerous stages expressed by different facies. Most residual lateritic pisoliths and nodules have thin (1-2 mm) goethite-kaolinite-rich cutans and were formed by the deposition of Fe and Al around a nucleus.

In the Darling Range, the lateritic resid-

Table 1. Salient regolith, landform and vegetation features in the Darling Range, Kalgoorlie and Leonora-Wiluna Regions.

Regolith	Darling Range	Kalgoorlie Region	Leonora-Wiluna Region*
Rainfall	1000mm	230-250 mm	≈200mm
Vegetation	Eucalyptus (Jarrah)	Eucalyptus (Salmon gum)	Acacia (Mulga)
Landform	Undulating lateritic plateau, high relief	Gently undulating terrain, low relief	Gently undulating terrain, low relief
Depth of weathering	Variable	Highly variable	Variable
Thickness of *in situ* profiles	Shallow (upper slopes) to deep (midslopes)	Very shallow (uplands) to deep (plains)	Deep
Calcareous clays	Absent	Abundant	Trace
Pedogenic carbonates	Absent	Abundant	Trace
Plastic red clays	Absent	Abundant	Absent
Ferruginous granules in soils	Absent	Common	Trace
Aeolian quartz in top 1m	Absent	Abundant	?
Colluivum/alluvium	Shallow	Shallow to deep	Deep
Hardpan in colluvium/ alluvium	Absent	Shallow, mild	Deep
Lateritic residuum	Extensive, discontinuous (bauxitic)	Patchy (ferruginous)	* Extensive, discontinuous (ferruginous)
Fe-rich duricrust	Absent	Patchy	Patchy
Hardpan in lateritic residuum	Absent	Absent	Common
Silicified/calcified lateritic residuum	Absent	Common	Common
Mottled zone	Extensive (bauxitic)	Common	Common
Mega-mottle in paleochannel profiles	Absent	Common	Absent
Ferruginous saprock/ saprolite	Absent	Common	Extensive
Fe-segregations in saprolite	Absent	Few	Abundant
Geochemical sampling media	Lateritic residuum	Fe-granules and mottles in soils, calcareous soils	Lateritic residuum, Fe-saprolite, iron-segregations

* Buried complete laterite profiles occur

uum is very highly weathered and markedly aluminous. The major secondary minerals are gibbsite, hematite, and goethite. Inland, the lateritic residuum from similar parent rock types tends to be less aluminous and more ferruginous and the major minerals are kaolinite, hematite, and goethite. Black lateritic pisoliths both in Darling Range and inland are generally magnetic and are more abundant near surface. The non-magnetic pisoliths contain higher amounts of goethite and kaolinite relative to the magnetic pisoliths, while maghemite is present only in magnetic pisoliths.

Quartz and resistant minerals such as talc and chromite survive through much of the lateritic profile and are an aid towards bedrock identification. Iron as well as some minor and trace elements in lateritic residuum also reflects the composition of underlying bedrock. Lateritic residua formed from granite are generally low in Fe due to the small amounts of Fe in the parent rock whereas those derived from ultramafic rocks are slightly lower in Al but higher in Fe than those from mafic rocks. Lateritic residuum, formed from ultramafics is, however, richer in Co, Ni, and Cr, which may be used to distinguish mafic from ultramafic-derived laterites.

Various other forms of Fe enrichment (iron segregations) also occur within the saprolite

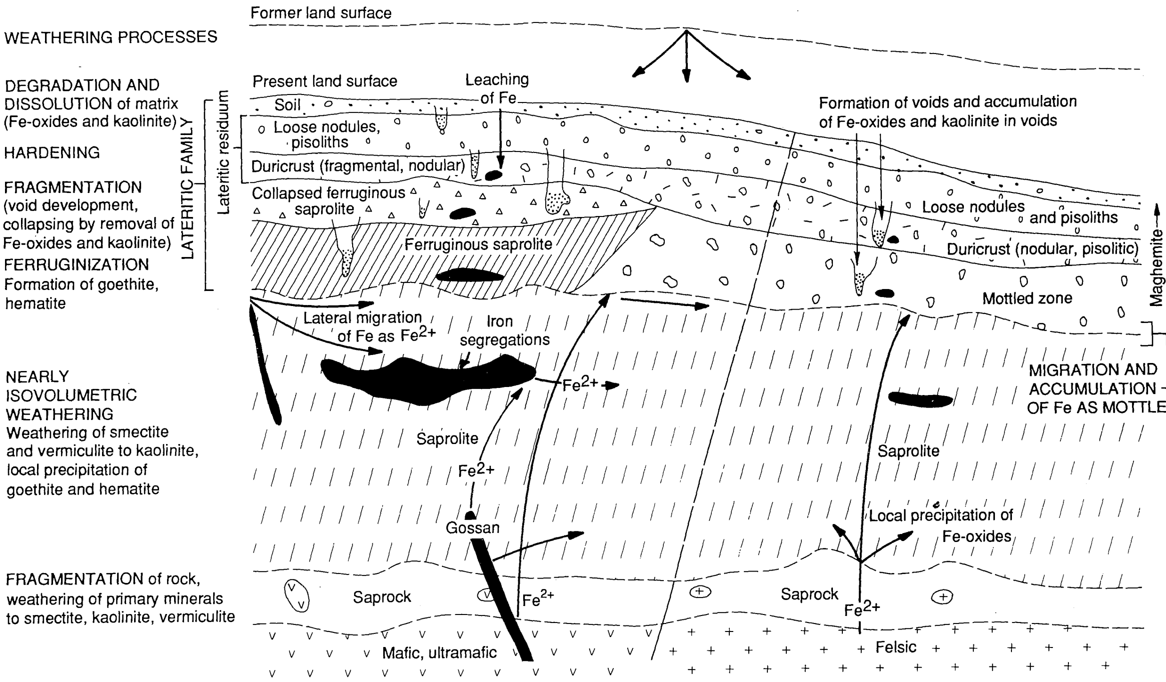

Fig. 1. A schematic diagram of the differences in the nature of the weathering mantle developed from mafic, ultramafic and felsic bedrocks. This diagram is based on findings in the Darling Range, Mt. Gibson, Lawlers, Mt. McClure and Bottle Creek districts.

and ferruginous saprolite. These iron segregations, representing zones of intense ferruginization, occur as pods, lenses, and large slabs.

Regolith distribution and stratigraphy

Several well-defined regolith types recur in all three regions and relate, directly or indirectly, to a deeply weathered mantle and to its modification by regolith-landform processes. The regolith materials are either horizons of a deep profile developed by *in situ* weathering of bedrock or consist of transported debris, derived from local weathering profiles by erosion. Many of the regolith types resulting from these complex processes, occur in distinctive patterns. These are described in terms of the distribution of:

- *residual regimes* where the near-complete lateritic profile is preserved;
- *erosional regimes* where the lateritic profile has been truncated to the level of saprolite/bedrock;
- *depositional regimes* characterized by sedimentary units largely derived by the erosion of the lateritic profile (Anand & others 1989; Anand & others 1991).

Erosion has occurred in each of the geographical regions discussed, however, the extent of the stripping varies. In Leonora–Wiluna region (e.g. in the Lawlers and Mt. McClure districts), residual regimes vary considerably in area depending on erosional stripping, which can be extensive, exposing various levels of the saprolite. The detritus from this process has commonly accumulated in low-lying areas forming alluvial and colluvial plains. The depositional regimes represent areas that are dominated by a regolith generally of diverse origin. Research and extensive exploration drilling have shown that complete laterite profiles can occur buried beneath the sediments particularly of alluvial plains. In some districts (Lawlers, Mt. McClure) buried complete lateritic profiles are common (Fig. 2).

In the Kalgoorlie region, residual regimes, as defined above, are localised, patchy and are dominated by black Fe-rich duricrusts. In depositional regimes, calcareous clays (with a thickness of 0.2-1m) are common at surface. Their immediate substrate is red clay rather than lateritic residuum as seen in many of the depositional regimes at Lawlers (Fig. 3). Red clays are generally underlain by a thick saprolite. The landscape is characterized by extensive stripping of upland areas, very shallow to deep weathering, patchy development of laterite and extensive occurrence of red soils. In contrast, lateritic residuum is widely preserved in the Darling Range. Depositional regimes are restricted in the Darling Range possibly because of high relief coupled with high rainfall, which together cause sediments to be mostly removed.

Calcareous earths and pedogenic carbonates are extensive in the Kalgoorlie region. In contrast, in the Leonora–Wiluna region, there is little

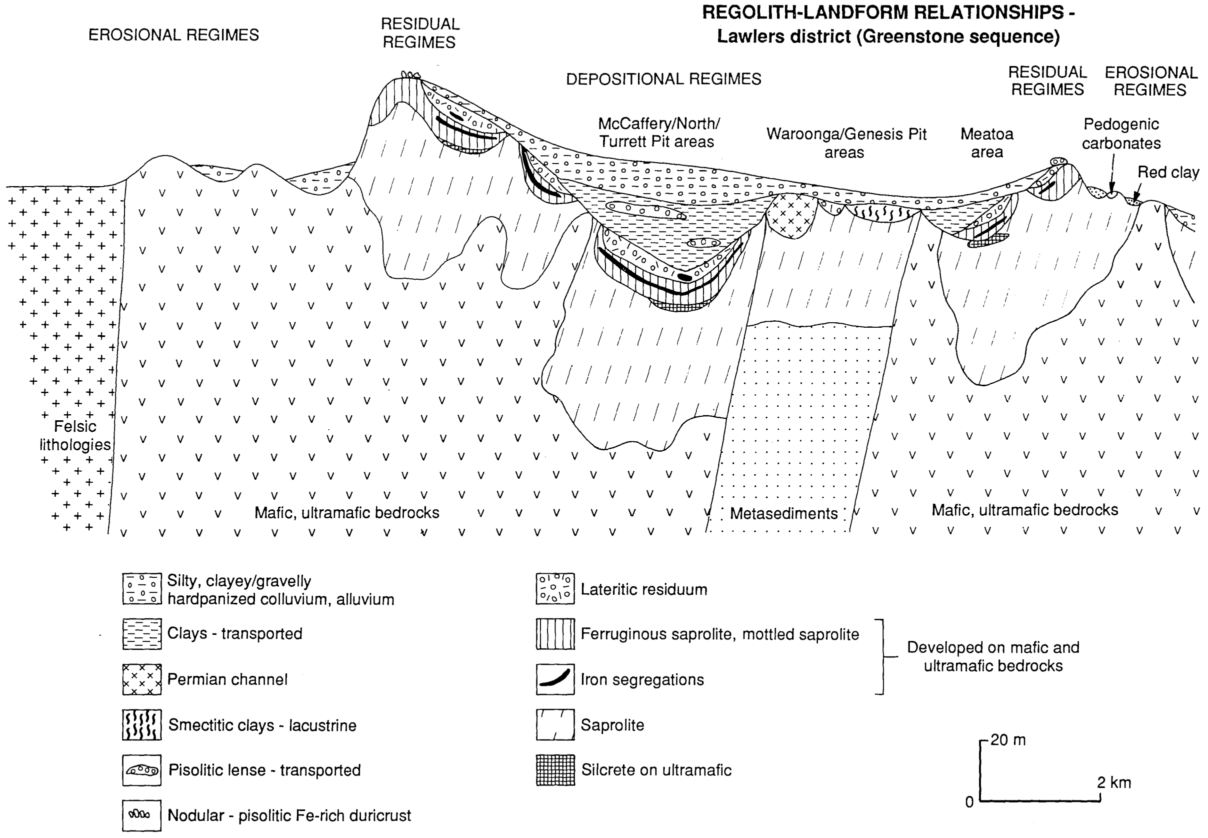

Fig. 2. Schematic cross-section for the Lawlers district showing regolith stratigraphy and landforms.

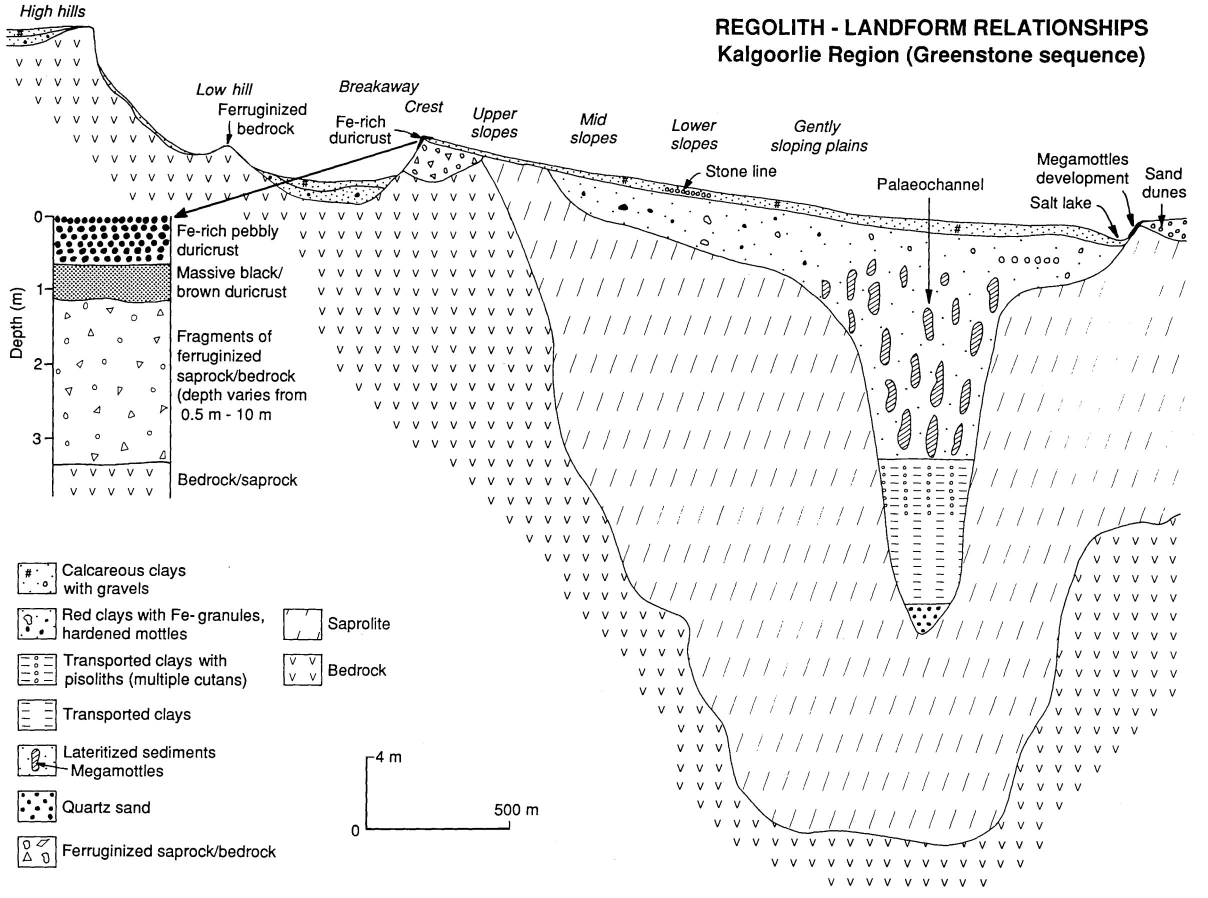

Fig. 3. Schematic cross-section for the Kalgoorlie region showing regolith stratigraphy and landforms.

development of pedogenic carbonate, but valley calcretes are common along stream channels. Hardpan is extensively present, both in the residual and transported materials, in the Leonora–Wiluna region. *Hardpanization*, commonly occurs within the top few metres of the regolith, particularly in wide, past or present depressions. The maximum penetration of hardpanization seems to be about 15 m. Widespread hardpanization of many regolith units indicates mobilization and deposition of silica in the upper regolith. Hardpanization appears to have resulted from periodic waterlogging of the sediments and locally-underlying regolith, followed by desiccation under semi-arid to arid conditions (Bettenay & Churchward, 1974). Some of the carbonate has developed subsequent to the hardpan, forming stringers of soft carbonate along subhorizontal partings. Calcrete is most extensive on the more stripped land surface. Erosion and stripping of the upper, more weathered, parts of the regolith, appear to be important factors influencing the gross distribution of carbonates coupled with the distribution of mafic and ultramafic rocks.

Hardpan and calcrete do not occur in the regolith of the Darling Range. However, strong leaching of the upper horizons under a thick vegetative cover has given rise to a bauxitic horizon.

Ferruginous materials

A wide variety of ferruginous materials occur in the lateritic landscapes of these three contrasting regions. They occur as crusts, lag, as gravel components in soils, colluvium, alluvium and as segregations and infusions in upper saprolite. Because each specific type of ferruginous material is closely linked to its position in the regolith stratigraphy, the distribution of ferruginous materials in the landscape is determined by the nature of regolith-landform regimes. Important patterns of geochemical dispersion from mineral deposits can be preferentially contained or preserved within these ferruginous materials. For the purpose of geochemical exploration, two major families of ferruginous materials are recognized, based upon their mesoscopic and chemical characteristics as well as their position in the regolith stratigraphy. These are the *lateritic family* and the *iron segregation* family.

The lateritic family (lateritic duricrust, loose lateritic nodules and pisoliths, ferruginous saprolite) result from ferruginization and residual accumulation in the upper lateritic profile. A large part of their Fe is derived from the weathering of underlying bedrocks. They are yellowish brown to dark reddish brown and largely consist of kaolinite, hematite, goethite and maghemite. Yellowish-brown or greenish cutans, 1-2 mm thick, are typical of residual lateritic pisoliths and nodules. Original rock texture may be partly preserved or completely destroyed.

The very diverse iron segregation family results from extreme ferruginization and has developed predominantly within saprolite. Its members are not confined to a single unit of the regolith stratigraphy. Their Fe is derived from a variety of sources including weathering of Fe-rich lithologies, gossans, leaching from upper horizons and upland areas. Iron segregations are black and are dominated by goethite, with variable amounts of hematite and quartz. It is significant that the iron segregations do not have cutans. The members of the iron segregation family can also be distinguished chemically from members of the lateritic family. Iron segregations have generally higher Fe, Mn, Zn, Co, Cu and Ba and lower Al_2O_3, TiO_2, Cr, V, Ga and Zr contents than the laterite family. Different thresholds have therefore, to be used in geochemical exploration based on samples of iron segregations, or a lag derived from them, than those used in laterite geochemistry.

Regolith–landform procedures for exploration

Geochemical exploration

In geochemical exploration, regolith units form the dominant sampling media in the initial stages of most programmes in those areas where bedrock has very restricted outcrop or is completely concealed beneath surficial regolith units. Understanding the regolith-landform framework for a region assists our appreciation of geochemical dispersion and thus provides a basis for developing sampling strategies in weathered terrain. As discussed above, the Kalgoorlie and Leonora–Wiluna regions are characterized by different arrays of regolith types and each requires a different geochemical exploration approach particularly in terms of choice of sampling media.

Regolith-landform control for an exploration area is provided by carrying out regolith-landform mapping, establishing the regolith stratigraphy within these mapped units, and synthesizing these to form a regolith-landform model. It is important also to make use of existing published or otherwise available regolith maps, regolith models, and geochemical dispersion models.

Different geochemical thresholds usually apply to different sampling media and hence to different regolith-landform mapping units. Thus one

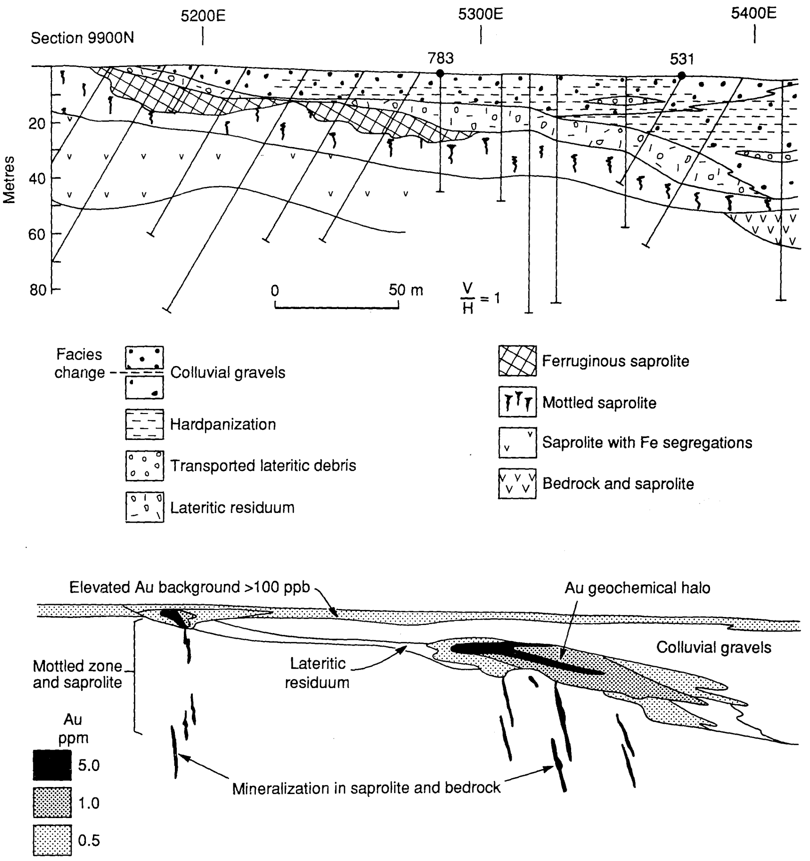

Fig. 4. Diagrammatic cross-section along line 9900 north in the North Pit area, Lawlers district, showing regolith stratigraphy and dispersion of Au in lateritic residuum.

purpose for producing a regolith-landform map is to delineate areas or units within which exploration geochemical data may be treated uniformly. If the variation in sample characteristics is too great, geochemical dispersion anomalies arising from ore deposits will be lost among the natural variation in sample characteristics, related to changes in regolith-landform situations. Regolith-landform maps also identify and delineate areas characterized by complex surficial relationships which may require specialized exploration approaches in contrast with areas which require, for example, straight-forward soil sampling. For these reasons it can be very useful in lateritic terrain to consider regolith-landform relationships in terms of the residual, erosional, and depositional regimes discussed above.

When regolith-landform regimes are mapped in an area, it generally becomes clear which geochemical sampling media to use. Where the lateritic horizon is preserved, duricrust, pisoliths and nodules form an ideal sampling medium for seeking widespread dispersion haloes for Au and base metals exploration. These may be collected from the surface or near surface in residual regimes. In depositional areas, seeking geochemical haloes in buried residual laterite and ferruginous saprolite can be of great advantage in exploration (Fig. 4). This requires accurate, sub-surface sampling of the lateritic materials and knowledge of the regolith stratigraphy (Anand & others 1991; Smith & others, 1992). In drilling to sample buried laterite, it is important to recognize and distinguish between the transported lateritic debris and residual laterite. Where the profile is truncated, ferruginous saprolite, iron segregations and soils are suitable sampling media (Anand & others, 1991).

In the Kalgoorlie region where the occurrence of lateritic residuum is patchy, alternative sampling media are required. Calcareous soil, ferruginous granules and mottles in soils are the preferred sampling media, even in areas of transported cover, and give superjacent anomalies to concealed mineralization (Butt & others, 1991; Dell, 1992).

Geophysical exploration

Geophysical modelling and interpretation require regolith models which incorporate the observed spatial variability of regolith units as well as the variability of their physical and mineralogical properties. Interfaces are particularly important. Current research in the Co-operative Research Centre for Australian Mineral Exploration Technologies focusses upon establishing such models, incorporating knowledge of the spatial and three-dimensional distribution of the regolith units, their stratigraphy, facies, facies variations, characteristics and relationships to bedrock lithologies. Such regolith models established from field relationships and theoretical models produced by interpretation of geophysical data sets are then reconciled in a phase of comparative research.

References

Anand, R.R., Smith, R.E., Innes, J., & Churchward, H.M. 1989, *Exploration Geochemistry about the Mt. Gibson gold deposits*, Western Australia, CSIRO Division of Exploration Geoscience Report 20R, 93pp.

Anand, R.R., Churchward, H.M., Smith, R.E., & Grunsky, E.C. 1991, *Regolith-landform development and consequences on the characteristics of regolith units, Lawlers district, Western Australia*. CSIRO Division of Exploration Geoscience Report 166R, 160pp.

Bettenay, E., & Churchward, H.M. 1974, Morphology and stratigraphic relationships of the Wiluna hardpan in arid Western Australia. *Journal of Geological Society of Australia*, 21, 73-80.

Butt, C.R.M., Gray, D.J., Lintern, M.J., Robertson, I.D.M., Taylor, G.F., & Scott, K.M. 1991, *Gold and associated elements in the regolith - dispersion processes and implications for exploration*, CSIRO Division of Exploration Geoscience Report 167R, 114pp.

Dell, M.R. 1992, Regolith-landform relationships and geochemical dispersion about the Kanowna-Belle gold deposits, W.A. Honours thesis, University of Tasmania, 89pp.

Smith, R.E., Anand, R.R., Churchward, H.M, Robertson, I.D.M., Grunsky, E.C., Gray, D.J., Wildman, J.E., & Perdrix, J.L. 1992, *Laterite geochemistry for detecting concealed mineral deposits, Yilgarn Craton, Western Australia*, Summary Report for CSIRO-AMIRA Project P240, CSIRO Division of Exploration Geoscience, Restricted Report 236R, 170pp.

Geochemical exploration concepts and methods in the Eastern Goldfields Province

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Deeply weathered terrains, such as that of the Eastern Goldfields Province, present a number of problems that affect most mineral exploration techniques. The widespread deep regolith, 20-100 m thick, implies that outcrops are rare and mostly weathered. This restricts the use of conventional geological mapping, and places increased reliance on the integrated use of geophysics and geochemistry. Of these, geochemistry appears to have a predominant role, particularly for exploration at a sub-regional to local scale, but can only be effective if the characteristics of the terrain are understood and the most appropriate sampling and interpretational techniques are used. In the Eastern Goldfields, the most common targets are supergene and primary Au, and base metals, dominantly nickel, with most exploration at the district to local scale. Therefore, the most important steps are, firstly, to develop an understanding of the weathering history of the region and the dispersion characteristics of the principal ore elements and possible pathfinders at each stage of that history and, secondly, to derive a generalized dispersion model based on the particular landform-regolith characteristics of the location to be explored (Butt & Zeegers, 1992). This procedure will assist in the selection of the most effective exploration methods.

Regolith evolution and element dispersion

The regolith of the region has developed over a very long period, probably since the mid-Mesozoic, during which it has been subjected to several major changes of climate. Two climatic episodes have been of particular importance. These were, firstly, seasonally humid, warm to possibly sub-tropical climates during the Cretaceous to mid-Miocene and, secondly, drier climates since the Miocene. The early, humid climates, probably equivalent to those of the present wetter savannas, caused extensive, deep, broadly lateritic weathering. The later arid to semi-arid climates, which still prevail, have resulted in a general lowering of water-tables, with changes to, and slowing of, chemical weathering.

The distribution of elements in the regolith is related to the different weathering processes that prevailed during the principal climatic regimes. In general, only the processes that refer to past regimes of long duration, or to extreme or recent regimes, have had a significant and lasting effect. Thus, many of the dominant geochemical (and mineralogical) characteristics of the regolith can be related to the development of deep, intensely weathered regoliths in humid conditions with high water-tables, whereas others are related to later more arid environments with lower water-tables; some of the latter processes, particularly as they affect Au, are still active. The features produced by these later events appear as modifications of the pre-existing profile and tend to be reflected more by the minor components of the regolith.

The geochemical effects of the principal stages in the evolution of the regolith in the Kalgoorlie region can be summarized as follows:

1. Lateritic weathering under warm humid conditions

- Progressive weathering of sulphides, carbonates, feldspars and ferromagnesian minerals and the leaching of mobile elements (S, Na, Cs, Ca, Mg, Sr, Mn, Co, Ni, Cu, Zn).
- Retention of less mobile elements in secondary minerals, principally kaolinite and Fe oxides (Si, Al, Fe, Ba, Cr, Ti, V, As, Sb, Sc, Ga, Mn, Cu, Ni).
- Dissolution or replacement of secondary minerals (e.g., kaolinite, barite) and some resistant primary minerals (e.g., muscovite) during the formation of ferruginous horizons, accompanied by remobilization and some loss of their constituent elements (Si, Al, Cr, Ba, K, Rb) and the recrystallization

and accumulation of Fe oxides in secondary structures. Mobilization of Au as an organic complex.

- Accumulation of elements immobilized in resistant primary minerals (Cr in chromite; Zr, Hf in zircon; K, Rb in muscovite; Ti in rutile; REE, Sn, Ta, Nb, Th, W) or in stable secondary minerals (Ti in anatase; V in Fe oxides).

2. Weathering under warm, semi-arid conditions

Although many of the mineralogical and geochemical characteristics formed during humid deep weathering are retained, arid conditions produce some important modifications to the pre-existing regolith.

- Decline of the water-table and vegetation loss, which has led to instability of the landsurface and minor erosion, although dehydration and hardening of lateritic duricrusts, especially over mafic rocks, has preserved some soft regoliths. Deposition of the erosion products has resulted in a colluvial/alluvial cover over much of the landscape.
- Continued, but slowed, weathering, mainly at the base of the profile. However, the dissolved weathering products gradually accumulated as evaporation exceeded precipitation and, together with the accession of marine salts associated with rainfall, resulted in progressive salinization of the groundwater.
- Mobilization of Au and Ag, particularly in the near-surface, as halide complexes. Mobilization has probably continued intermittently to the present, with progressively lower water-tables, with Au precipitation at redox fronts beneath and related to the water-table.
- In some locations, the precipitation of alunite, probably under acid conditions with relatively high water-tables, apparently post-dating at least some Au mobilization. Silica, introduced into the profile or derived from dissolving clay minerals, has precipitated in various regolith horizons, to form hardpans and silcrete.
- Continued leaching of base and transition metals (Cu, Co, Pb, Mn, Ni) and, in some locations, REE, with minor precipitation in the mid to lower saprolite.
- Release of soluble alkaline earth metals at the weathering front and their transport to the surface, probably by evaporation and/or evapotranspiration; vegetative cycling of these elements has led to their gradual accumulation in the near-surface horizons. This dilutes the concentrations of many elements but, importantly, represents a site for the secondary accumulation of Au.

Many of these features are evident in the regolith developed over Au mineralization in the Mystery Zone at Mt. Percy, 2 km north of Kalgoorlie (Fig. 1). For example, Ca is strongly leached from much of the regolith, but is concentrated at the surface. Gold is concentrated in the Fe oxide- and carbonate-rich surface, leached from the underlying mottled and plasmic clay horizons and variably dispersed and concentrated in the saprolite, whereas As has been dispersed, mainly into Fe oxides in the upper saprolite and ferruginous zone, but retained throughout the leached clay zone.

Implications for exploration

Comparison with equivalent regoliths in the present humid tropics suggests that Au is largely immobile during deep weathering under humid conditions, except in the uppermost, ferruginous horizons. Here, primary Au is dissolved by organic complexes in neutral to acid conditions and reprecipitated as very pure fine-grained particles, generally with secondary Fe oxides. It accumulates progressively with time, resulting in the development of lateritic Au deposits. Conversely, many sulphide-hosted metals are strongly leached, particularly from the near-surface horizons, greatly hindering the detection of primary mineralization. The residual accumulation of resistant accessory minerals, such as cassiterite and platinum group minerals, and the coprecipitation of chalcophile elements, such as As, Bi and Sb with Fe oxides, however, may result in characteristic geochemical signatures being retained in gossans or dispersed in lateritic gravels and lag.

One of the most significant features of weathering under arid conditions is the destruction or burial of any lateritic horizons and their widespread geochemical haloes. In eroded areas, therefore, the surface expression of mineralization is generally restricted and may be strongly leached. In depositional areas, barren overburden may overlie either a buried lateritic horizon or an erosion surface. However, Au remobilization has resulted in the formation of supergene enrichments at depth and, in the southern Yilgarn, minor accumulation in pedogenic carbonates gives surface expression even to buried mineralization. Nickel presents a complex problem, for Ni derived from silicates accumulates in saprolite during the two weathering phases, commonly to concentrations similar to or exceeding those in leached gossans, thereby generating false exploration targets.

Exploration strategies and procedures

Regolith-landform mapping is an important first step to determining the appropriate geo-

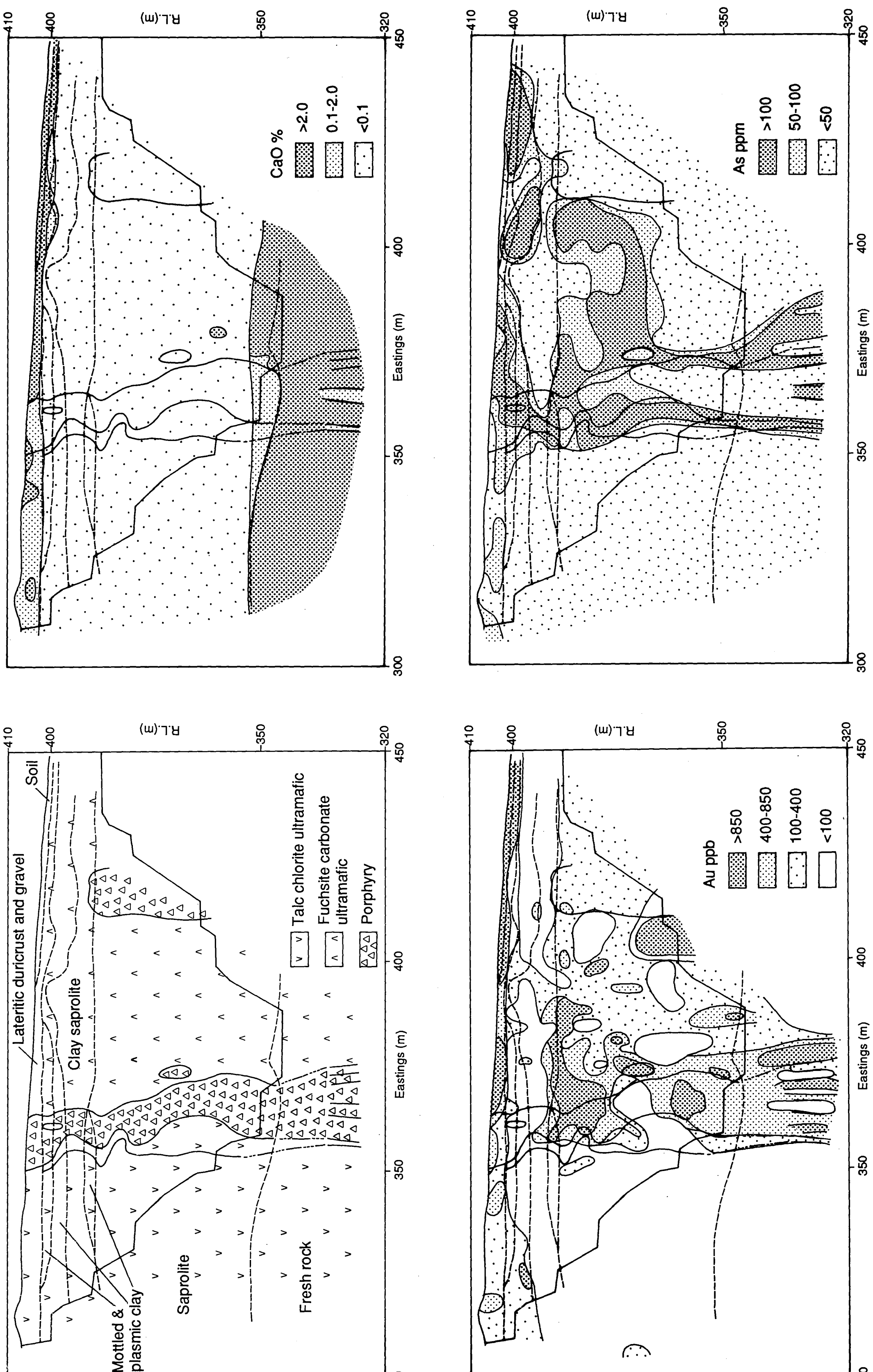

Fig. 1. Geological and regolith section across the Mystery Zone, Mt. Percy, showing the distributions of CaO, Au and As (after Butt, 1991; Butt and others, 1991).

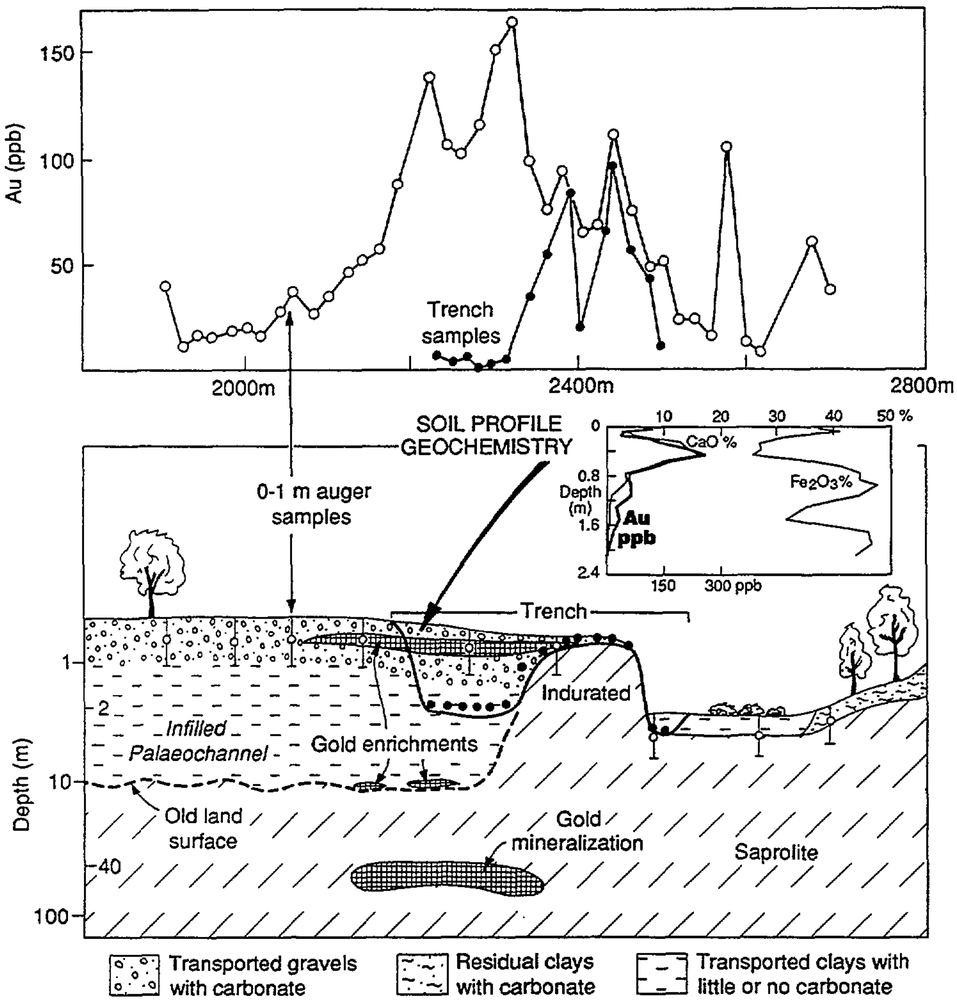

Fig. 2. Landscape section across part of the Panglo Au deposit, north of Kalgoorlie, illustrating the importance of sampling soil carbonate horizons in Au in exploration. Shallow carbonate-rich samples from the trench give a significant response to buried mineralization, whereas deep, carbonate-poor samples have background Au contents (after Lintern and Scott, 1990).

chemical exploration procedures. Such mapping may initially be supplemented by stratigraphic drilling and should be updated as exploration proceeds. Principal objectives include identification of depositional areas and determination of the degree of preservation of the deep weathering profile and, in particular, of the ferruginous lateritic horizon. In the northern Yilgarn, it is important to distinguish the latter from red-brown hardpans.

Where the lateritic horizon is preserved, ferruginous pisoliths, nodules and duricrust form an ideal sampling medium for seeking widespread dispersion haloes for Au and base metal exploration. These may be collected from the surface in residual areas or by drilling in depositional areas. Specific recommendations for this procedure are given by Smith & others (1992).

Where the profile is truncated, surface sampling of gossans, ferruginous lag or specific soil fractions, determined by orientation surveys, are suitable surface techniques in erosional areas. Specific targets are explored by close-spaced drilling. In depositional areas, drilling may be necessary from the outset. Logging of the drill cuttings for regolith characteristics as well as lithology is essential for data interpretation and may reveal important controls on element distributions and provide a guide for preferred sample media. The possible occurrence of sub-horizontal enrichments of supergene Au, especially in saline areas, may guide planning and interpretation of drilling programs.

Multi-element analysis is recommended, particularly in the earlier stages of exploration. Suitable element suites are:

Base metals: Cu, Pb, Zn, Ag, As, Ba, Bi, Se, Hg and Sn.

Nickel: Ni, Cu, Mn, Co, Pt, Pd, Ir and Te. Cr, Mn and Zn have use as negative indicators.

Gold: Au, As, Bi, Sb, Pb, W and Mo. K or Rb indicate sericitic alteration zones.

For Au exploration in semi-arid areas

south of about 30S, Au enrichments in pedogenic carbonate are of specific importance. This material, which generally occurs in the top 1-2 metres of the profile, is the preferred sample medium, even in areas of transported cover, and gives superjacent anomalies to concealed mineralization. Typical results from the Panglo deposit, 40 km north of Kalgoorlie, are shown in Fig. 2. The Au anomaly is present only in the carbonate horizon in both residual and transported material; deeper sampling (2-6 m) gives no useful response. The enrichment is thought to be due to active cycling of Ca and Au via vegetation, driven by evapotranspiration. Only Au appears to be enriched in carbonates and, indeed, base metal concentrations tend to be depressed by dilution. Gold may concentrate strongly in carbonates even in lateritic horizons, but only the ferruginous fraction yields a multi-element signature (Butt & others, 1991; Lintern & Scott, 1990).

Conclusion

For geochemical exploration in deeply weathered terrains, such as the Eastern Goldfields Province, it is necessary to:

- Define the objective of the programme (for example: mapping, reconnaissance, specific commodity or style of mineralization) and the scale;
- Determine the nature of the landscape in terms of the geomorphology and regolith;
- Recognize the problems posed by the terrain and the limitations it places on exploration methods;
- Estimate the probable dispersion models that apply in the area;
- Select the most appropriate sampling and analytical techniques necessary to detect the expected geochemical expression of the target.

Recognition of this process, whether formally or informally, is essential for effective exploration.

Acknowledgements

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References

Butt, C.R.M. 1991, *Geochemical dispersion in the regolith, Mystery Zone, Mt. Percy mine, Kalgoorlie, Western Australia.* Report 129R, CSIRO Australia, Division of Exploration Geoscience, Perth. 226pp.

Butt, C.R.M., & Zeegers, H. 1992, *Regolith Exploration Geochemistry in Tropical and Subtropical Terrains.* Handbook of Exploration Geochemistry, 4. Elsevier, Amsterdam. 607pp.

Butt, C.R.M., Gray, D.J., Lintern, M.J., Robertson, I.D.M., Taylor, G.F., & Scott, K.M. 1991, *Gold and associated elements in the regolith - dispersion processes and implications for exploration.* Report 167R, CSIRO Australia, Division of Exploration Geoscience, Perth. 114pp.

Lintern, M.J., & Scott, K.M. 1990, *The distribution of gold and other elements in soils and vegetation at Panglo, Western Australia.* Report 129R, CSIRO Australia, Division of Exploration Geoscience, Perth. 96pp.

Smith, R.E., Anand, R.R., Churchward, H.M., Robertson, I.D.M., Grunsky, E.C., Gray, D.J., Wildman, J.E., & Perdrix, J.L. 1992, *Laterite geochemistry for detecting concealed mineral deposits.* Report 236R, CSIRO Australia, Division of Exploration Geoscience, Perth. 171pp.

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Recent developments in Regolith mapping

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In the process of mapping and classifying regolith (all materials above unweathered bedrock) the role of the regolith mapper can be divided into three fundamental stages: *sensing, recognition and interpretation*, in much the same way as the stages are recognised as part of the process of land evaluation (Gibbons & others, 1968). The first stage is sensing, and is our physical reaction to phenomena. The second stage is recognition in which we assign meaning to the stimuli we receive. The third stage is interpretation where the regolith mapper assesses the significance of the phenomena observed groups, or divides the material into mappable regolith units according to scale. The end result of this process is a regolith map. It should be as factual as the process can allow but it must be recognised that there will always be an element of interpretation within it.

The development of regolith mapping concepts in Australia can be related to early work by Christian and Stewart in the Northern Territory (Craig & others, 1993). Some more notable influences in mapping concepts and strategies are provided by Stewart & Perry (1953), Mabbutt, (1968), Stewart (1968), Ollier (1977), and Jennings & Mabbutt (1986). Early regolith mapping approaches in Australia have tended to rely heavily on the field mapper, although not always, to gather the data and give it meaning ie, undertake the sensing and carry out the recognition process and finally, to do the interpreting. More recently in Australia there is an increasing trend away from these early established roles in regolith mapping. The trend comes in particular from the ongoing development and accessibility of remote sensing technology. Experience shows that there are those among us who do not always recognise the three separate basic roles in regolith mapping *(sensing, recognition and interpretation)*. As a result some, perhaps with vested interests, are tending to overpromote the importance of the sensing stage at the expense of the still very important and so far still very human stages of recognition and interpretation. We need to ensure that in our desire to map regolith effectively and more efficiently we maintain the highest possible integrity of data, through to and including the interpretation stage. It is vital that an appropriate balance be maintained between the mapping stages assigned to technology and those left to the experience of the mapper.

Technology not only now enjoys an increased level of acceptance in data gathering but also it is now effectively employed beyond the final stages of mapping in the presentation phase. The automation of mapping, data manipulation, data interrogation and presentation is increasingly embraced by scientists, managers and clients under a "mistletoe" like canopy of efficiency and cost effectiveness. Technologies applied to this part of the regolith mapping process have widely recognised values (Rattenbury & others, 1992). The pitfalls are still present but their explanation is beyond the scope of this discussion.

The underpinning of present regolith mapping techniques in Australia by work which began in the fifties and extended to the seventies is well recognised by Craig & others (1993). Until recently geological maps have contained basement geology and some regolith information, for example regolith shown as Cza or Czl. Probably because of the dual role of geological maps in the immediate past, there is still a tendency to believe that regolith mapping is simply the same as geological mapping and that if you can map geology then you can map regolith the same way. This is far from the truth. Regolith materials lack adherence to the law of continuity of "strata" so often helpful in solving geological mapping problems. Usually regolith polygons are surrogates for a complex internal pattern of materials and so it is rare to simply map a pure regolith material. It is rare to map a "geologically" pure material. Geological polygons are often internally complex units described as formations, groups etc and placed in a time framework. This simple similarity does not make geological mapping and regolith mapping equivalent techniques. This basic similarity does give us insight from a geological point of view about what we can expect a regolith map to show in terms of material purity. Geological mapping techniques have taken about 150 years to reach their present level of sophistication, yet there is an expectation that regolith mapping techniques have required a minimal amount of time for development and refining. Few experienced regolith mappers would hold this view. We need to recognise that regolith mapping still needs to be given latitude and development time along the way, despite the pressing need for its immediate productivity. We should be prepared to accept that mapping regolith and geology are not equivalent procedures.

The first regolith map published in Australia by the Bureau of Mineral Resources, Geology and Geophysics (BMR) was the 1:5 Million continental scale map (Chan & others, 1986). That map was produced using a combination of aerial photography, literature and map review and Coastal Zone Colour Scanner (CZCS) satellite imagery. The map now serves as a regolith overview of the continent in much the same way as the geological map of Australia provides an overview of continental geology. It also served as a proving ground for ideas, mapping techniques and strategies for further work. The map was followed by a move to 1:1 Million scale regolith mapping of selected parts of Australia for example, Hamilton, VIC; Kalgoorlie, WA; and Clermont, QLD (Ollier & Joyce, 1986; Chan & others, 1988; Craig, 1989; Chan & others, 1992). AGSO's current regolith mapping technique (regolith landform mapping at 1:250 000) clearly owes much to the original experience gained from mapping the Kalgoorlie sheet in the Yilgarn. The techniques have continued to develop over the last three years as a result of experiences elsewhere in Australia through the commencement of the National Geoscience Mapping Accord between the Commonwealth, States and the Northern Territory. The "second generation" philosophy of the geological mapping program in the Yilgarn bears directly on the associated regolith mapping component by ensuring new technologies for example, satellite imagery, aircraft gammaray spectrometric imagery and the presentation and analytical power of Geographic Information Systems (Rattenbury & others, 1992) are used wherever appropriate and available. Aerial photography or other proven technologies are still in use and are at times more effective. This broad use of technologies has been closely coupled with an integrated understanding of the role of geomorphology, and regolith development through landscapebased mapping principles. The mapping of appropriate geomorphic features where they are effective clues to the evolution of landscapes and regolith will play an increasing role in AGSO's regolith mapping strategies across Australia.

The Yilgarn has served well as an early proving ground for the development of regolith mapping techniques in Australia. Geoscience agencies such as AGSO Minerals and Environment; CSIRO Division of Exploration and Mining (laterite geochemistry group); and Geological Survey of Western Australia (GSWA) have each made significant individual contributions through their Yilgarn work to a better understanding and improved mapping of regolith.

There are recognisable trends through time in the scale of regolith mapping and the purpose for which it is done. These trends in Australian regolith mapping are best seen in the world context of landform based mapping schemes in Fig. 1. Early landform based mapping schemes were scale directed, for example the CSIRO's land system mapping was primarily directed towards work at 1:250 000 scale. The most recent lead is AGSO's development of a scale independent mapping system. The distinct advantage of AGSO's approach is that one mapping concept applies to all scales thereby eliminating the need to devise new classifications, mapping concepts and techniques each time there is a need to vary the scale of mapping. Aspects of a scale independent mapping approach are more fully discussed by Craig & others (1993) and to a lesser extent by Pain & others (1991).

The recent development in regolith mapping mentioned earlier is the stronger move towards increased automatic data collection, mainly in the form of satellite and airborne remote sensing. There is an associated risk of too vigorously promoting what recognition and interpretation can or cannot be applied to these forms of remote sensing without adequately ensuring their limitations are fully understood. The tendency to overpromote can often be detected in discussions where greatly accelerated rates of regolith mapping are being sought, where a greater range of material identification is expected during the mapping process, or even erroneously where there is hope of all but eliminating the need for fieldwork on the grounds of cost, or some other combination of these factors. These views are often strongly held by those with very limited or no regolith, land or geomorphic mapping expertise or experience. Despite their limitations, satellite and airborne remotely sensed data are a very valuable tool for regolith mapping. The data from this type of imagery can help provide vital additional clues about the surface expression nature and distribution of regolith. For example, Thematic Mapper (TM) imagery as single band images, colour composites or as more complex ratioed images, often assist with identifying and recognising additional regolith attributes at the surface beyond that identified in the field and with photographic interpretation. Further help comes from aircraft gammaray spectrometrics as described in Wilford (1992), and from some forms of magnetic imagery (Fleming, pers comm). The extent to which these techniques provide useful mapping information also depends, among other things, on the present and palaeogeomorphic setting and processes. Bedrock geology conditions, the density of regolith field observations and the scale at which regolith data is to be presented, all influence how useful digital imagery might be. Associated with the emerging tendency to overpromote remote sensing technology there is a trend towards simultaneous undervaluation of the usefulness of aerial photography in regolith mapping. Unfortunately aerial photography is now increasingly dismissed as old technology. Not so much by those who know how to use this medium but more so by those who do not. A view more frequently expressed now is that regolith mappers can achieve their mapping goals only by the use of new remote sensing technologies. This shows a lack of understanding of both regolith attributes and the capabilities and limitations of remote sensing technology.

LANDFORM BASED MAPPING SCHEMES

SCALE	SMALL				LARGE
CSIRO AUSTRALIA	......	LAND SYSTEM	LAND UNIT	LAND FACET	LAND ELEMENTS (NOT MAPPED)
SOIL CONSERVATION AUTHORITY, VICTORIA	LAND ZONE	LAND SYSTEM	LAND UNIT	LAND COMPONENT	.....
OXFORD, MEXE UNITED KINGDOM	.....	LAND SYSTEM	LAND FACET	LAND ELEMENTS (NOT MAPPED)	.....
USSR	MESTNOST	UROCHISCHE	SUB-UROCHISCHE	ZVENO	FACIA
JAPAN	PROVINCE	SECTION	ASSOCIATION	SERIES	LANDFORM TYPE
GERMANY	MACROCHORES	MESOCHORES	MICROCHORES	ECOTOPE COMPLEX	.....
AGSO			REGOLITH LANDFORM UNITS		
CSIRO/AMIRA				REGOLITH LANDFORM UNITS	
GSWA				REGOLITH LANDFORM UNITS	

Fig. 1. Landform based mapping schemes showing hierarchical relationships between basic mapping units and subunits (from Craig & others, 1993 modified from Christian & Stewart 1953).

Aerial photography provides the most realistic view of the regolith because it records data in the visible spectrum, which is precisely the same part of the spectrum as the human receptive processes by which field observations are conducted. This link is too important to ignore. The three dimensional view of the surface provided by stereo aerial photography allows the regolith mapper to relate surface form and process to landscape evolution and regolith materials by a combination of observation and interpretation. So far it is not possible to emulate all aspects of this process using remotely sensed imagery. For very useful reasons satellite imagery may selectively record data outside the visible spectrum therefore any mapping boundaries determined from these images may not be obviously related to landform boundaries. Only recently has it become possible to examine remote sensing imagery combined with digital elevation models (DEMs), and/or stereoscopy together with computer assisted "draping" of other data sets onto DEMs. The effectiveness of this process still requires more rigourous assessment. Gibbons & others (1968) stressed that people and instruments can each have a useful role but that instruments alone cannot do the intuitive and interpretive stage needed in landscape based mapping. This statements still holds for digital image processing. Where imagery such as aerial photography is closely linked to the processes of intuitive reasoning and interpretation used in mapping the regolith, it ought not be cast aside rather it should be a basic tool. If the only reason given for casting aside aerial photography as a useful working medium is that it is old technology then this is a simple admission of shortsightedness. There should be enough scope for regolith mappers to make use of whatever works best. On this count those with the expertise and experience should be the source of the best advice. There is obvious danger in regolith mapping being too strongly driven by any technology simply for its own sake.

The very pragmatic trends now developing in regolith mapping in the Yilgarn and elsewhere in Australia are those involving the judicious use of remotely sensed imagery as an adjunct to a basic framework derived initially from fieldwork using aerial photography. Basic regolith polygons in current regolith mapping are based on the relationship between materials and landform. Landforms help provide the fundamental regolith polygon boundary. The landform boundary is the most useful and reliably repeatable boundary available to regolith mappers. At present these boundaries are more easily and inexpensively delineated using stereoscopic aerial photographic interpretation. To what extent this can be replaced by using stereoscopic digital terrain models is yet to be evaluated. Where there is uncertainty with landform based regolith boundaries, boundaries defined by gammaray spectrometrics can be usefully employed. In other cases boundaries defined by high frequency magnetics, and airborne or satellite multispectral scanner imagery can help. For the most part these efforts are all aimed at producing a reliable two dimensional regolith map. However, the third dimension also needs attention.

We are all too aware that the third dimension in regolith is harder to deal with and it is far less accessible. Work to be undertaken in the Yilgarn by the Australian Mineral Exploration Technology Cooperative Research Centre's (AMETCRC) Regolith Characterisation program may go some way to resolving some of these problems. It is far more difficult to show the regolith third dimension effectively on a map. Much of AGSO's regolith 3D information resides in the national regolith database (RTMAP) and is being linked to digital regolith maps in GIS environments. When dealing with regolith materials the concept of stratigraphy is not as simple as it can be with traditional geological materials. Regolith materials result from the interaction of geomorphic processes at or near the surface of the earth and are by their nature quite spatially variable. This process variability leads to complications such as multifaceted landscape surfaces in time and space and therefore diachronous surfaces are more likely to be a rule rather than an exception. Topographically inverted chronosequences add further complication and are difficult to recognise in the field. Regolith materials may be older near the surface and younger at depth thereby contrasting significantly with the simple law of superposition for example, weathering profiles developed in association with a fluctuating water table. In some cases, AGSO addresses the third dimension in its regional regolith mapping program by incorporating simple information onto the map face by the use of overprint symbols or varied colour intensities, but increasingly now by including information in a linked database to the digital regolith maps. The reason for mapping regolith, despite the methodology employed being essentially the same, often leads to a change of scale change. CSIRO's Laterite Geochemistry Group uses the same regolith mapping methodology as AGSO and GSWA but in addressing different issues tend to map regolith at larger scales (Craig & others, 1993).

Overall, the trend in mapping Australian regolith is towards the mapping methodology and concepts used by AGSO. An AGSO, CSIRO and GSWA regolith mapping working party has been established and is addressing a number of issues concerning regolith mapping in the Yilgarn. One issue is to determine to what extent terminology may be standardised (Craig & others, 1993). AGSO has already ensured that its RTMAP database structure is well documented to allow external agencies to arrange their own datasets into an easily transferable format for inclusion in a variety of national datasets.

Recent cooperative work within the AMETCRC has led to joint regolith mapping between the three major government geoscience agencies working in the Yilgarn. AGSO, CSIRO and GSWA, together with Curtin University, have each contributed to the production of a special regolith map brought about by the needs of AMIRA project P240A. Through initiatives by AGSO, this work will be incorporated into AGSO's National Geoscience Mapping Accord work program by producing 1:250 000 scale regolith maps for both the Kurnalpi and Kalgoorlie sheet areas. This will be done by extending from a special regolith map which equally straddles parts of both sheet areas. Regolith mapping in the Yilgarn is now far more integrated than before and shows the way for more desirable and promising future developments.

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References

Chan, R.C., Craig, M.A., D'Addario, G.W., Gibson, D.L., Ollier, C.D., & Taylor, G. 1986, The Regolith Terrain Map of Australia 1:5 000 000. *Bureau of Mineral Resources, Australia* Record 1986/27.

Chan, R.C., Craig, M.A. Hazell, M.S., & Ollier, C.D. 1992, Kalgoorlie 1:1 Million scale Regolith Terrain Map. *AGSO (BMR)* Australia.

Chan, R.C. Ollier, C.D., & Gibson, D.L. 1988, Regolith terrain data: Kalgoorlie 1:1 M sheet SH51, Western Australia. *Bureau of Mineral Resources, Australia, Record 1988/3.*

Christian, C.S., & Stewart, G.A. 1953, General Report on survey of Katherine Darwin region, 1946. CSIRO *Land Research Series, 1.*

Craig, M.A. 1989, Preliminary report on regolith mapping for the Clermont 1:1 M sheet area, Queensland. *Bureau of Mineral Resources, Australia*, unpublished report.

Craig, M.A., Anand, R.R., Churchward, H.M., Gozzard, J.R. Smith, R.E., & Smith, K. 1993, Regolith landform mapping in the Yilgarn Craton, Western Australia: towards a standardised approach. *CSIRO Division of Exploration Geoscience, Unrestricted Report* 338.

Gibbons, F.R., Rowan, N.J., & Downes, R.G. 1968, The Role of Humans in Land Evaluation, in *Land Evaluation*, ed. Stewart, G.A., Macmillan Australia, pp 231238.

Jennings, J.N., & Mabbutt, J.A. 1986, Physiographic outlines and regions, in *Australia A Geography* Volume 1 the natural environment, ed D.N. Jeans, Sydney University Press, pp 8097.

Mabbutt, J.A. 1968, Review of Concepts of Land Evaluation, in *Land Evaluation*, ed. Stewart, G.A., Macmillan Australia, pp 1128.

Ollier, C.D. 1977, Early landform evolution, in *Australia A Geography* Volume 1 the natural environment, ed. D.N. Jeans, Sydney University Press, Sydney University Press, pp 97116.

Ollier, C.D., Chan, R.C., Craig, M.A., & Gibson D.L. 1988, Aspects of landscape history and regolith evolution in the Kalgoorlie region, Western Australia. *BMR Journal of Australian Geology and Geophysics*, 10, pp 309321.

Ollier, C.D., & Joyce, E.B. 1986, Regolith terrain units of the Hamilton 1:1 000 000 sheet area, Western Victoria. *Bureau of Mineral Resources*, Australia, Record 1986/33.

Pain, C.F., Chan, R.C., Craig, M.A., Hazell, M., Kamprad, J., & Wilford, J. 1991, RTMAP, BMR regolith database field handbook. Minerals and Land Use Program, Series 1. *Bureau of Mineral Resources*, Record 1991/29.

Rattenbury, M., Craig, M.A., Oversby, B., & Whitaker, A. 1992, Adding layers towards a GIS data package, in *Geographic Information Systems, Cartographic and Geoscientific Data Standards, Workshop Proceedings*, Bureau of Mineral Resources Record 1992/27.

Stewart C.S., & Perry, R.A. 1953, Survey of Bowen-Townsville region, 1950, CSIRO Land *Research Series, 2,* Australia.

Stewart. G.A. 1968, Land Evaluation, in *Land Evaluation*, ed. Stewart, G.A., Macmillan Australia, pp 110.

Wilford, J.R. 1992, Regolith mapping using integrated Landsat TM imagery and high resolution gammaray spectrometric imagery Cape York Peninsula, Surficial Geology Series No 3, Minerals and Land Use Program, *Bureau of Mineral Resources Australia*, Record 1992/78.

Follows p. 205

Exploration for blind orebodies

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The search for orebodies which do not outcrop is the challenge to probe and interpret the third-dimension. The question to be answered is not whether we can find such deposits, but rather, whether we can find such deposits at a cost which justifies the search in financial terms. Does the likely reward justify the cost and risk?

Mackenzie and Doggett (1993) have assessed the economics of exploration in Australia over the 32-year period 1955-86. The average cost of finding and delineating economic deposits during this period was $51 million with the following commodity breakdown:

- for gold—A$ 17 million,
- for nickel—A$ 19 million, and
- for copper-lead-zinc—A$ 219 million.

The industry's average discovery cost for gold and nickel are acceptable; the discovery cost for base metals is not.

We need to ask ourselves why has the cost of discovering an economic base metal deposit been more than ten times the cost of discovering an economic gold or nickel deposit? I suggest the answer lies in the fact that much of the search for gold and nickel has been conducted in areas where surface indicator methods of exploration were effective. In contrast, much base metal exploration has perhaps focussed on concealed ground, seeking the "blind" deposit, often before adequate technology was available. Clearly, we cannot justify searching for "blind" base metal deposits unless we can dramatically change the cost of discovery.

It is unrealistic to think that rising metal prices will justify an increasing cost of discovery. The prices of metals continue to fall in real terms. Moreover, there are many parts of the world where surface indicator techniques have still to be effectively applied and where we can therefore expect low-cost discoveries to be made. If we are to make the search for "blind" deposits a justifiable utilisation of financial resources we, the explorers, must become a lot smarter.

Geochemists will be challenged to use the advances in regolith mapping, analytical chemistry and computing power to better understand:

- element migration and dispersion in weathered and transported materials, and
- the definition of primary geochemical haloes associated with ore.

But smart geochemists, working closely with the geologist are required, for once we try to look 60 to 70 metres beneath the surface and drill for samples, the sampling cost escalates dramatically. A sample can be collected at the surface and analysed for $12/sample. A sample from a depth of 70 m beneath a salt lake will cost $700 to collect and analyse. For such exploration to be an efficient use of exploration funds the drilling must be well targeted and the geochemist able to interpret the proximity or absence of ore with far fewer samples than would be available from surface exploration.

The effective use of geophysics is also essential once the focus of mineral exploration moves to search for deposits not exposed on the present land surface. This is already evident in the almost universal use of airborne magnetic surveys. But, geophysical data must be used to solve geological problems and identify ore, not just to define anomalies.

Borehole geophysical logging, hole to hole and surface to hole surveys will need to become routine to expand the search beyond the restricted range sampled by the drill. It follows that documenting the petrophysical properties of ore and the rocks associated with ore must become routine.

Multi-component geophysical surveys and computing power provide the geophysicist-geologist team with the means to resolve the nature of concealed bedrock. But the effective integration of regional geophysics into regional mapping programmes requires drilling to provide some "ground truth" by way of the petrophysical character of overburden and bedrock. More resources will need to be devoted in future to targeted, stratigraphic drilling to advance such work.

Seismic surveys revolutionised petroleum exploration and gave petroleum geologists a substantial advantage over mineral explorers in interpreting sub-surface geology, and seismic technology has now been developed to the point where the data can be used to directly detect the presence of hydrocarbons. Advances in geophysical instrumentation and computing have now given geoscientists working with crystalline rocks the tools to use seismic methods. Such surveys can now help to resolve structure and, in time, will be used to directly detect mineralisation. Seismic tomography using boreholes to position signal source or receivers will become routine in the search for ore at both a regional and mine scale.

The 1990s has seen the geophysicist assume a more prominent role, and at times, the lead role, in the search for orebodies, especially orebodies not exposed at the surface—i.e. the "blind" deposits. This trend will only accelerate. We will also see an increasing number of geophysicists based at mines to document the geophysical characteristics of the ore environment and to assist both surface and underground mine area exploration.

One of the most encouraging developments in mineral exploration has been the acceptance of the need to adopt a multidisciplinary team approach to organisation. Such an approach focuses all concerned on the main objective, which is to find ore. The geologist's role is not just the making of geological maps, nor just the development of theories of ore genesis. The geochemist's and geophysicist's roles are not just the definition of geophysical or geochemical anomalies. Everyone's role is the discovery of ore deposits at the lowest possible cost.

The discovery of the giant Olympic Dam deposit in 1976 well illustrates the power of the multidisciplinary team and how critical teamwork, team spirit and team support can be to success.

The discovery of the Olympic Dam deposit was the most important and most exciting mineral discovery worldwide in the 1970s and the most important in Australia since the discovery of the Kambalda nickel sulphide deposits in 1966. The deposit contains of the order of 2000 million tonnes with an average grade of 1.6% Cu, 0.6 kb., U_3O_8 & 0.6 g/Au per tonne. It is one of the largest copper deposits discovered, the world's largest uranium deposit and it will ultimately rank in gold production with Australia's largest gold deposit at Kalgoorlie. This deposit, which was the first of its type found anywhere in the world and whose discovery caused a worldwide resurgence of interest in exploration for similar deposits in mid-Proterozoic rocks, was discovered beneath 300m of younger, barren sediments. The Olympic Dam breccia complex is now recognised as a huge Proterozoic volcanic feature (Reeve & others, 1991) with diatreme facies which may have root zones of ultramafic and mafic rocks (Cross, 1992). The search followed a trail 3800 km long and lasted 20 years at a cost of A$30 million, and it very nearly failed. The deposit was discovered because of the power of a multidisciplinary team working for a company prepared to drill deep "wildcat" holes to test an idea, an idea which was based on both empirical and theoretical scientific logic (Woodall, in press).

The road to the discovery of blind ore deposits is neither solely paved with empirical or conceptual ideas: it is a blend of theory with observation and concept with empiricism (Woodall, in press). Exploration models (i.e. exploration strategies) are modes of travel and not precise destinations (Adams, 1985). When empiricism is dominant in our exploration strategies, we walk a more certain path. When concept (i.e. theory) dominates, there is greater uncertainty and greater risks, but the path may lead to the discovery of previously unknown ore deposit types, as was the case at Olympic Dam where the exploration strategy led to the discovery of the metal sought, but in an unexpected deposit type. Herein lies the power and potential of conceptual exploration.

For the mineral explorer, the most critical decision is area selection. The application of even the most sophisticated search techniques is futile if applied over poorly endowed terrain. Where there is outcrop, and evidence of ore reaches the surface, area selection using low-cost, surface indicator, prospecting techniques may be adequate. But, in concealed terrain, or where the ore deposit does not reach the surface, it is critical to understand ore-forming processes and to be able to recognise, from limited data, where those processes have been active. The problem is all to do with the source of metals, their mode of transport, their migration paths and the recognition of sites where those metals can be trapped and concentrated to form major ore deposits. This is the greatest of all challenges facing those who would search for blind deposits.

To adequately tackle this task of area selection we need to have a better understanding of the processes which result in the formation of major ore deposits. The study of minor ore occurrences alone is inadequate. Why are the giant ore systems where they are? Where is the next one? Why does each major mineral deposit or mineral field have an element of uniqueness? Of what importance are deep-Earth fractures, which on empirical evidence are associated with ore? Of what importance is deep-Earth convection, which localises fluid flow and heat flow? What part do plumes of ascending fluid play in ore formation; plumes which originate near the core-mantle boundary and near that part of the Earth richest in iron and sulphur, the two most common constituents of ore? Why the unique timing of metal enrichment in the crust of the Earth and how does this relate to the chemical evolution of the Earth. The successful explorer will be concerned about all these things.

References

Adams, S.S. 1985, *Using Geological Information To Develop Exploration Strategies For Epithermal Deposits.*

Berger, B., & Bethke, P.M., Geology and Geocemistry of Epithermal Systems, *Reviews in Economic Geology,* 2., pp. 273-296.

Cross, K. 1992, *The Olympic Dam Deposit: Breccia-hosted Cu-U-Au-Ag (REE) Mineralisation in a High Level Volcano-plutonic Setting.* Extended abstract from presentation at Selwyn Memorial Lecture.

Mackenzie B.W., & Doggett, M. 1993, *Economics of Mineral Exploration in Australia.* Centre for Resource Studies, Queen's University, Kingston, Ontario; Co-published with Australian Mineral Foundation, Glenside, South Australia.

Reeve, J.S., Cross. K.C., Smith, R.N., & Oreskes, N. 1991, *Olympic Dam Copper-Uranium-Gold-Silver Deposit.* The Geology of the Mineral Deposits of Australia and Papua New Guinea, Volume 2, Australasian Institute of Mining and Metallurgy, pp. 1009-1035.

Woodall, R. 1992 (in press), *Empiricism and Concept in Successful Mineral Exploration.* Keynote Address at 11th Australian Geological Convention, Ballarat, Victoria, Australia, 20 January, 1992.

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Application of geographic information systems (GIS) to regional–scale gold prospectivity mapping

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In the hundred years since the discovery of the Coolgardie and Kalgoorlie goldfields in 1892 and 1893 respectively, gold production from Western Australia has been cyclic, linked primarily to global economic factors including the two world wars and the great depression (Rowe, 1989). Although production has been variable, and recently has been at its highest, the mean ore-grade of deposits has steadily decreased (fig. 1; Groves & others, 1990). The majority of Western Australia's gold is located in the granite/greenstone terranes of the Yilgarn Block, an area notorious for its low relief and sparse outcrop (often as low as five percent exposure). Since most known deposits occur in areas of high exposure, the Yilgarn Block is still an attractive target for high ore-grade gold deposits. However, it is apparent that future exploration needs to concentrate on areas of low exposure, for which conventional prospecting and exploration techniques are not currently as successful as desired. In this paper, the potential role of Geographic Information Systems (GIS) in mineral-resource appraisal and exploration programmes is addressed. An example is used to show how GIS can be used to test and refine conceptual models regarding gold mineralisation. The paper concludes with an outline of the methodology for creating regional-scale prospectivity maps currently being developed and trialed at the Key Centre for Teaching and Research in Strategic Mineral Deposits at The University of Western Australia (Robinson, 1990; Knox-Robinson & others, 1992, 1993).

Current exploration techniques

In an attempt to discover the location of new deposits, both proximal and distal to presently-known gold-bearing systems, numerous surveys can be conducted. Geochemical surveys are often implemented in areas close to known deposits, with rock and soil samples being assayed for gold and gold-associated elements (Smith & Anand, 1990). Structural surveys, both at local- and regional- scales, also play an important role in the exploration process, allowing the identification of structures similar to those known to contain mineralisation (Vearncombe & others, 1990). More recently, exploration implementing geophysical and remote-sensing techniques has become common-place. High-resolution aeromagnetic and gravity surveys, subsequently filtered using digital image-processing techniques, have been used to map greenstone terrane to better define subsurface geology (Whitaker & others, 1987). Such surveys have revealed many previously unrecognised geological features, some of which are potentially important for gold mineralisation (Symons & others, 1990). Yet another exploration tool that is becoming increasingly more common is the use of airborne multi-spectral scanners (AMSS). Data from a suitable AMSS can be used to generate maps delineating areas rich in particular minerals at the surface, such as sericite, which are abundant within the alteration haloes of many gold deposits (Honey & Daniels, 1986). All of these methods have been used individually with varying degrees of success. However, it is becoming increasingly apparent that exploration programmes will only succeed in the future if they are able to integrate and incorporate the results from all available survey techniques. It is also evident that conventional geological maps are not being utilised to their full potential in an exploration project. Once created, geological maps are invariably used in a simplistic and subjective manner, with important relationships that are too subtle to be identified by the human eye often being overlooked.

For more effective exploration, it is important to use all the available data, including con-

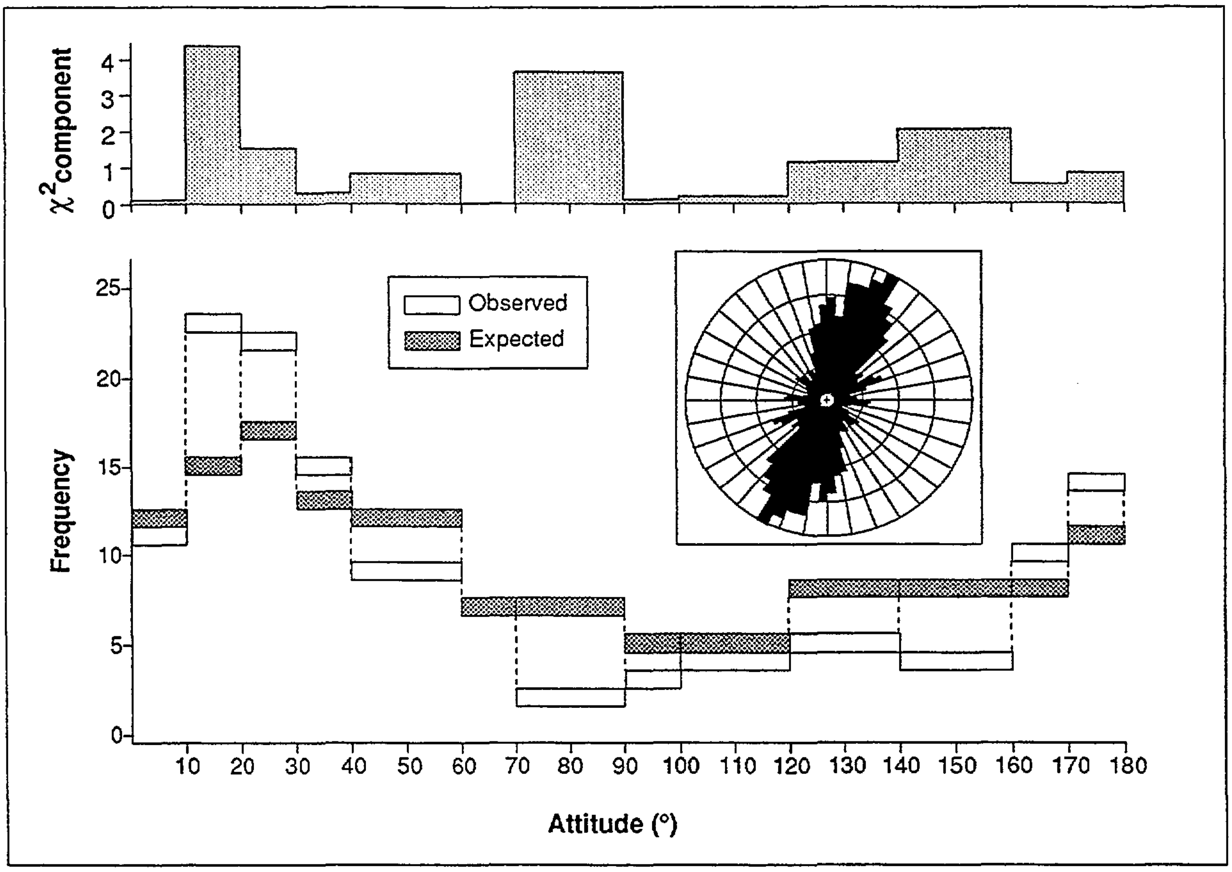

Fig. 1. Results of an attitude analysis examining for a spatial relationship between gold deposits and the attitude of crustal-scale faults in the Murchison Province of Western Australia. Bottom graph shows the observed and expected number of deposits in each fault-attitude category, and the top graph indicates which attitude categories the observed and expected frequencies deviate the most.

ventional geological maps. The results of the different survey techniques need to be integrated into a single and unified product that can be easily examined by exploration geologists. Incorporating and analysing spatial (and relevant non-spatial) data from a variety of different sources are tasks perfectly suited to a GIS. At the Key Centre, research implementing the use of GIS in applied geology has been underway for a number of years (Robinson, 1990; Knox-Robinson & others, 1992). The aims of this, and future research, include documenting the nature of Archaean lode-gold deposits in the constituent provinces of the Yilgarn Block, and the generation of regional-scale gold-prospectivity maps, that delineate areas considered favourable for hosting mineralisation (Knox-Robinson & others, 1992, 1993). Present research involves the analysis of geological map information, and the quantification of relationships between known deposits and surrounding map features.

Testing and refining conceptual models

Although the method that has been developed is empirically-based, it is important that conceptual theories regarding the siting of ore deposits can be tested and refined. Furthermore, if the concepts are found to be valid, it should be possible to incorporate them into the final prospectivity map. The method developed at the Key Centre has this capability.

An example of a conceptual model that has been tested using a GIS is one which suggests that if deposition is related to a particular type of lineament, such as a fault or shear, then mineralisation may be preferentially hosted close to portions lying within a restricted range of attitudes. The basis of this conceptual model is that regional stresses acting on a region prior to (or synonymously with) a major mineralisation event may result in zones of dilatancy forming preferentially along lineaments lying in particular directions. This model was tested during the construction of a gold prospectivity map for the Murchison Province of the Yilgarn Block at a scale of 1:500 000. The Murchison Province is ideal for testing this model as it is identified as undergoing five episodes of deformation, with gold mineralisation being associated with the later events (Watkins & Hickman, 1990). These later events may therefore have created higher relative dilatancy along sections of the older lineaments trending in a specific range of attitudes.

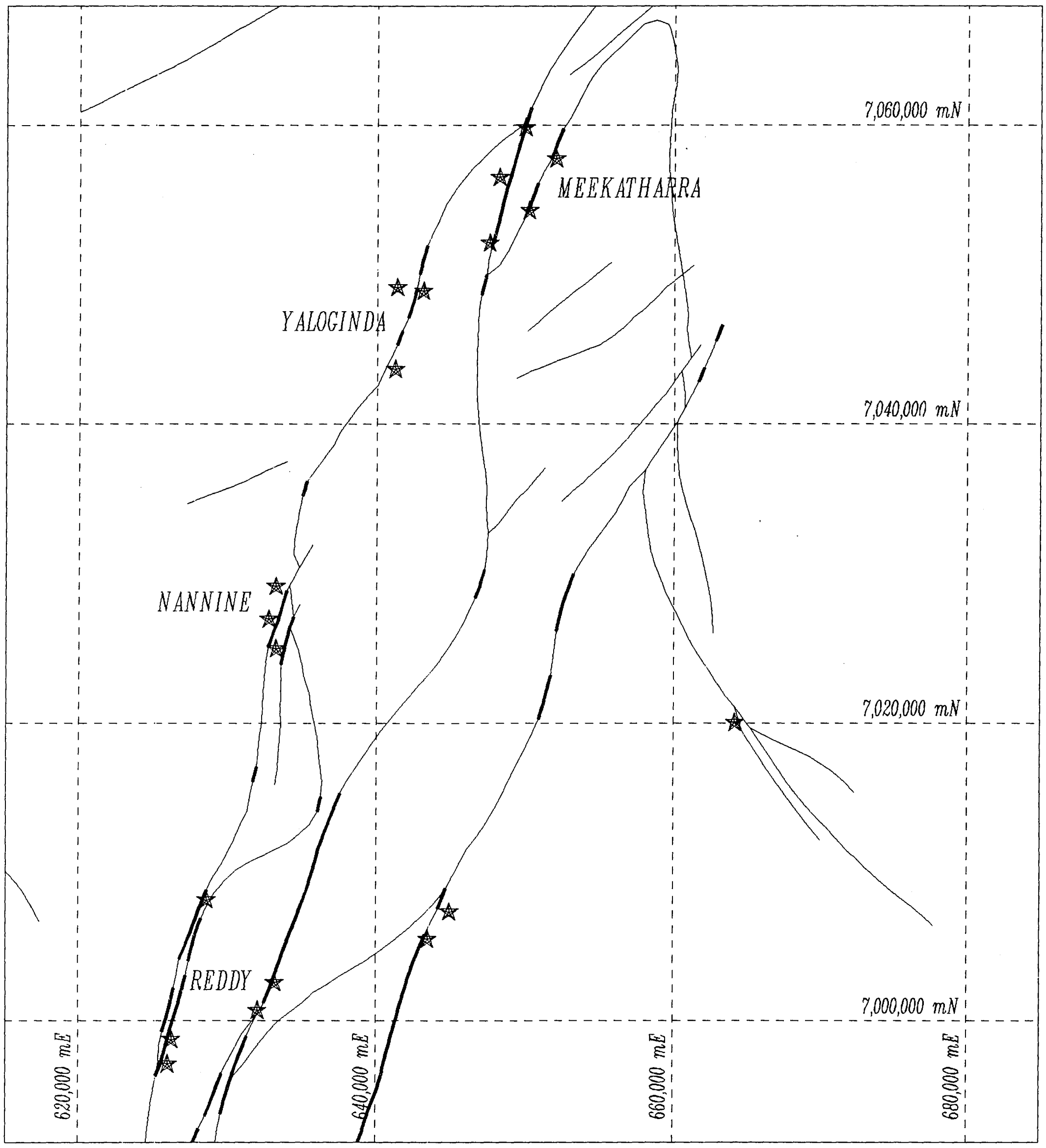

Fig. 2. Map of the northeastern portion of the Murchison Province showing crustal-scale faults and large gold deposits. Thick lines represent sections of the faults trending between 13 and 23 °.

Once a spatial relationship was verified between the positions of known deposition and the crustal-scale faults (Knox-Robinson & others, 1992), the GIS is used to split the faults into 500 m segments. For each segment, the attitude is calculated and stored in a related database. For large deposits (containing in excess of 100 kg extractable gold) lying within 1.5 km of a fault the attitude of the closest segment is recorded. These values are then compared to the number of deposits expected if deposit location is independent of fault attitude. To enable appropriate statistics to be calculated, fault attitudes are condensed into 13 groups, and a Chi-square test (Rock, 1988) is used to determine whether the observed and expected deposit distributions differ significantly (Fig. 1). Although the test fails to conclude that the observed and expected distributions are significantly different, the contribution of each attitude group to the Chi-square value indicates that the majority of the discrepancy between the two distributions is accountable to only two attitude ranges. Sections of faults lying with an attitude between 10 to 30° have more than the expected number of deposits associated with them, and lineaments trending between 70 and 90° have a lower than expected number of proximal deposits. Interrogation of the spatial database shows that the majority of the deposits that lie in proximity to lineaments trending between 10 and 30° are spatially restricted to the northeastern portion of the Province. The bulk of these deposits lie along an anastomosing array of faults and shears from Reddys in the south to Meekatharra in the north. The array is interpreted to be a result of the first deformation event and has subsequently been folded by later events (Watkins & Hickman, 1990). The faults also show indication

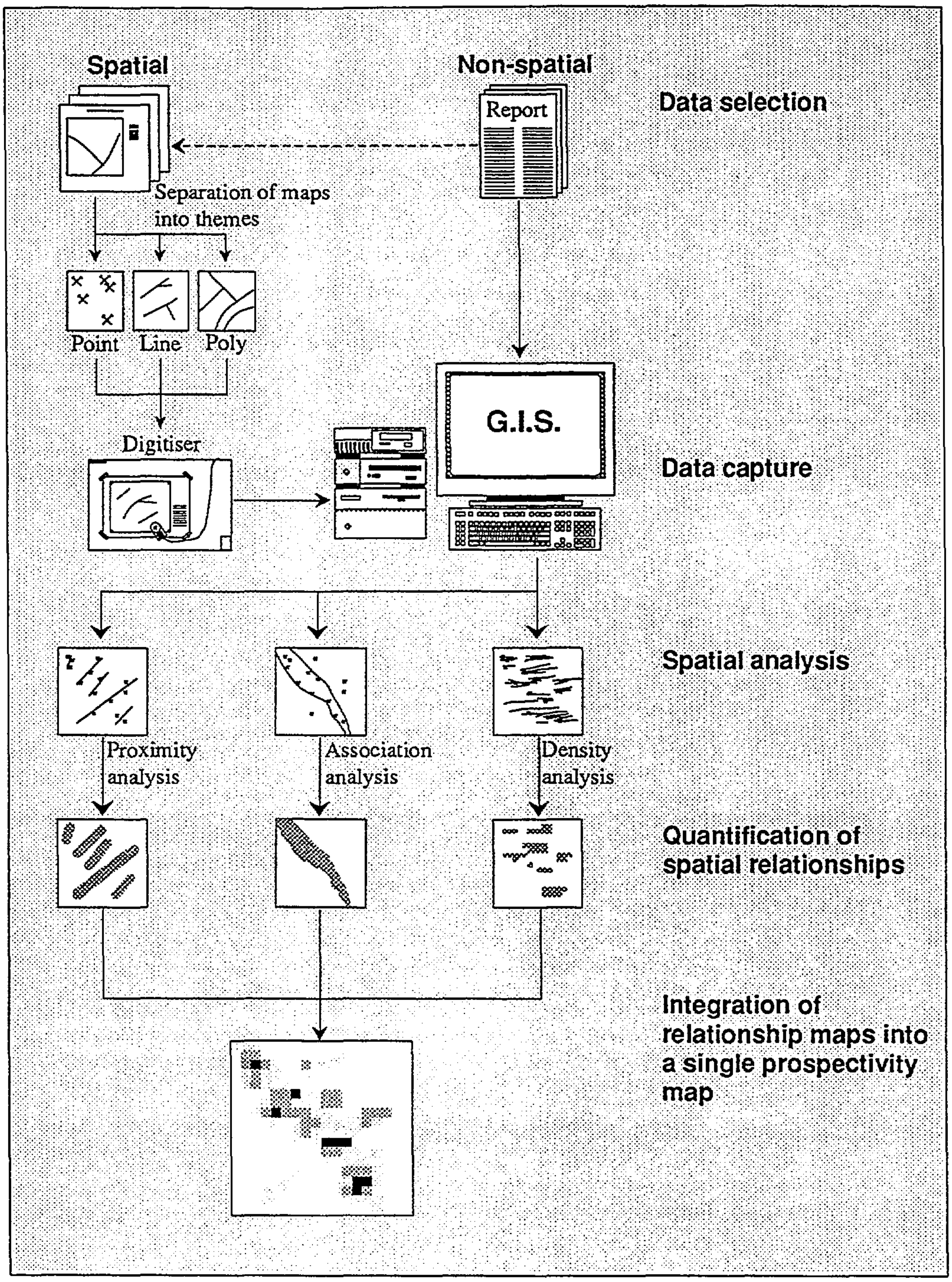

Fig. 3. Method for creating prospectivity maps currently being developed and trialed within the Key Centre at the University of Western Australia.

of re-activation by the fourth recognised deformation event which comprised regional east-west compression. This portion of the Murchison Province therefore fulfils all of the necessary pre-requisites for the existence of an attitude relationship. Application of a similar analysis to that conducted above confirms that a statistically-significant attitude association exists within this smaller region, with 16 out of 19 deposits lying in close proximity to sections of the lineaments lying in the restricted range between 13 and 23° (Fig. 2).

GIS therefore have the potential to test conceptual theories regarding mineralisation, and to determine the extent to which such an association may exist.

Creation of prospectivity maps

As outlined above, the methodology developed at the Key Centre is empirically-based, utilising relationships between known deposits and other map features. The method involves digitising relevant spatial information into a GIS as a series of separate thematic layers, and the construction of a comprehensive database of the known deposits within the region. Spatial relationships between the known deposits and other map features are quanti-

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fied onto a map comprising areas of low and high favourability. Three types of spatial relationship are recognised: association dependence in which deposits are associated with a particular feature (for example, host rock dependence); proximity dependence in which deposits are hosted closer to a particular feature (for example, deposit size versus distance to faults); and density dependence in which deposits are related to an abundance of a particular feature (for example, more deposits occurring where there are a greater density of crustal fractures). Once several spatial relationships have been identified and quantified, the resulting favourability maps are combined into a single prospectivity map (Fig. 3), using Bayesian statistics (Bonham-Carter, 1990), or if the sizes of the deposits are to be taken into account, an Algebraic method which has been developed at the Key Centre.

Only a subset of the deposits in the area are used in defining deposit parameters used in the creation of a prospectivity map, consequently the predictive capability of the map can be tested by determining if more than the expected number of the remaining deposits lie within the areas deemed to be highly prospective. Furthermore, if outcrop information is stored in the GIS, an estimate of the total amount of 'blind' gold in the study region can be made. By incorporating other relevant information into the GIS such as tenement boundaries, national parks, aboriginal reserves, and location of important amenities, a regional-scale prospectivity map can be re-assessed to further constrain the area on which efforts should be directed.

Summary

It is obvious that the potential of GIS in mineral exploration is vast. Their ability to identify relationships between layers of related data is only now being realised. The ability to easily integrate data from a number of sources, both vector (map data) and more recently raster (aeromagnetic and gravity data) in one system provides the exploration geologist with a powerful tool for modelling the complex systems for gold formation. Although GIS are in their early development stage in the field of geology, it is obvious that techniques, such as the ones developed at the Key Centre, can greatly enhance future exploration.

References

Bonham-Carter, G.F., & Agterberg, F.P. 1990, Application of microcomputer-based geographic information system to mineral potential mapping, in *Microcomputer applications in geology*, eds. J.T. Hanley, & D.F. Merriam, Pergamon Press, Oxford, pp 49-74.

Honey, F.R., & Daniels, J.L. 1986, Rock discrimination and alteration mapping for mineral exploration using the Carr Boyd / Geoscan airborne multispectral scanner. *Proceedings Fifth thematic conference, Nevada* 1986, unpaginated.

Knox-Robinson , C.M., Robinson, D.C., Gardoll, S.J., & Groves, D.I. 1993, The present and the future - GIS applications in applied geology, *Proceedings ACADS conference, Perth* 1993, unpaginated.

Knox-Robinson, C.M., Robinson, D.C., & Groves, D.I. 1992, The use of geographic information systems as a gold prospectivity mapping tool, with reference to the Archaean Yilgarn Block of Western Australia: requirements and limitations, *Australian Institute of Geoscientists*, Bulletin 12, pp 71-83.

Robinson, D.C. 1990, Gold prospectivity of the Southern Cross Greenstone Belt - Western Australia: mineral resource assessment using deposit models and a geographic information system. Unpublished B.Sc (Honours.) Thesis, The University of Western Australia.

Rock, N.M.S. 1988, *Numerical Geology*, Springer-Verlag, Berlin.

Rowe, R.J. 1989, *Gold in Western Australia: a reference book of gold industry technology*. Park Print. Western Australia.

Smith, R.E., & Anand, R.R. 1990, Geochemical exploration, in *Gold deposits of the Archaean Yilgarn Block, Western Australia: nature, genesis and exploration guides*, eds. S.E. Ho, D.I. Groves, & J.M. Bennett, Geology Department (Key Centre) & University Extension Publication 20, pp 331-336.

Symons, P., Anderson, G., Hamilton, L., Beard, T., Stately, R., Roth, E., & Ho, S.E., 1990. The structural and host rock settings of primary mineralisation at the Boddington gold mine, in *Gondwana: Terranes and Resources,* Tenth Australian Geological Convention, Hobart, 1990. Geological Society of Australia, Abstracts 25, 145-146.

Vearncombe, J.R., Grigson, M.W., Hronsky, J.M.A., & Libby, J.W. 1990, Regional structure and deposit location, in *Gold deposits of the Archaean Yilgarn Block, Western Australia: nature, genesis and exploration guides*, eds. S.E. Ho, D.I. Groves, & J.M. Bennett, Geology Department (Key Centre) & University Extension Publication 20, pp 348-350.

Watkins, K.P., & Hickman, A.H. 1990, Geological evolution of the Murchison Province, Western Australia, *Geological Survey of Western Australia*, Bulletin 137.

Whitaker, A., Wellman, P., & Reith H. 1987, The use of gravity and magnetic surveys in mapping greenstone terrane near Kalgoorlie, Western Australia. *Exploration Geophysics* 18, pp 371-380.

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Application of airborne EM in mineral exploration

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The ideal method for the extraction of geological information from EM data would be to transform the EM data to a 3D physical property map of conductivity. This 3D map could then be interpreted using the correspondence between the conductivity and geology of units of interest. EM methods are however limited by geometrical sensitivity to a specific lateral range and maximum depth. There is a further limitation due to wide variations in diffusion velocity which restrict application to the detection and mapping of only a limited range of geological units.

There are major difficulties in extracting 3D physical property maps from EM data, due solely to the complexities of the mathematics of vector diffusion. At present, numerical forward modelling is "geologically approximate" in that it is largely limited to only the simplest geometrical shapes such as spheres, uniform layers, thin sheets and tabular bodies. A forward model to calculate an expected response from a vastly simplified geological model may take hours on a supercomputer. Inversion, the much harder and slower process of mathematically predicting a physical property model from field data, is generally attempted only for uniform horizontal layering.

Considering the major difference between the expected geological complexity of an exploration target and achievable physical models for EM, recent research has considered "physically approximate" (but fast) methods that can realistically invert large quantities of AEM data. Case histories of geological mapping and mineral deposit detection using both physical and geological approximations illustrate both the major successes of AEM and its severe limitations. A CRC research program is underway to greatly extend the scope of AEM to geological mapping of and beneath the Australian regolith.

Seismic data have traditionally been presented in data sections whose geometry bears a very close relationship to the underlying geology, and therefore whose interpretation in the petroleum business has been by geologists rather than geophysicists. While expensive on a line-km basis, the data in soft-rock environments is extremely cost-effective and is considered absolutely essential. In mineral exploration, the geophysical data considered to be most cost effective is magnetics. Airborne magnetics has proved effective in direct detection of anomalous geology but now is used primarily as a mapping tool. Interpretation of magnetics for mapping purposes is usually undertaken by geologists.

AEM have on the other hand has been considered too expensive to use as a mapping tool; and has mainly been applied to massive sulphide exploration in relatively resistive terrains. Research in recent years has focussed on advances on two fronts:

- 1) Improvements in instrument sensitivity and reduction of noise to extend the depth range and resolving power of AEM; and
- 2) in techniques for the presentation and modelling of AEM data.

This does not involve refinements of multitrace squiggle plots or herringboned contours of raw data, but rather the production of physical property plans and sections that attempt to display conductivity structures in their correct spatial location. These displayed structures are necessarily a smoothed/fuzzy rendition of the actual structure.

The two fundamental scales in EM

In geological mapping, the most critical parameter is scale selection and the mapping scale is a simple choice of desired outcomes. In EM, mapping scales are often predetermined more by the geology than choice or the instrumentation! This arises from consideration of the two fundamental scales affecting an AEM measurement.

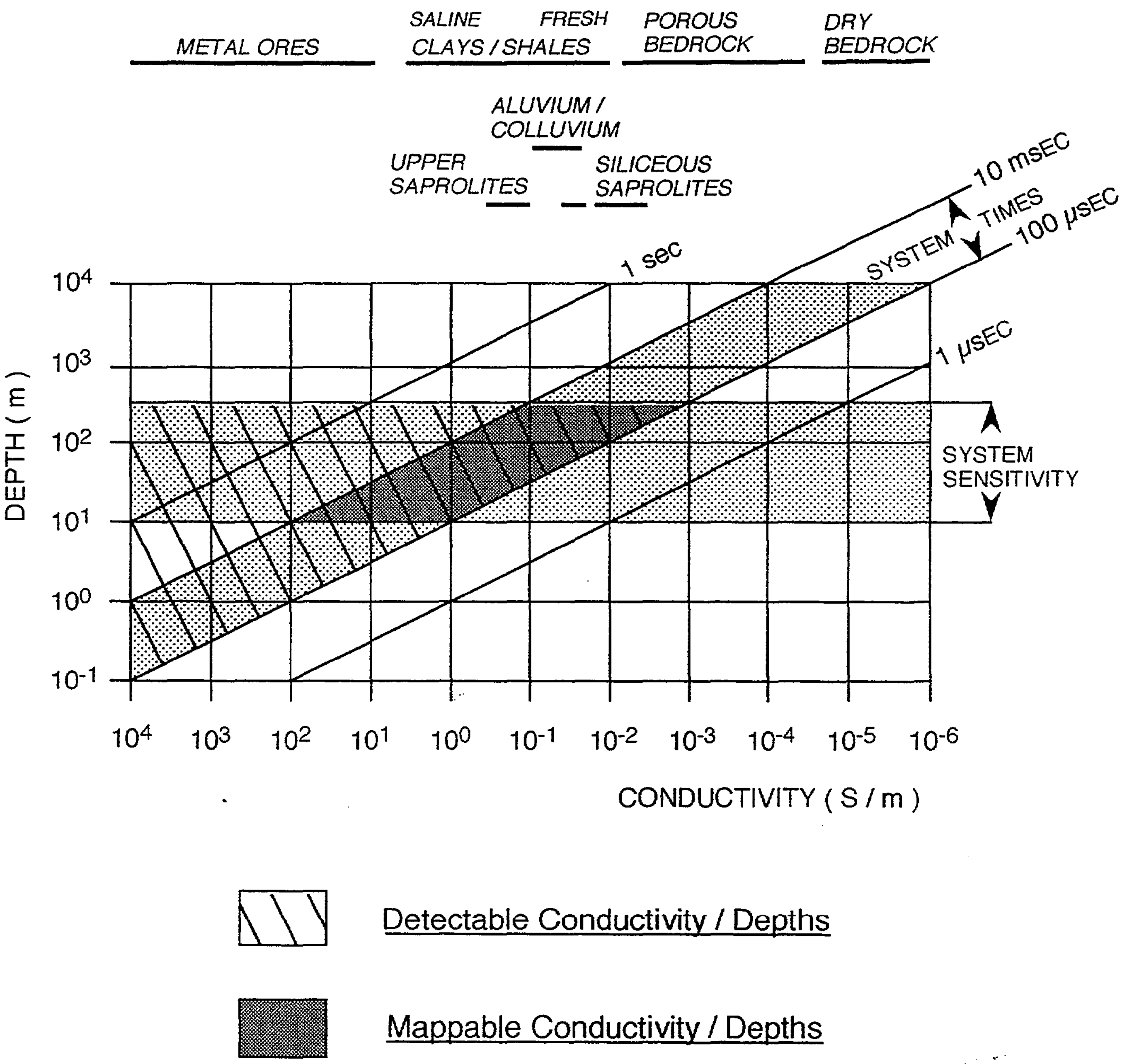

Fig. 1. An EM system measuring between 0.1 and 10 msec can only map details within a narrow range of depths dependent on local conductivity. Any zones with conductivity and thickness (depth) below the 0.1 msec line are "off-scale resistive". Any zones above the 10 msec line are detectable but will not be fully penetrated.

Geometry (and physical sensitivity)

The first scale length is essentially a geometrical one related to factors such as transmitter/receiver separation: if the receiver has a sensitivity/noise level sufficient to detect the field of the transmitter only to a certain distance, then the system can only detect targets at depth considerably less than this. Resolution is also a function of distance from a (detectable) target: 5 m depth resolution may be easily achievable for targets within 20 m of the receiver, but would be very difficult for a target 200 m away.

An AEM system can fly at an altitude of not less than about 100 m, with transmitter and receiver separated by a maximum of about 100 m. This implies a geometrical depth resolution not much better than say 10 m. With readings taken every 10 m, the minimum horizontal spatial resolution is about 10 m too. Sensitivity and noise considerations limit the absolute maximum depth to which a conductor may be detected to much less than 500 m even in ideal conditions.

Diffusion (and geological sensitivity)

The second length scale in EM is a function of geology and the frequency/timing range of instrumentation. Any geological unit may be physically characterised with its conductivity structure. Uniform conductivity is the usual assumption made, but anisotropic and inhomogeneous conductivity structures are very common depending on geological fabric, contained fluids, etc. Let us consider only regions of uniform conductivity.

An EM system measuring in the time domain can measure only a limited range of delay times following an abrupt discontinuity in the transmitter waveform. Due to signal fidelity considerations, most existing AEM systems measure only the 0.1 msec to 10 msec range. It is very difficult for physical reasons to get good data much shorter or much longer than these times.

An EM field does not travel at the speed of light through an extensive conductor: it induces current systems which oppose the change in the incident EM field, and which diffuse slowly away "dragging" the EM field with them. The velocity of this diffusion of the induced current system tends to continually decrease until the current system reaches the edges of any conductive region. At this point diffusion movement ceases. At all times, the energy in the current is being converted to heat in the rocks and so the current decays away to zero, whether it meets the edge of a conductor or not.

An EM system measuring between 0.1 and 10 ms will thus be sensitive over very different distances in different rocks or soils. This is illustrated in Fig. 1. In saline shales of conductivity say 1S/m (or 1 ohm-m resistivity) the penetration depths at 0.1, 10.0 msecs are 10, 100 m respectively. This implies that the EM system can obtain only an average conductivity for the top 10 m, and the field will only penetrate to 100 m before the receiver stops reading and the transmitter sends another pulse. Detail is however theoretically possible between these 10 and 100 m depths.

In crystalline shield rocks (dry or with permafrost) the conductivity may only be 1 microSiemen/m and the EM field will have diffused 10 km before the first measurement sample is taken at 0.1 msec! Since the geometrical sensitivity is only a few hundred metres at best, this rock is "off-scale resistive". A massive sulphide ore zone on the other hand may have a conductivity of 1000 S/m or more, and the penetration depths in an AEM time window will extend from 30 cm to 3 m.

At the geometrical scale of 10 m to 300 m highlighted in Fig. 1, we see that detailed mapping is only possible for a very limited range of rocks; (which includes the sediments, metasediments, saprolites and other regolith constituents, and groundwater). Any more conductive materials will be *detectable* and easily separable from resistive rocks, but the transmitter EM field will not penetrate to any significant distance.

Real systems with localised primary fields and real conductors with non-uniform conductivity and limited size require modifications be made to these conclusions: if the field completely penetrates through a conductive region it is possible to detect more distant/deeper regions of greater conductivity, but any detail in regions of lesser conductivity is lost.

Extracting physical properties from EM data

Forward modelling

Forward modelling may be performed either through scale modelling (Frischknecht, 1988) or mathematical (usually numerical, Hohmann, 1988) modelling. Both procedures are slow and therefore expensive, and have very significant limitations. Numerical modelling is very restricted in its potential complexity and the range of geometrical shapes amenable to modelling; scale modelling is restricted by a lack of suitable materials to model all conductivities of interest at laboratory scales.

An accurate forward model of reasonable complexity can be expected to take a day or so of modelling time with any available method. Some simple cases such as uniform horizontal layering, spheres and isolated thin sheets however, may be calculated in a few seconds or minutes on desktop computers.

Type curve and nomogram compilation

Nomograms, which contain compiled characteristic information from a number of simple forward models (West & Bailey 1989), are a frequently used aid in AEM interpretation. These nomograms may for example, relate observed shape information to dip, observed amplitudes to depth, or observed time decays to target conductance. Nomograms have generally been compiled for tabular targets in relatively resistive environments.

Inversion

Inversion is the mathematical technique by which data is fitted with an "acceptable model" through calculation or use of many forward models. Some of the errors associated with the modelling process are also analysed. Inversion is routinely attempted at present only for uniform, horizontal layering: inversion takes longer than forward modelling by a factor of about 3 to 10 in time per parameter being fitted. This could amount to months on even a mainframe or supercomputer, and is clearly uneconomic at the present! However, research in this field is advancing rapidly (Hohmann & Raiche, 1988).

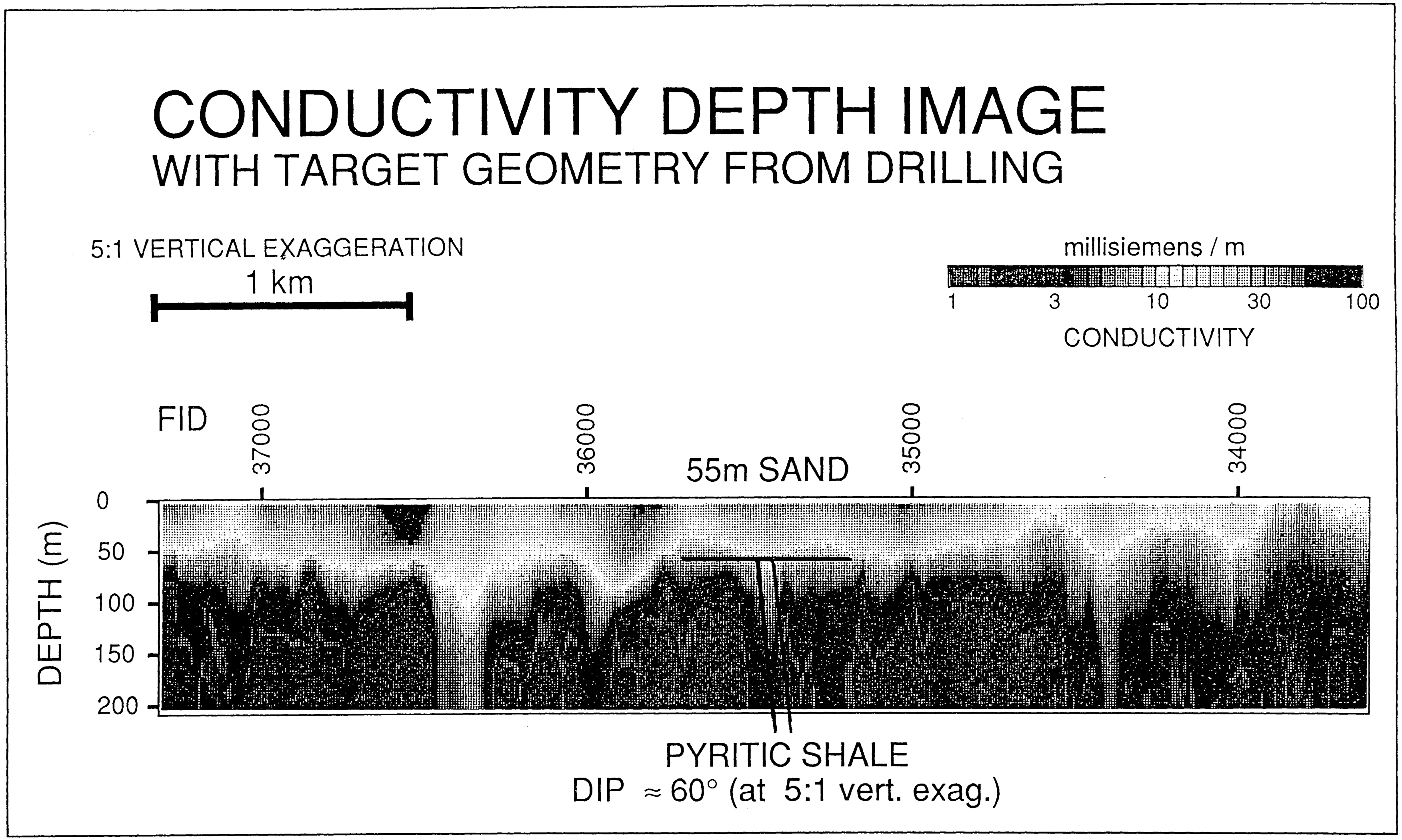

Fig. 2. A photocopy of a colour CDI section where tens of metres of sand cover the bedrock. The CDI transform is mathematically reasonable for the imaging of horizontal layers.

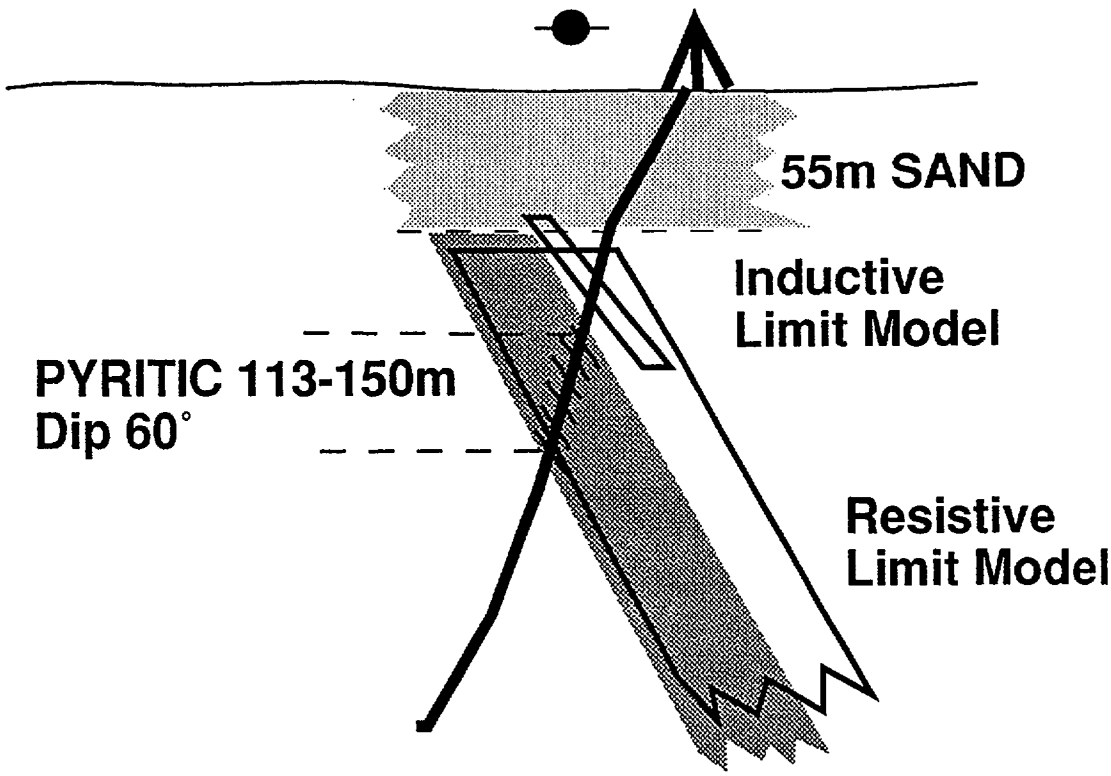

Fig. 3. Correspondence between automatically selected and fitted approximate models and simplified geology for a single target anomaly.

Approximate methods

Recent work (Eaton & Hohmann 1989; Macnae, & others 1991) has focussed on methods for calculation of fast approximate rather than exact models for EM systems. The justification for this approach is twofold: the exact (or at least physically accurate) models than can be calculated are vastly oversimplified from the actual physical properties of a geological structure; and second they are simply too slow to apply to all data collected in mineral exploration. A 1000 line-km AEM survey may have a response at every survey point and many tens or hundreds of "bumps" that are potentially anomalous.

Methods for conversion of EM data to conductivity-depth images (CDI) for areas where the conductors are relatively flat-lying are fairly common. Recent research has also determined that localized targets can be usefully fitted with models that are only correct at mathematical extremes of the EM induction process. These extremes are known as the inductive and resistive limits. Research has therefore focussed on techniques for the prediction of these limits from time-domain AEM data, and on methods for extraction of local source geometry. Figures 2 and 3 present the results of automatic anomaly picking and approximate model fitting to show the successful modelling of a steeply dipping zone of pyritic shale under 55 m of conductive (saline groundwater) sands.

Actual application and examples

Quasi-layered mapping

There are several geological problems involving sub-horizontal structures to which AEM has been succesfully applied in mapping. These include the mapping of resistive basement topography under a conductive shale cover, and the mapping of shale and metasedimentary horizons.

The geometry of regolith structures is frequently quasi-layered, and as discussed above it is right in the ideal scale for EM mapping (Mayes, 1992). We therefore anticipate that in the near future the CRC research will provide means for useful geological mapping of regolith and by inference bedrock with AEM.

Local target mapping

In simple cases where an isolated target is detected within a resistive host, with or without a uniformly conductive cover, we believe that accurate and automatic determination of target characteristics is achievable. Case history examples will be used to illustrate this with data from Africa (Figs. 2 and 3) and North America.

We anticipate that similarly successful results will be obtained using Australian data. We have a commitment from AEM contractors to provide digital Geotem and/or Questem data from published case histories over McArthur River, Abra and

Freddie Well; and subject to its delivery will discuss the results at the conference.

References

Eaton, P. A., & Hohmann, G.W. 1989, A rapid inversion technique for transient electromagnetic soundings, *Physics Earth Planet Interiors* 53: 384-404.

Frischknecht, F. C. 1988, Electromagnetic physical scale modelling, in Nabighian M.N., ed. *Electromagnetic methods in applied geophysics*, 1: 364-441.

Hohmann, G. W. 1988, Numerical modelling for electromagnetic methods in geophysics; in Nabighian M.N., ed. *Electromagnetic methods in applied geophysics* 1: 313-363.

Hohmann, G. W., & Raiche, A.P. 1988, Inversion of controlled-source electromagnetic data; in Nabighian M.N., ed. *Electromagnetic methods in applied geophysics*, 1: 469-503.

Macnae, J. C., Smith, R., & others. 1991, Conductivity-depth imaging of airborne electromagnetic step-response data, *Geophysics* 56(1): 102-114.

Mays, K.A. 1992, *Applications of geophysical electrical and magnetic methods to regolith mapping at Lawlers, Western Australia;* B.Sc. Hons thesis, Curtin University.

West, G. F., & Bailey, R.C. 1989, Inverse methods in geophysical exploration, in Garland G.D., ed. *Proceedings of Exploration 1987*; Ontario Geological Survey special publication.

The new Mobile Metal Ion approach to the detection of buried mineralisation

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Mobile Metal Ions appear to be released from metal-containing orebodies, and the ions become weakly attached to surface soils. Careful use of weak extractants and very low level chemical pre-concentration and analysis techniques can be used to obtain significant and reliable element signals to enable the anomaly patterns to be enhanced, resolved and interpreted for the detection of blind ore-bodies. Whilst the exact mechanism for release, transport and "fixation" of the metals is as yet not clear, the technique is of considerable importance to the exploration industry, because of its apparent ability to operate through considerable thicknesses of overburden. The present paper presents case history information from twelve deposits, and over 10,000 individual analyses using the Mobile Metal Ion Process. A summary of the important steps in the integrated process, and the virtues and possible shortcomings are also given. The paper will also attempt to outline possible mechanisms currently being investigated for the formation of Mobile Metal Ion (MMI) anomalies, which are fundamental to the correct appreciation and application of the technique.

The Mobile Metal Ion Process

The Mobile Metal Ion Process is the integration of a number of discrete steps and processes, which are often carried out separately in geochemical exploration, but which because of the low level nature of the responses, must be extremely carefully quality controlled and linked together. In some cases the integration has required a degree of "new thinking" on behalf of participants to obtain the full benefits.

The following are the major steps in the process:

- (1) DATA COLLATION — The collation of existing data relating to the target mineralisation, topophil map, geophysical data, aeromagnetic data, aerial photographs, conventional geochemistry, drill logs,and geology can contribute significantly to the intelligent design of a sampling program.
- (2) FIELD INSPECTION AND SAMPLING — After field inspection to establish regolith and landform situations (only major changes in these appear to have any affect on MMI), sampling is carried out. Fortunately, simplicity of sample requirements is one of the major advantages of MMI. Commonly a 2 kg sample seived to -2 mm is used as the initial sampling requirement.
- (3) EXTRACTION OF METALS — Extraction of the metals is a very critical factor in the MMI process. The following extractants have been investigated, at various concentrations to find optimum extraction conditions. No one solution is capable of giving good extraction for all metals. The optimum digests are proprietary, and no further information on their composition will be given. It should also be noted, that because of the complexity of the dissolutions, the process cannot be directly compared with standard analytical techniques in terms of procedures, practices or cost.
- (4) PRE-CONCENTRATION — Metals are, where necessary, concentrated onto various electrode surfaces, to enable the extremely low levels of metals in the extractant solutions to be converted to readable analytical signals.
- (5) ANALYSIS — One of the most crucial factors in the MMI process is the pre-concentration and analysis at extremely low levels. Early tests showed that the ICPMS technique was not always suitable for the low level analysis of base metals in solutions with high electrolyte concentrations as required from the extractions. The technique was however, shown to be most suitable for low level analysis of precious metals in some of the extracts used. The Portable Digital Voltammeter, PDV2000 (Chemtronics Ltd.) has been used exclusively for the very low level analysis of base

TABLE. 1. Extractants investigated for suitability for partial extraction.

ACETIC ACID	HYDROCHLORIC ACID	SODIUM CYANIDE
AMMONIUM HYDROXIDE	NITRIC ACID	SODIUM HYDROXIDE
ASCORBIC ACID	POTASSIUM BROMIDE	SODIIUM HYPOCHLORITE
CALCIUM HYDROXIDE	POTASSIUM IODIDE	SODIUM NITRATE
CITRIC ACID	SODIUM ACETATE	SODIUM PYROPHOSPHATE
DEIONISED WATER	SODIUM CHLORIDE	SULPHURIC ACID

TABLE 2. Metals analysed in the MMI process, and their detection limits in extractant solutions.

ELEMENT	DETECTION LIMIT	ELEMENT	DETECTION LIMIT
Au	1ppb	Pb	1ppb
Ag	1ppb	Pd	1ppb
Bi	1ppb	Pt	1ppb
CD	1ppb	Sb	1ppb
Cu	1ppb	Tl	1ppb
Ni	10ppb	Zn	10ppb

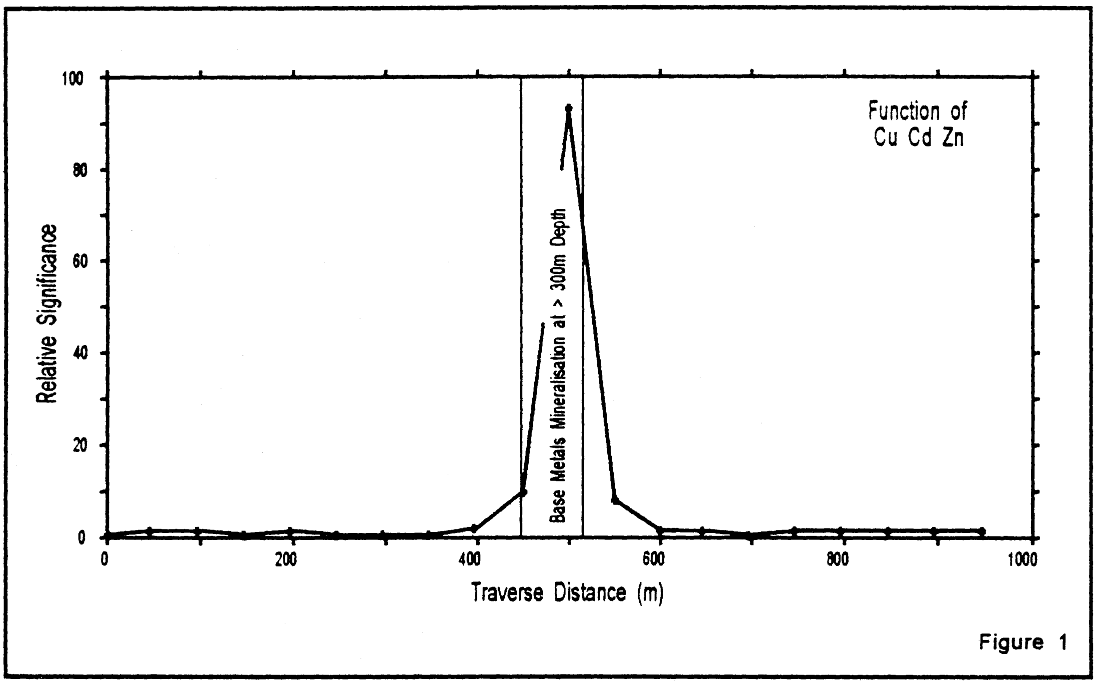

Fig. 1. Mobile Metal Ion transect, across one of the grid lines in Case History number 6.

metals. It uses the Anodic Stripping Voltammetry technique, which is ideally suited to low level analysis in the presence of high electrolyte concentrations. The lower limits of detection are not only important for the anomalous samples, but are also crucial for the establishment of "background". The metals which have been analysed, with their lower limit of detection in p.p.b. in the electrolyte solutions, are shown in Table 2.

■ (6) DATA CONTROL, ANALYSIS AND INTERPRETATION — A software system has been developed (WAMTECH Pty. Ltd.) to control the flow of analytical information through a series of quality control procedures. Software has also been developed to highlight relative single element responses or the significance of coincident metal anomalies. The latter takes the form of a function of anomaly significance across a transect (see Fig. 1.) or a coloured two dimensional image, with warmer colours denoting a higher significance, and cooler colours a lower significance. In all cases the metals comprising the significance factor are displayed in the legend. This method of presentation allows for very rapid interpretation, and the unusually sharp nature of MMI peaks minimises reconnaissance drilling, and allows for accurate siting of drillholes. This can significantly reduce project drilling costs.

CASE HISTORY NUMBER & LOCATION	MINERALISATION STYLE AND SIZE	DEPTH & TYPE OF COVER	MMI ANOMALY SIGNIFICANCE	CONVENTIONAL GEOCHEM
1 SOUTH AUST	Cu, Pb, Zn SUB-ECONOMIC	COLLUVUIM 1-5m WEATHERED 30m	SUBTLE Cu, Pb, Zn, DIRECTLY ABOVE	LAG ANALYSIS IN-EFFECTIVE
2 NORTH AUST	Pb, Zn, Ag SUB-ECONOMIC	LATERITE 1-2M WEATHERED TO 20-90M	STRONG Cu, Pb, Zn, DIRECTLY ABOVE	BROAD SOIL ANOMALY
3 WA	Ni ECONOMIC	AEOLIAN SAND COVER TO 20-80M	Cu, Ni, Zn SUBTLE INCONCLUSIVE	SOIL Ni & Cu DISPLACED
4 WA	Au SUB-ECONOMIC	COLLUVIUM 10M WEATHERED 70m	NO SIGNIFICANT ANOMALIES	NO SIGNIFICANT ANOMALIES
5 WA	Au ECONOMIC	WEATHERED 60m	STRONG Au DIRECTLY ABOVE	UNKNOWN
6 E AUST	Pb, Zn ECONOMIC	COLLUVIUM 1-20M MIN. AT >300m	SHARP Zn, Cd, Cu	NO SIGNIFICANT ANOMALIES
7 WA	Au, Cu LOW GRADE	SAND 0-2m OVER WEATHERED SEDIMENTS	V. WEAK INCONCLUSIVE	NO SIGNIFICANT ANOMALIES
8 WA	Au, Cu, Pb, Zn, SUB-ECONOMIC	SAND 0-2m MIN. AT >300m	WEAK Pb, Zn, Cu ABOVE	NO SIGNIFICANT ANOMALIES
9 WA	Pb, Zn SUB-ECONOMIC	SOIL COVER MIN. AT >300m	Pb ,Zn OVER D.H.	NOT KNOWN
10 WA	Au, Cu, Pb, Zn, ECONOMIC	WEATHERED 15m MIN. AT 25-30m	Zn, Cd, Pb, Cu, Au OVER PRIMARY	BROAD SOIL GEOCHEM. HIGHS
11 WA	Ni, Cu ECONOMIC	COLLUVIUM 0-2m MIN AT 70m	Ni, Cd, Pb, Cu, Pd OVER MIN. ZONES	V. WEAK BROAD SOIL ANOMALIES
12 CHILE	Cu ECONOMIC	COLLUVIUM	Cu STRONG & SHARP	NOT KNOWN

TABLE 3. Case history summary for the MMI process.

Case history results

A number of case histories have been carried out using the MMI process. For confidentiallity reasons it is not possible to identify exact details of orebodies. The following table does however give some broad indication of the range of situations covered, and the relative success achieved.

Two of these examples will be examined in some detail. Figure 1 shows the MMI Anomaly Significance Function (Z) on a transect across strike of the buried mineralisation, in case history number 6.

In the above example, note that the zone of mineralisation (at a depth of greater than 300m), projects to very closely the position of the MMI anomaly.

The second example, case history number 11, is the Nepean nickel deposit near Coolgardie, Western Australia. The ore zone contains massive nickel sulphide, with sulphides of copper, lead, cobalt and minor gold, platinum and palladium mineralisation.

Several factors are of interest in this particular study. Firstly, the laterites to the west of the mineralised zone, which show the highest nickel responses by conventional analytical procedures, do not have a high MMI response. The MMI response is at a maximum over the ore zones, and in fact, in combination with the other elements in the chosen response (anomaly significance) function, delineates the ore zone(s) with remarkable accuracy. Secondly, as mentioned, it is the coincidence of several anomalies from individual elements contained in the mineralization, which is a significant factor in the sharpness and the confidence with which the ore zone is delineated. Thirdly, several other previously undetected prospective zones are indicated to the east of the mined ore zone.

Discussion

1) Summary of essential features of MMI anomalies

Our case history studies to date, lead us to the following conclusions:

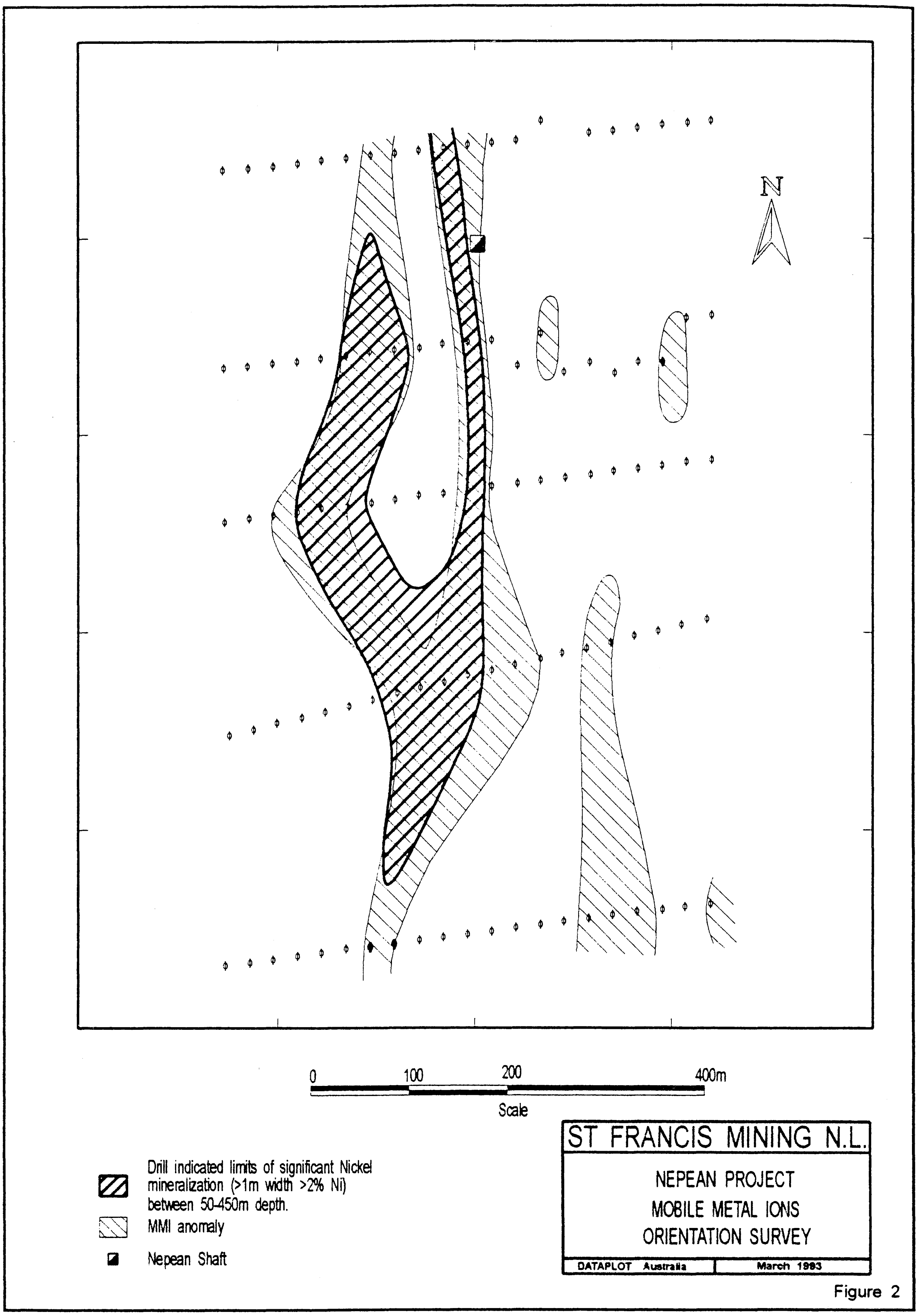

Fig. 2. MMI survey of the Nepean Nickel Mine Site Area.

- MMI anomalies exist, and can be used to detect buried mineralisation.
- MMI anomalies are clearly different to conventional geochemical anomalies in their appearance, intensity and potential application to exploration.
- The mechanism of formation of MMI anomalies is almost certainly very different from those responsible for the formation of normal multi-element geochemical anomalies.

Some of the individual and relevant observations which lead us to these conclusions are:

- MMI anomalies comprise only elements present in the mineralisation in significant amounts.
- The anomalies are sharp, and in most cases directly overlay and define the extent of the surface projection of buried primary mineralised zones.
- When primary mineralisation is of high grade, MMI anomalies are capable of penetrating significant thicknesses of overburden.
- The incidence of false anomalies is very low, compared to normal geochemical methods.

2) Relationship of MMI to other geochemical methods

One of the first reports of the "geogas" phenomenon was by Malmqvist and Kristiansson (1984). In this report the primary gases detected were nitrogen, argon, oxygen and methane over a massive sulphide deposit in Central Sweden. Subsequent variations of the technique utilise plastic collection strips and very sophisticated instrumentation to detect ultra-trace levels of metal ions on the collectors. Compared to the MMI technique, sample collection is not as robust, and the technique is very expensive, when applied on the scale required for exploration.

The CHIM, MPF and TMGM methods developed in the USSR during the nineteen eighties have recently come under increasing scrutiny. In the CHIM method, carbon electrodes are implanted into the soil, and voltages applied to pre-concentrate metal ions on the electrodes. Solution from the collectors are then analysed using polarographic and AAS techniques. The authors, Antropova and others (1992), list several examples for the detection of buried mineralisation. The United States Geological Survey has recently published their findings on this technique (Smith & others, 1993). This method is clearly very similar to the MMI technique, even to the use of carbon electrodes for pre-concentration, and polarographic techniques for the low level analysis. However, the MMI sampling technique, of bulk soil collection and controlled laboratory addition of extractant, allows for a much improved and reproducible extraction of metals, and a more cost effective, flexible and robust exploration program.

3) Possible mechanisms of formation of MMI anomalies

In that there are many, and significant differences between the anomaly patterns generated by mobile metal ions as compared to the geochemical anomalies developed in gossans or residual soils, in lateritic processes, or by hydromorphic processes, the mechanism of formation of mobile metal ion anomalies is very likely to involve some new or at least, at present poorly understood, geochemical transport concepts. These concepts will be fundamental to a correct application of the MMI Process, and to the correct interpretation of results, particularly for example in relation to high rainfall zones, areas with significant present day rates of surface erosion, and areas with major changes of lithology or regolith within a single exploration target zone.

The Geochemical Research Centre (GRC) has been established at Technology Park Bentley, Western Australia, with the aim of providing participants with information on the mechanism of formation of mobile metal ion anomalies. The Centre is currently considering mechanisms involving:

- Transport of metals "swept" along with evolving gases.
- Formation of hydrides, chlorides or other volatile metallic species.
- Volatilisation of sulphides.
- Formation of metallic "aerosols".

The elucidation of the mechanism is not just concerned with the mode of transport, but also with the form of fixation of the metals in the soil regime. For this, The Centre is utilising the study site areas provided by participating companies to examine the effects of different regolith, mineralogical, climatic and geomorphological situations on the presence, strength and persistence of anomalies.

Conclusions

Due to the increasing need for exploration techniques to operate effectively in areas of transported overburden, this new geochemical technique has the potential to complement geophysical methods for the detection of "blind" mineralisation. Because of the very sharp, and coincident nature of the anomaly peaks, it has the potential to significantly reduce drilling costs. As such, it is the total exploration budget which will be affected by the introduction of the technique into the exploration program.

It is for this reason, and due to the fact that the process is dependent on the correct, systematic and careful execution of a number of steps, that the method cannot be simply regarded as an another analysis technique. No laboratory, which is handling minesite and "normal" geochemical samples could hope to achieve the required level of quality control for such low level samples, without the introduction of extra-ordinary cleaning procedures or separate laboratory procedures.

We have introduced the concept of the MMI Process to reinforce the fact that the method must be implemented and utilised in a fully integrated way into exploration programs, not only to achieve results, but to attain the budget efficiences.

Another word of caution is also required. There is often a tendency, after the initial scepticism has abated, to regard any new geochemical technique as a universal panacea, and in some cases to mis-apply it. The Mobile Metal Ion technique will be no different; there has to be a practical limit to its usefulness. However, if carefully applied in an integrated and systematic manner it seems certain to make a large contribution to the detection of buried mineralisation.

Acknowledgements

The work described in this paper predates and precludes any carried out under the auspices of the G.R.C. Acknowledgements are due to those companies who have kindly permitted us to release the broad outlines of the preliminary case history surveys.

References

Antropova, L.V., Goldberg, I.S., Voroshilov, N.A., & Ryss, Ju.S. 1992, New methods of regional exploration for blind mineralization: application in the USSR, *Journal of Geochemical Exploration.* 43, pp 157-166.

Malmqvist, L. & Kristiansson, K. 1984, Experimental evidence for an ascending microflow of geogas in the ground, *Earth & Planetary Science Letters 70*, pp 407-416.

Smith, D.B., Hoover, D.B., & Sanzolone, R.F. 1993, Preliminary studies of the CHIM electrogeochemical method at the Kokomo Mine, Russell Gulch, Colorado, *Journal of Geochemical Exploration* 46(3),pp257-278.

The Kanowna Belle Case Study: the discovery of a concealed orebody

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In early 1990 the Golden Valley Joint venture between Delta Gold N.L. and Peko Gold Ltd. discovered Kanowna Belle, now recognised to be a plus 3 million ounce, mostly porphyry-hosted, structurally-controlled Archean gold deposit.

Geology and weathering

Kanowna Belle is situated 20 km northeast of Kalgoorlie in the Kanowna felsic complex which forms part of the Boorara Domain of the Archean Kalgoorlie Terrane (Swager & others, 1990). The Kanowna Belle deposit occurs within a series of interpreted thrusts, striking northeast and dipping southeast in the vicinity of the deposit and transgressing the local lithologies. The mineralisation is closely associated with one of these structures, the Fitzroy Fault, a planar feature dipping 60° southeast consisting of a characteristic gouge or ultramylonite. The Kanowna Belle sequence comprises distinct hangingwall and footwall rock types, generally separated by the Fitzroy Fault. The footwall sequence is mostly a polymict conglomerate and the hangingwall sequence consists of felsic angular rudites with occasional pebble-boulder beds and mafic flows. A feldspar-phyric to aphyric porphyry, the Kanowna Belle Porphyry, ranging from less than 10 m to 80 m in thickness appears to intrude along a pre-existing shear zone cut later by the Fitzroy Fault, which transgresses the porphyry at a low angle.

Regolith elements developed within the Kanowna district, range from the extensive salt lakes, clay pans, kopi and sand dunes developed on the main Gidgi paleodrainage valleys to the north of the now abandoned Kanowna townsite, to the thin calcareous soils developed over subcropping to outcropping metasedimentary rocks in the townsite. West of the townsite an area of broad, shallow, seasonal drainages connects with the large paleodrainage system to the north and contains the paleochannels which include the Kanowna deep-leads. Shallow gravel or sheetwash-filled channels, separated by "islands" of transported red clays containing ferricrete granules developed over saprolite typify this area. Lenses of calcrete are developed locally within this deeply weathered area, where the depth of weathering ranges from 20 m to 120 m. Kanowna Belle lies near the eastern margin of this drainage basin.

The regolith profile overlying the Kanowna Belle deposit consists of calcareous soils, up to a metre thick, overlying a 2 m to 5 m thick layer of red clays, which are mottled at depths greater than 2 m. A silcrete cap or hardpan 1 m to 10 m thick marks the base of the mottled zone above highly leached saprolite. The saprolite is up to 50 m thick, with the deepest development immediately overlying the Fitzroy Fault.

Mineralisation

Gold was discovered at Kanowna in 1893, with production peaking around 1900 and rapidly declining after 1915. The field is estimated to have yielded almost one million ounces, about half of which came from mining of quartz veins, mostly in the White Feather Reef structure, in and adjacent to the Kanowna townsite, and the remainder from deep-lead deposits to the north and west of the townsite. The deep-leads occur within alluvial paleochannels of probable Tertiary age, the gold occurring in a basal clayey grit and in shallower clay horizons. In the latter case, supergene processes are interpreted to have re-deposited gold derived from the alluvial mineralisation.

Alteration at Kanowna Belle is developed as an asymmetric envelope mostly above the Fitzroy Fault and consisting of three principal mineral assemblages; a peripheral chlorite-calcite assemblage, an extensive sericite-carbonate assemblage up to 150 m thick and a more localised quartz-albite-pyrite assemblage closely associated with ore-grade mineralisation. A large proportion of the sericite-carbonate alteration zone is gold-anomalous, exhibiting values in excess of 0.1 ppm gold up to 120 m into the hangingwall of the fault.

The main orebody at Kanowna Belle is the Lowes Shoot, a tabular mostly porphyry-hosted body, which has a strike length ranging from 350 m to 500 m and a thickness of 5 m to 50 m and which remains open below a vertical depth of 800 m. The Lowes Shoot mineralisation shows a close spatial relationship to the Fitzroy Fault, generally being above it in the upper parts of the deposit and tending to occur below it at depth. Smaller mineralised bodies occur in the Hilder Shoot (situated in the footwall of, and subparallel to, the Lowes Shoot at the north-east end of the deposit), in the Troy Shoot (a steeply dipping high-grade east-west hangingwall body oblique to the main strike of the Lowes Shoot) and in shoots developed in the hangingwall to the upper part of the Lowes Shoot.

Supergene gold mineralisation is significant at Kanowna Belle, with a well-developed subhorizontal mineralised horizon, as defined by gold values greater than 0.1 ppm, occurring at depths of 35 m to 45 m below surface as a series of lenses between 1 m and 4 m thick at the base of the saprolite. This mineralisation extends for up to 200 m from the margins of the primary ore-grade mineralisation and thus presents a larger target for exploration. Significantly however, this supergene blanket is mostly developed above the hangingwall of the Fitzroy Fault. Very small pods of shallow supergene mineralisation, generally less than 20 m in length, are developed at depths of 5 m to 12 m, within or at the base of the silcrete horizon. Gold values in the saprolite outside of these supergene enrichments are low, usually less than 10 ppb, with rare localised peaks of 50 ppb to 100 ppb at the water table around 18 m to 20 m depth.

Exploration

Following ground acquisition by both companies in the early 1980's, Delta Gold N.L. and Peko Gold Ltd. formed a joint venture in 1983 to explore both for deep-lead and primary deposits at Kanowna. The Golden Valley Joint Venture was formed in early 1988 to expand the venture and to mine deep-lead resources. During the period 1989 to 1993 the Golden Valley Joint Venture operated the small QED heap-leach mine, processing 87 ,000 tonnes of deep-lead ore and recovering 75 000 ounces of gold.

Early systematic exploration of the area consisted of vertical scout rotary air blast (RAB) drilling at 1000 m by 200 m spacing directed towards deep-lead targets and possible associated primary mineralisation. In mid-1987 this drilling intersected gold mineralisation, including 2 m at 11 g/t from 52 m depth and 4 m at 3 g/t from 28 m depth. These intercepts were made in a flat soil-covered area with no old diggings situated 2 km west of the Kanowna townsite in what is now known to be the northern and eastern peripheries of the Kanowna Belle deposit. In late 1987, follow-up RAB drilling in the same area intersected anomalous gold values towards the base of some holes, however other holes failed to penetrate the 40 m depth of leaching and gold depletion characteristic of the Kanowna Belle area.

Following the re-organised joint venture arrangement, greater attention was focussed on surface, low-level gold geochemical exploration techniques with the result that during the period from mid-1988 to mid-1989 three programmes of soil geochemistry were carried out over the area of anomalous RAB intersections. These programmes varied from local 200 m by 40 m spaced whole-soil orientation sampling with cyanide extraction (bleg), district-scale bleg sampling on 500 m centres, to follow-up minus 80 mesh soil sampling (AAS-carbon rod determination) on 40 m centres. All of the sampling programmes confirmed anomalous values in the vicinity of the original RAB intersections, with the minus 80 mesh results giving the best response, defining a bullseye anomaly of greater than 60 ppb gold with a diameter of 350 m and a peak value of 150 ppb gold, compared to a background of about 10 ppb to 20 ppb gold.

RAB drilling during and after these geochemical programmes was centred on soil anomaly peaks, which resulted in a best intersection of 8 m at 4 g/t from 45 m at the base of the saprolite zone in the eastern Lowes Shoot area, providing the first target for reverse circulation (RC) drilling. It is significant to note that the centres of the various soil anomalies are displaced about 100m to the north relative to the primary mineralisation and overlie the surface projection of the 60° southeast-dipping Fitzroy Fault. This meant that drill testing vertically below the soil peaks sampled the poorly-mineralised or barren footwall zone in most cases.

In late 1989 the first RC holes were drilled into the deposit in the eastern Lowes Shoot area, giving intersections of 11 m at 7 g/t from 42 m and 8 m at 3 g/t from 51 m. The small pods of shallow supergene gold mineralisation in the vicinity of the Fitzroy Fault were not intersected by this drilling or by the earlier RAB drilling. At this stage emphasis was placed on testing what appeared to be a deeper flat-lying supergene style of mineralisation, with drilling extending the sub-horizontal mineralisation to the south and west and testing the zone to depths of 80 m. This led to high grade intersections in what is now Troy Shoot and in turn encouraged further drilling which resulted in the recognition of the size potential of the deposit.

By June 1992 the total resource had increased to 15 million tonnes grading 5.3 g/t to a vertical depth of 650 m. Drilling at the Lowes Shoot to a depth of about 1000 m to further extend the resource is being completed. Gold production from open cut mining of the deposit is scheduled to start in September 1993 and a feasibility study into underground mining has commenced.

Summarising the significant factors affecting the timing and method of discovery of Kanowna Belle:

- While Kanowna Belle is a concealed deposit, it is not a blind deposit insofar as a distinct gold-in-soil anomaly is developed.
- The soil anomaly is displaced relative to the primary mineralisation and caused a delay in recognition of the size of the mineralised system. Gold dispersion upwards along the Fitzroy Fault zone could explain the position of this anomaly.
- Intense leaching and gold depletion of the saprolite horizon did not facilitate early recognition of the primary mineralisation despite the development of a large, primary gold-anomalous alteration halo in the hangingwall rocks.
- Early drill intersections of the well-developed lower supergene horizon provided encouragement for further drilling.

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References

Swager & others 1990, Geology of the Archean Kalgoorlie Terrane - an explanatory note - *Western Australian Geological Survey, Record* 1990/12.

Follows p. 231

Geological mapping applications of the QUESTEM airborne electromagnetic system in mineral exploration

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The QUESTEM system is now being used extensively for its geological mapping capabilities. Applying a range of image processing and data integration techniques to the airborne EM data both in grid and line form, allows the data to be viewed and interpreted in similar ways to what is now considered routine for magnetic data.

Palaeochannels within the Kalgoorlie District have been mapped in two recent QUESTEM surveys. The younger palaeochannels are mapped from the aeromagnetic data, while the older and deeper channels appear to be conductive and are detected on the later-time channels of the electromagnetic data. Some of these features are subtle and difficult to distinguish with standard presentations of electromagnetic data. Locating and tracing the various channels has important environmental and mineral exploration applications. For example, gold is currently being mined from channels at Lady Bountiful.

The second example is a QUESTEM line from the McArthur River Basin in the Northern Territory. Imaged conductivity sections generated from the line data have been correlated to geological cross-sections. Variations in conductivity between different siltstone and sandstone units are sufficient to identify specific sedimentary units. Differential weathering of units also assists the mapping and identification of specific geological units as it generates varying electromagnetic responses. Many of the faults in the basin are also conductive. From this analysis of the line data discrete anomalies were then selected for further investigation. Examples include modeling depth to conductive bodies below a resistive sedimentary cover and several anomalies of economic interest, including the HYC deposit.

Petrogenesis and gold mineralisation of the Christmas Well Granophyre, Laverton

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The Christmas Well gold deposit is located approximately 120 km north-northwest of Laverton in the north-eastern part of the Eastern Goldfields Province. The orebody is associated with the Christmas Well Shear Zone, a narrow, north-northwest-trending deformation zone that has affected ultramafic and intrusive granophyric rocks within a sequence of mafic and felsic volcanics and minor metasediments, which together form part of the Laverton Tectonic Zone of Hallberg (1986).

Gold mineralisation is restricted to the granophyre unit, which is slighty discordant to the regional foliation. The rocks have undergone extensive hydrothermal alteration and weathering in the mine area, but fresh material is available from diamond drill core. This reveals a medium to coarse-grained, grey, meso- to leucocratic gabbroic rock, with distinct granophyric intergrowths of quartz and alkali feldspar (mainly albite).

Fourteen of the least altered samples of granophyre were chemically analysed in order to determine petrogenesis. The rocks are classified as tholeiite, using both major and trace element discriminant plots, and show a late fractionation trend of progressive alkali enrichment. CIPW norms indicate high albite contents and a range in composition from trondhjemite and tonalite to granodiorite. However, they show a tholeiitic and not a normal trondhjemitic evolution trend.

A geochemical comparison was made with the Paddington gold deposit, which is also hosted in a differentiated tholeiitic intrusive (Robertson & others, 1988). This is considerably less siliceous and alkalic and more iron and magnesium-rich than at Christmas Well, suggesting that the latter is a much more differentiated intrusion. Comparison with late fractionated representatives of the classic Skaergaard tholeiitic intrusion in East Greenland reveals a much closer similarity, particularly with the Sydtoppen Transitional Granophyre (Wager & Brown, 1968).

Chondrite-normalised rare earth element data for the granophyres indicate moderate LREE enrichment and strong negative europium anomalies. Uniformity of HREE values suggests a common magmatic source, which is also supported by a constant La/Sm ratio (2.5) and small scatter in the LREE/HREE ratio. Evolution was controlled by crystal fractionation rather than partial melting, with the strong negative europium anomaly the result of plagioclase fractionation.

The brittle behaviour of the granophyre, and its spatial relationship to the Christmas Well Shear Zone, has resulted in an intense fracture system. Gold mineralisation occurs in two settings within the granophyre; in sub-vertically dipping north-northeast striking quartz veins, and in sub-vertical, shear-hosted lodes within a major shear zone along the western margin. The quartz veins are restricted to brittle domains in the granophyre, where gold is associated with horizontal fractures. A penetrative foliation increases toward the sheared western contact and is accompanied by sericite alteration and the development of a schistose fabric. The main ductile structure is a 3 to 8 m wide shear zone where finely disseminated gold occurs in association with pyrite. Shearing was the result of initial dextral movement along the Christmas Well Shear Zone during regional D2 deformation, controlled by northeast-southwest compression.

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References

Hallberg, J.A. 1986, Archaean basin development and crustal extension in the northeastern Yilgarn Block, Western Australia. *Precambrian Research* 31, 133-156.

Robertson, I.G., Jones, D.A. Smith, B.E. & Bloch, J. 1988, The Paddington Goldmine in Groves, D.I, Barley, M.E., Ho, S.E. and Hopkind, G.M.F. eds. *Western Australian Gold Deposits, Bicentennial Gold 88 Excursion Guide Book.* Geology Department & University Extension, University of Western Australia, Publication 14, 91-99.

Wager, L.R and Brown, G.M. 1968, *Layered Igneous Rocks*. Oliver and Boyd, 555p.

Gold mineralisation along the Fraser's–Corinthia shear zone in the Southern Cross greenstone belt, Yilgarn Block, Western Australia

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The Southern Cross greenstone belt of the Yilgarn Block comprises tholeiitic and high-Mg basalts, komatiites, and banded iron formations (BIF), overlain by younger sequences of terrigenous sediments. Host rocks to mineralisation along the NNW-trending Fraser's–Corinthia shear zone near the town-site of Southern Cross, are mafic actinolite schists and amphibolites, ultramafic tremolite-chlorite schists, BIF and micaceous schists.

The Fraser's–Corinthia Shear zone, which is about 50-100 m wide, is characterized by strong ENE-SSW flattening and relatively minor shearing. The shear zone is intersected by large-scale shear bands and exhibits a strong foliation, subparallel to shear zone boundaries and lithologies. It is concluded that one progressive deformation-metamorphic event, which is subdivided in several deformation stages (Table 1), led to gold mineralisation.

Peak metamorphic conditions (Table 1) are established from garnet-biotite and garnet-cordierite geothermometry, together with metamorphic assemblages, petrogenetic grids, and phengite geobarometry. Metamorphic grade increases southwards, from about 500°C at Corinthia in the north to 550°C near Southern Cross. Relative timing of metamorphism and deformation is indicated by syn- to post-kinematic garnet porhyroblasts, together with syn-kinematic andalusite and cordierite porphyroblasts. This suggests similar metamorphic conditions during D_1 and D_2.

Several major lode-gold deposits are located along the Fraser's–Corinthia shear zone, such as Corinthia, Hopes Hill, Fraser's and Polaris South. Each is located south of a kilometre-scale sinistral shearband and north of a kilometre-scale dextral shearband. Within the shear zone, gold concentrations are thus related to subtle variations in the strike of the zone, a result of these kilometre-scale shearbands.

Gold mineralisation on the mine-scale is controlled by *en echelon* quartz veins and extensional crenulation cleavages (ECC's), at a low angle to the main foliation. Folded, boudinaged, *en echelon* and undeformed crosscutting veins suggest that veining took place throughout deformation. Shear zone foliation is axial planar to highly deformed veins and alteration haloes, suggesting a close relationship of D_2 deformation and alteration. Gold mineralisation is associated with extensive calc-silicate alteration. Metasomatic minerals, such as diopside, biotite and tschermakitic hornblende, replace metamorphic minerals, and high thermodynamic variance (low number of phases) of high temperature assemblages indicate an open metasomatic system at high temperatures just after peak metamorphism. Stable isotope geothermometry from diopside-quartz pairs, equilibrium between tremolite-calcite-quartz and diopside, together with fluid inclusion results constrain P-T conditions during alteration and gold mineralisation to around 500°C at 3 kbars near Southern Cross (Table 1), and around 470°C at 3 kbar at Corinthia, suggesting a similar decrease of temperatures from north to south during alteration as during metamorphism. The close relationship of veining and deformation, together with alteration temperatures, which are only slightly below peak metamorphic temperatures, suggest that alteration took place immediately after peak metamorphism. Crosscutting prehnite veins and cracks post-date ductile deformation, and are possibly related to brittle faulting and kinking of mica bands in micaceous schists.

TIME		
deformation: D1	D2	D3
upright folding, granitoid emplacement, simultaneous dip-slip movement along Fraser's-Corinthia shear zone development of regional north-west trending foliation	dominantly flattening strike-slip and minor reverse movement along Fraser's-Corinthia shear zone development of shear zone foliation and ECC's	ongoing dextral north-south shearing, and oblique (reverse/thrust-dextral) shearing along the Fraser's-Corinthia shear zone, brittle faulting and kinking
metamorphism (mm): 550°C/3-3.5 kbars		mm: retrogression <300°C (prehnite veins)
	alteration+gold mineralization: 500°C/3 kbars	

TABLE 1. Relative timing of the progressive deformation event during goldmineralisation and metamorphism around Southern Cross, Yilgarn Block, Western Australia.

The evolution of regolith mapping in Australia: a Yilgarn perspective

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Regolith mapping by the Australian Geological Survey Organisation (AGSO) began in 1983. An overview map (1:5 M) of the regolith of the Australian continent (Chan & others, 1986) was the first continental regolith map of Australia produced and the experience gained together with earlier work by Stewart & Perry (1953), Christian & Stewart (1953), Stewart (1968), Ollier, (1977) and Jennings & Mabbutt (1986) helped to provide a firm base for the further development of AGSO's regolith mapping techniques including those applied to larger scales.

The regolith of the Yilgarn Craton is of course identified only in the broadest sense on the 1:5 M scale map but this map provides a much needed summary of the relative detail known about the Australian regolith cover. More detailed regolith mapping in the Yilgarn by AGSO began in 1985 and led to the publication of a preliminary 1:1 M scale regolith map of Kalgoorlie. A revised, full colour regolith map along with a map commentary has since been published (Chan & others, 1992).

AGSO's current regolith mapping technique which are aimed at regolith landform mapping at 1:250 000 scale clearly owes much to the original Yilgarn experiences. The techniques have continued to develop over the last three years as a result of experience elsewhere in Australia through the commencement of the National Geoscience Mapping Accord between the Commonwealth, States and Northern Territory. The "second generation" philosophy of the geological mapping program in the Yilgarn has direct relevance to the regolith program by ensuring new technologies ie satellite imagery, gammaray spectrometric imagery and the presentation and analytical power of Geographic Information Systems (Rattenbury & others, 1992) are used where available and appropriate. Regolith mapping continues to be recognised as a priority program effort especially in the Yilgarn because of the regolith complexity (Ollier & others, 1988) and the need of industry to understand regolith (Chan, 1988; 1989). AGSO draws directly upon experiences from its own varied regolith mapping programs around Australia and those of other agencies in developing a set of robust regolith mapping techniques and in developing a national regolith mapping strategy.

More effective and rapid progress is being made through cooperative working arrangements with other major geoscience agencies especially in the Yilgarn environment for example, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Geological Survey of Western Australia (GSWA), Curtin University, Cooperative Research Centre for Mineral Exploration Technologies (CRCMET) and Australian Mineral Industry Research Association (AMIRA).

AGSO's Yilgarn regolith program is dominantly focussed at a regional scale although the mapping technique is specifically designed to be scale independent and therefore can easily be focussed on other scales as needs arise. Initial data collection is at approximately 1:100 000 but publication is aimed at 1:250 000 scale. Collaborative work also tends to draw upon AGSO's regional regolith mapping skills to ensure overall consistency of mapping concepts at larger scales for example, 1:25 000 to 1:100 000, and to highlight the needs of data compatibility for easier addition of new datasets to RTMAP—the national regolith database developed and maintained by AGSO.

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References

Chan, R.C. 1988, Regolith terrain mapping for mineral exploration in Western Australia, in Embleton, C, ed. *Applied Geomorphological mapping methodology by example.* Zeitschrift fur Geomorphologie Supp. Bnd, 68, 205221.

Chan, R.C. 1989, Regolith terrain mapping a geomorphic base for mineral exploration. *Australian Institute of Mining and Metallurgy,* Bulletin and Proceedings, 294 (2), 2528.

Chan, R.A., Craig, M.A., D'Addario, G.W., Gibson, D.L., Ollier, C.D., & Taylor, G. 1986, The Regolith Terrain Map of Australia 1:5 000 000, *Bureau of Mineral Resources, Australia,* Record 1986/27.

Chan, R.A., Craig, M.A. Hazell, M.S., & Ollier, C.D. 1992, Kalgoorlie 1:1 Million scale Regolith Terrain Map. *Australian Geological Survey Organisation,* Australia

Christian, C.S., & Stewart, G.A. 1953, General Report on survey of KatherineDarwin region, 1946. CSIRO *Land Research Series, 1.*

Ollier, C.D. 1977, Terrain classification: methods, applications and principles, in Hails, J.R. ed, *Applied Geomorphology* Elsevier Amsterdam, pp 277316.

Ollier, C.D., Chan, R.A., Craig, M.A., & Gibson D.L. 1988, Aspects of landscape history and regolith in the Kalgoorlie region, Western Australia. *BMR Journal of Australian Geology and Geophysics,* 10, pp 309321

Rattenbury, M., Craig, M., Oversby, B., & Whitaker, A. 1992, Adding layers towards a GIS data package, in *Geographic Information Systems, Cartographic and Geoscience Data Standards,* Bureau of Mineral Resources, Australia, Record 1992/27.

Stewart C.S., & Perry, R.A. 1953, Survey of Bowen-Townsville region, 1950, CSIRO *Land Research Series, 2,*

Stewart, G.A., ed. 1968, *Land Evaluation.* Macmillian, Melbourne, 392pp

Timing of gold mineralisation in contrasting metamorphic settings: heterogeneous deformation and diachronous metamorphism in the Marda Greenstone Belt, Southern Cross Province, Western Australia

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The Marda greenstone belt is a relatively wide belt in the central Southern Cross Province. It contrasts with the adjacent Southern Cross belt in that it is moderately deformed and characterised by low to very-low grade metamorphism. The structural history of the Marda belt is complex, and is different for the central and marginal sections of the belt. The central section of the belt is characterised by: D_1, east-west trending upright megafolds without a penetrative regional fabric. D_2, north-south trending mesofolds and regional S_2 foliation. D_3, brittle-ductile shears along roughly east-west trending lithological contacts. D_4, northeast-southwest and northwest-southeast trending, conjugate faults.

In contrast, the margins are characterised by: D_1, regional shear zones subparallel to the granitoid-greenstone contacts, isoclinal mesofolding in the shear zones and regional S1 foliation. D_2, north-south trending quartz veins. D_3, east-west and north northeast-west southwest trending conjugate faults or shears.

The central part of the belt consist of mafic and ultramafic volcanic rocks, metasedimentary rocks, banded iron formation and acid volcanic rocks which were metamorphosed in the prehnite-pumpellyite facies. Spilitisation of the glassy matrix of some of these rocks indicates burial- or ocean-floor metamorphism. Minor mineral growth related to the D_1 and D_2 events however, suggest a later regionel metamorphic event synchronous to D_1 and D_2. Metamorphic conditions along the margins of the belt were of greenschist up to amphibolite facies with typical assemblages of actinolite-intermediate plagioclase-epidote-magnetite/ilmenite up to hornblende-intermediate plagioclase-ilmenite in high-strain mafic volcanic rocks.

Gold mineralisation in the low metamorphic-grade core of the greenstone belt at Marda occurs along the strike of an east-west trending sinistral D_3 shear zone and a north-south trending shallow dipping D_3 thrust which represent deformation in an east-west compressive regime. The total displacement on these faults is in the order of a few metres to a few tens of metres. Typical proximal alteration minerals such as siderite, ankerite, and gold-bearing sulphides overprint metamorphic minerals and shear-zone fabrics defined by chlorite and muscovite, which suggests that mineralisation was relatively late in D_3 and post-peak regional metamorphism.

In contrast, gold mineralisation along the higher metamorphic-grade margins of the belt at Jackson is hosted by regional D_1 shear zones, and mineralisation formed during D_1 was probably remobilised during D_2. Typical proximal alteration minerals such as calcite, chlorite, biotite, muscovite, and sulphides occur as elongated grains parallel to the regional S_1 foliation. Mineralised quartz veins are subparallel to S_1, and both unfolded and tight to isoclinally folded veins occur.

These observations indicate contrast in the relative timing of mineralisation in different metamorphic and structural settings in the Marda belt. Mineralisation in high strain recrystallised rocks of upper greenschist grade was early in the tectonometamorphic history, while mineralisation in recrystallised but low strain rocks of the prehnite-pumpellyite facies was relatively late in the tectonometamorphic history of the terrain.

If gold mineralisation was one event, as is suggested by available high precision geochronological data that have been collected so far in the Yilgarn Block, then deformation and metamorphism were heterogeneous and diachronous in different metamorphic settings in the Marda greenstone belt.

These observation have important consequences for gold exploration in the belt and for future models on greenstone belt evolution. Heterogenous and diachronous deformation and metamorphism within greenstone belts, and among adjacent greenstone belts, indicate the importance of localised tectonic and thermal processes relative to regional processes in the Southern Cross Province. Gold exploration in the Marda belt should consider the importance of small-scale, relatively late structures in the low metamorphic-grade central parts of the belt and larger-scale, relatively early regional shear zones along the higher metamorphic-grade and higher strain margins of the belt.

Palaeosols in laterite and silcrete profiles

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Much of the geological history of the Australian Precambrian Shield subsequent to its early development is recorded in Proterozoic cover rocks and younger basin sediments which occur in important stratigraphic sequences particularly on the margins of the shield. Within these sequences, stratigraphically associated or as companion materials, weathering zones and palaeosols were developed which individually and as assemblages of layers and horizons record the history of weathering and of soil formation since the Proterozoic.

Palaeosols stratigraphically associated with particular sediments were also developed on older materials exposed on the palaeosurface of the time to form a mosaic of palaeosols with the gross aspect of the soil much influenced by the older weathered rock, sediment or soil upon which it was formed.

Older weathering zones and bleached rocks were features of successive landscapes after the early Palaeozoic; ferruginous mottling, ferricrete and silcrete pans were formed after the early Cainozoic; mottled clay palaeosols—some of which have been described as "laterite"—were formed during and after the Pliocene. Materials in laterite and silcrete profiles are overlain in places by calcretes formed during and after the early Pleistocene and by younger soils.

Individual palaeosols which were developed at or below a palaeosurface by weathering and diagenesis and which have a horizontal disposition and discernible stratigraphic relationships are named.

Laterite and silcrete profiles are seen to be assemblages of palaeosols, stratigraphically associated deposits and companion materials which were formed in response to changes in groundwater conditions at particular times in the past.

The assemblages are distinctive and are characteristic of particular morpholithogical provinces.

The Keringal Gold Deposit

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The Keringal deposit is situated 35 kms southeast of Laverton, 16 kms southest of Granny Smith goldmine in the Eastern Goldfields Province. Keringal is a new discovery, identified in May 1992 by follow-up drilling of anomalous RAB geochemistry. Exploration is still in progress.

The Keringal area was selected for exploration since it is located along a major north-south trending aeromagnetic structure. This terrain bounding fault cuts through mafic volcanics south of the Mount Weld Carbonatite and provides a favourable structural setting. Outcrop is poor, obscured by large alluvial washes and palaeo-drainage channels.

Local geology comprises a north to north-northeast trending sequence of mafic and ultramafic rocks with minor sediments. East of the prospect, dolerites and gabbros outcrop, however typically Keringal is deeply weathered with shallow transported cover. Immediately west of the dolerites a thick sequence of undeformed komatiitic ultramafics occur. Towards the mineralisation these become progressively more sheared, brecciated and altered, with a steep east dipping foliation. The southern part of Keringal is dominated by a wedge of tholeiitic basalts within the ultramafics, into which several porphyries intrude.

The mineralisation is focused at the northern end of this tapering mafic wedge mostly hosted within highly weathered ultramafic saprolite and quartz veins. Mineralisation forms a broad sub-horizontal north-south trending supergene blanket, which overlies an east dipping weathering trough. Grade enrichment also occurs along the margins of the mafic wedge and associated porphyry contacts. Most of the deposit drilled to date is hosted within the saprolite with better intersections of 71m at 5 ppm Au and 43 m at 4 ppm Au.

Fresh rock intersections are typically narrower and associated with intensely altered and veined ultramafics and mafics. The ultramafic package ranges from least altered talc-serpentine-carbonate rocks through to highly silicified quartz-carbonate-fuchsite-pyrite assemblages. Rare spinifex textures are seen in the least altered rocks. Mafics range from tholeiitic pillow basalts composed of chlorite-carbonate-quartz to intensely recrystallised quartz-carbonate-albite-sericite-pyrite-arsenopyrite varieties. Porphyritic intrusives are granitic in composition, that is quartz-feldspar-biotite with moderate sericite-pyrite alteration and quartz-carbonate veining. Late stage thin lamprophryic dykes occur throughout the sequence possibly related to the Mount Weld Carbonatite.

Exploration continues at Keringal and no resource estimates are available at this stage. Current drilling defines an envelope of mineralisation 1600 m long and up to 250m wide at greater then 10 g.m. Infill drilling commences in June to confirm grade distribution.

Structure, metamorphism, alteration and timing of gold mineralisation at Marymia Gold Project in the Marymia Dome

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With the discovery of the Marymia and Plutonic gold deposits, the Marymia Dome has been opened up as a new gold province north of the Yilgarn Block. The Dome is a north-east–south-west trending terrain of greenschist- to amphibolite-facies metamorphic rocks and granitoids, enveloped by Proterozoic rocks, on the northern edge of the Yilgarn Craton approximately 200 km north of Wiluna. It is unconformably overlain by the Bangemall Group (1.6-1.1 Ga) to the north, and is in structural contact with the Glengarry Group (1.9-1.8 Ga) to the south. The nature of the contact with the Earaheedy Group (1.7-1.6 Ga) to the east is uncertain.

The south-west portion of the Dome, consisting of the Peak Hill Metamorphic Suite, is thought to be also Proterozoic in age, while the rocks in the north-east are more akin to the Archaean greenstone belts in the Yilgarn Craton. No absolute or relative timing constraints have yet been published for these sequences. The contact between the north east and south west portions of this Dome is not exposed, and its nature remains unclear.

The north-east portion comprises two greenstone belts;

- the Baumgarten belt, which has been interpreted as an antiformal sequence of tholeiitic basalts and ultramafic units structurally overlain by metasedimentary rocks, and
- the Plutonic–Marymia belt which comprises complexly folded sequences of ultramafic units, amphibolites, banded iron formations (BIF), metasedimentary rocks and granodioritic porphyries.

Both belts are enclosed in granitoid complexes which potentially include Archaean and Proterozoic intrusions. The two existing gold deposits on the latter belt, namely Plutonic Gold Mine and Marymia Gold Project, are located at the south west and north east extremities, respectively, adjacent to the granitoid-greenstone contact.

The Marymia Project incorporates two ore-bodies, Keillor 1 (K1) and Keillor 2 (K2). Mineralisation at K1 is predominantly associated with BIF units which are inter-digitated and infolded with amphibolites, ultramafic schists and porphyries. The K2 ore body is confined to a mafic sequence with inter-volcanic graphitic shales. Both ore-bodies have a strong penetrative, sub-vertical, D_1 foliation which is complexly folded and deformed by two folding events (F_2 and F_3). Gold mineralisation at K1 is hosted in quartz veins predominantly in north-plunging, F_2 fold hinges within a structurally complex zone adjacent to a near 90° flexure in the granitoid-greenstone boundary. In K2, gold mineralisation clearly follows a north east-south west trending shear zone parallel to the main D1 foliation. Gold mineralisation is hosted within sub-parallel and *en-echelon* quartz-vein sets of variable thickness (mm- to m-scale) along these D_1 foliation planes.

Alteration associated with gold mineralisation in both ore-bodies is restricted to a few centimetres adjacent to mineralised quartz veins. In K1, this alteration of the dominant BIF host rocks comprises amphibole with biotite and locally minor carbonate, with additional pyrrhotite, chalcopyrite, pyrite and lesser amounts of scheelite and galena. Mineralisation is characterised by intense silicification of the ore-zone at K1 and also at K2. The alteration around mafic hosted, auriferous, *en-echelon* quartz vein sets at K2 includes amphibole and alkali feldspar with minor biotite and calcite, and additional pyrite, chalcopyrite, pyrrhotite, traces of galena and scheelite. Potassic alteration is weakly developed in both ore zones, but is less evident in K2. The composition and texture of the amphiboles in the metamorphic and alteration lithologies, together with the nature of alteration, particularly the lack of strong carbonate alteration, are consistent with synchroneity of mineralisation at Marymia with peak lower-amphibolite facies metamorphism. A later, retrograde greenschist-facies metamorphism is unrelated to gold mineralisation. This overprint is best developed in the mafic sequence at Marymia, with assemblege including abundant clinozoisite/epidote and chlorite, with albite and minor carbonate.

Preliminary Pb-isotopic studies of galena, intergrown with gold, and hence directly related to gold mineralisation, yield a Pb-Pb model age for mineralisation of approximately 2650 ± 35 Ma. Although this result is based on limited data, the age of gold mineralisation at Marymia is thus clearly Archaean and broadly consistent with the late-Archaean (2.66-2.63 Ga) age of gold mineralisation in the Yilgarn Craton to the south. By implication, the Marymia sequence must represent an Archaean greenstone belt. Thus, the Marymia Gold Project can be classed as a greenstone-hosted lode-gold deposit formed during peak lower-amphibolite facies metamorphism by infiltration of fluids during complex deformation. Gold mineralisation is controlled by both D_1 and D_2 structures, but whether these relate to discrete or progressive events is not yet known.

Evidence for fluid mixing and immiscibility and implications for gold mineralization in the Missouri and Sand King deposits, Eastern Goldfields Province, WA

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Many historical gold deposits are present in the Siberia district of the Eastern Goldfields Province but only Sand King, Missouri and Theil Well have operated in recent times. The Missouri deposit produced 20.8 kg of gold between 1899 and 1912 (Montgomery, 1909). Historic workings were sunk to a depth of approximately 100 m and further open pit mining was carried out during 1987 and 1988. Gold mineralisation occurs in the weakly plagioclase-phyric, low-Mg (Missouri) basalt and the associated quartz-feldspar porphyry is not a significant host rock. The mineralised structure is a 0.5-2 m wide fracture with abundant quartz veining and quartz(-plagioclase)-biotite-carbonate-pyrite alteration assemblages are developed adjacent to quartz veining.

The Sand King deposit has an estimated total resource of approximately 8.6 tonnes of gold, and since 1980, it has provided over 80% of the gold produced from the Siberia district (Hill and Bird, 1990). The ore is hosted by zones of quartz-biotite-pyrite veining and brecciation in the Missouri basalt. Gold occurs mainly as inclusions and fractures in the margins of the quartz-biotite-pyrite veins and in the 0.5-2 m wide biotite-plagioclase-pyrite (pyrrhotite) alteration assemblage adjacent to the vein systems. Galena, chalcopyrite, sphalerite, scheelite and tellurides also occur in minor quantities. Both deposits lie within the amphibolite facies metamorphic aureole flanking the monzogranitic batholith to the west.

This fluid inclusion study forms part of the National Geoscience Mapping Accord project on the Eastern Goldfields and was undertaken to investigate the nature of the ore-bearing fluids and to determine possible mechanisms for gold deposition in the high metamorphic grade region of the Siberia district. Six types of fluid inclusions have been recognised from microthermometry and laser Raman microprobe analyses and they are classified according to their composition as follows:

Type I inclusions contain CH_4 as the only detectable volatile species in the vapor phase. Generally, they are monophase and have negative crystal to irregular shapes. Inclusions containing methane vapour and up to 50 vol.% water have also been included in this group for reasons given below.

Type II inclusions are CO_2-rich. In many of these inclusions only CO_2 is observed at room temperature, either as a single phase or as both liquid and vapor. Other CO_2-rich inclusions also contained an aqueous phase with the volumetric proportions of CO_2 ranging from 30 to 95% but was typically greater than 50%. In rare cases, some contain a small daughter mineral as well which has been identified as calcite by Raman microprobe analysis.

Type III inclusions are multiphase and contain approximately 50 vol.% vapor and between two to four solid phases. Crystals of muscovite and carbonate have been identified by Raman spectroscopy. These inclusions are quite rare and have only been observed in early, highly-strained quartz surrounded by thin sulfide or fuchsite veins. Raman microprobe analyses indicate that the vapor phase of these inclusions contain an average of 48.2 mole% CO_2, 51 mole% CH_4 and 0.4 mole% H_2S.

Type IV aqueous inclusions contain variable amounts of CO_2 and CH_4 in the carbonic phase and consist of either one phase or two phases (liquid water + carbonic vapor) at room temperature. Occasionally, these inclusions also contain a small carbonate daughter mineral. The Raman microprobe analyses showed a wide variation in CO_2/CH_4 ratios which ranged from 0.86 to 0.09.

Type V inclusions typically contain between 5 and 10 vol.% vapor and are highly saline. Some also contain up to three daughter minerals with a single halite crystal being the most common type, especially in late calcite vein fill. The Raman microprobe could not detect any species in the vapor phase of Type V inclusions and H_2O is assumed to be the only volatile species. Halite daughter crystals melted between 122 and 123°C giving a salinity of 28 equiv. wt.% NaCl.

Type VI inclusions are secondary, low salinity aqueous inclusions which may or may not contain a vapour bubble of about 5 vol.%. The Raman microprobe did not detect any species in the vapor phase and, hence, H_2O is assumed to be the only volatile species. They have been observed to cross-cut trails of carbonic inclusions and appear to be the latest population of fluid inclusions. Final melting temperatures of ice range from -5 to 0° with a mode at -3.5°C giving an average salinity of 5.8 equiv. wt.% NaCl.

The evidence from fluid inclusions suggests that a CH_4-rich fluid has been generated during metamorphic dehydration reactions involving carbonaceous interflow sedimentary units (and possibly the Black Flag Group). On cooling below 400°C this fluid will unmix to CH_4-rich and H_2O-rich fluids. Thus, the Type I inclusions represent heterogeneous trapping of the immiscible phases.

The CO_2-rich (type II) fluids are believed to have entered the system during the intrusion of the post-D_2 to syn-D_3 granitoids (Witt & Swager, 1989). The wide range of CO_2/CH_4 ratios observed for Type IV inclusions is thought to result from mixing of the CO_2-rich fluid with the CH_4-rich fluid. The presence of muscovite in Type III inclusions indicates a high K^+ content and suggests that they were associated with the potassic alteration event (Witt, 1991) which is evident in both deposits. The high salinity (Type V) and low salinity (Type VI) inclusions both homogenise over the range from 76 to 220°C which suggests that these represent the influx of late stage brines and meteoric fluids, respectively.

Gold mineralisation is believed to be roughly synchronous with the intrusion of the adjacent granitoids and the regional D_3 deformation event (Witt, 1993). The precipitation of gold may have been caused by the large changes in the oxidation potential resulting from mixing between the CO_2-rich and CH_4-rich fluids. Alternatively, even minor increases in the CH_4 concentration as a result of mixing would have greatly increased the immiscibility field in the CO_2-CH_4-H_2O system and gold may have precipitated as a result of phase separation. Thus, mineralisation may have occurred by either redox changes or by phase separation but fluid mixing, as evident in this study, would have greatly enhanced either mechanism.

References

Hill, B.D., & Bird, P. 1990, Sand King Gold deposit, in *Geology of the Mineral Deposits of Australia and Papua New Guinea*, ed. F.E. Hughes, The Australian Institute of mining and Metallurgy, Melbourne, pp 377-381.

Montgomery, A. 1909, *Department of s Mines Western Australian Annual Report.*

Witt, W.K. 1993, Lithological and structural controls on gold mineralization in the Archaean Menzies-Kambalda area, Western Australia, *Australian Journal of Earth Sciences*, 40, pp 65-86.

Witt, W.K. 1991, Regional metamorphic controls on alteration associated with gold mineralization in the Eastern Goldfields province, Western Australia: Implications for the timing and origin of Archean lode-gold deposits, *Geology*, 19, pp 982-985.

Structural controls of gold mineralisation at the Granny Smith mine, Laverton, WA: the role of heterogenous stress distribution

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The Granny Smith gold deposits are situated 250 km north-east of Kalgoorlie and 20 km south of Laverton at latitude 28°48' S, longitude 122°25' E in the Laverton–Leonora area of the North Eastern Goldfields Province of the Archaean Yilgarn Block, Western Australia. The deposits (Goanna, Granny, and Windich) formed late in the structural history of the Yilgarn Block, in a largely brittle structural régime at a high crustal level.

Gold mineralisation is located along a north-south striking deformation zone that partly follows the contact between granitoid and metasedimentary rocks. The granitoid is a composite, elongate (about 2 km x 5 km) and zoned calc-alkaline granitoid pluton, which has porphyritic and more mafic margins. Several plagioclase porphyry dykes trend subparallel to bedding in the metasedimentary rocks near the granitoid margin. In detail, the mineralisation is largely controlled by the contact between the granitoid and metasedimentary rocks, although at the Goanna deposit, it is along a reactivated reverse fault along the western limb of an anticline. The mineralisation especially follows the granitoid contact where it has shallow or moderate dips (2°E). Where the dip of the contact is steeper, mineralisation occurs in the footwall granitoid up dip from the concave part of the contact or in the hangingwall metasedimentary rocks down dip from the convex part of the contact. In the granitoid and in much of the hornfelsed sedimentary rocks, gold mineralisation occurs in a conjugate network of thin carbonate-quartz breccia veins and their alteration haloes. The orientation of the conjugate sets varies in different parts of the granitoid, and small reverse movements along veins are common. Some of the plagioclase porphyry dykes and surrounding metasedimentary rocks in the hangingwall of the main zone of mineralisation are also mineralised. In contrast to the conjugate veinsets in the granitoid, veins and faults in the sedimentary rocks are parallel to bedding. As a consequence, the mineralized zones are narrower but have a higher gold-grade.

The granitoid-hosted segments of the deposits are characterized by two stages of mineralisation: an earlier low-grade hematite alteration and a later, overprinting high-grade sericite-carbonate alteration. In the hematite alteration, which is not only fracture controlled but also occurs as more pervasive hematite staining of feldspars, chlorite is predominant ferromagnesian mineral and magnetite is common whereas in the sericite-carbonate alteration they are rare. In the sericite-carbonate alteration, distal alteration is typified of breakdown of clinopyroxene and amphibole and the development of sericite biotite chlorite + carbonate alteration. The proximal alteration zone is defined by more intense fracturing and increasing carbonate-sericite-silica-pyriterutile alteration (bleaching). The main sulphide phase in mineralisation is pyrite; other ore minerals present are pyrrhotite, chalcopyrite, sphalerite, galena, arsenopyrite and telluride minerals. Native gold occur as inclusions and on the grain boundaries of sulphides or tellurides, and as individual grains and clusters between quartz grains. Gold occurrence is similar in veins and alteration haloes.

The variation in the geometry of mineralisation is thought to have resulted from the rheological effects of variations in the dip of the granitoid contact during compressional deformation. Where the dip of the contact is less than about 50°, slip occurred along the contact, whereas at greater contact dips, the shear strength of the contact exceed the shear strength of the granitoid, and the stress was released through conjugate fracturing of the granitoid. In the metasedimentary rocks the deformation was by slip along bedding planes (dip about 50°E) or along pre-existing faults, or via fracturing the plagioclase porphyry dykes which are all original heterogeneities close to the favourable orientation for slip. Variations in the orientations of conjugate veins within the granitoid are interpreted to indicate that the local stress field was heterogeneous and controlled by the shape of the granitoid contact. The greatest variations in vein geometry and implied stress orientations occur in the zones where the contact is most irregular. These are also the areas of highest grade mineralisation. The overall structural control on the deposit is thus focussing of fluid flow in a regional-scale, low mean-stress region created by the geometry of the granitoid intrusion. Within this region, several permeable structures became mineralised, but irregular contact of the granitoid caused deposit-scale variations in fluid flow and resulted in heterogeneous gold grades along the contact zone.

Lithogeochemical discrimination of mafic intrusives in the Kalgoorlie sequence

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Dolerite(-gabbro) intrusives are important hosts for gold deposits throughout the Eastern Goldfields, particularly the Golden Mile Dolerite in the Kalgoorlie area (e.g., Golden Mile, Mt Charlotte), and hence are significant exploration targets. The purpose of this study has been to develop diagnostic lithogeochemical parameters for identification of these mafic intrusives, and their internal differentiation, as well as understanding their petrogenesis.

The Kalgoorlie sequence is a 3.3-4.0 km thick succession of ultramafic to mafic volcanic rocks and a number of strikingly concordant mafic sills, traditionally termed 'dolerites', that make up the lower part of the Archaean Norseman–Wiluna greenstone belt. The 'dolerites' generally have been documented as part of the stratigraphy (Keats, 1987) and recent studies (Clout & others, 1990) have identified five separate 'dolerite' intrusives within the Kalgoorlie sequence. These include three new stratigraphic units, the Aberdare, Eureka and Federal Dolerites (Clout & others, 1990), in addition to the Golden Mile Dolerite emplaced along the Black Flag Beds/Paringa Basalt boundary and the Williamstown Dolerite emplaced between the Paringa Basalt and Kapai Slate.

The Aberdare Dolerite, which is structurally equivalent to and abuts the Golden Mile Dolerite across the Adelaide Fault, previously was interpreted as part of the Golden Mile Dolerite in the closure of the 'Kalgoorlie anticline', whereas the Eureka Dolerite within the Paringa Basalt, to the east of Kalgoorlie, has been interpreted as stratigraphically thinned Golden Mile Dolerite on the east limb of the fold (Travis & others, 1971). The Federal Dolerite, also within the Paringa Basalt, is on the west limb of the 'Kalgoorlie syncline', to the west of the Mount Charlotte mine.

All 'dolerites' are differentiated sills, each with a number of distinct lithological units. The Williamstown Dolerite has two major units, an upper subophitic and granophyric gabbro and a lower ultramafic unit which includes pyroxenite and peridotite. The Eureka Dolerite is a differentiated sill with chilled margins (no pyroxene) and subophitic gabbroic units on either side of a central quartz gabbro. The Federal Dolerite is a weakly differentiated sill that appears to be of more uniform composition, but with granophyric textured units in the central portions of the sill. The Aberdare Dolerite is a weakly differentiated sill, with fine-grained chilled margins and subophitic gabbro on either side of at least three central subophitic and granophyric gabbroic units. The Golden Mile Dolerite (Travis & others, 1971) has been divided into ten lithological units, including upper and lower chilled margins (units 1 and 10), an ultramafic layer (unit 2), a gabbroic unit with clusters of tabular pyroxene (3), a pyroxene-phyric gabbro with aggregates of skeletal oxides (4), a gabbroic unit with bladed plagioclase laths and sparse skeletal oxides (5), a subophitic and granophyric gabbroic unit (6) and a subophitic microgabbro (unit 7) which are below a central granophyric quartz gabbro (unit 8) and a thick subophitic and granophyric gabbroic unit (9).

Geochemically, the Golden Mile, Aberdare, Eureka and Federal Dolerites have tholeiitic affinities, whereas cumulate-textured units within the Williamstown Dolerite are komatiitic and the granophyric gabbroic unit is a high-Fe tholeiite. Chrondrite normalised rare earth element (REE) patterns for the Golden Mile Dolerite and Aberdare Dolerite are markedly similar and hence are probably co-magmatic. Similarities in REE patterns for the Federal Dolerite and Eureka Dolerite also indicate that these intrusives are co-magmatic, but from a different source to the Golden Mile and Aberdare Dolerites. The Williamstown Dolerite has different REE patterns to the other four 'dolerites'. This threefold geochemical grouping of the 'dolerites' is confirmed on binary discriminant diagrams, including La~Sm, La~Yb, Yb/Sm~La/Sm, Cr~Ni, Cr~Y, Cr~Ce/Sr, Zr/Y~Zr, and ternary plots such as TiO_2~MnO~P_2O_5.

Although, structurally, there may be five 'dolerites', geochemical data indicates that there are only three magmatic units and that the Golden Mile and Aberdare Dolerites are co-magmatic, as too are the Eureka and Federal Dolerites. The Williamstown Dolerite is clearly separate from the other 'dolerites'. Work is continuing on lithogeochemical characterisation of differentiated units within 'dolerites' and matching of units between intrusives of similar origin.

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References

Clout, J.M.F., Cleghorn, J.H., & Eaton, P.C. 1990, Geology of the Kalgoorlie gold field, in *Geology of the Mineral Deposits of Australia and Papua New Guinea*. The Australian Institute of Mining and Metallurgy, Melbourne: p.411-431

Keats, W. 1987, Regional geology of the Kalgoorlie-Boulder gold mining district. *Geological Survey Western Australian Report* 21.

Travis, G.A., Woodall, R., & Bartram, G.D. 1971, The geology of the Kalgoorlie Goldfield, in *Proceedings of a Symposium on Archaean Rocks*, Geological Society of Australia Special Publication, 3: 175-190

Textural evidence for epigenetic gold mineralisation of banded iron formation (BIF) at Mt. Morgans, Laverton area

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The question of whether gold deposits hosted by banded iron formation (BIF) are of syngenetic or epigenetic origin is still a controversial matter, and in recent years new arguments for syngenetic gold deposition in BIF have been put forward. However, for the Mt. Morgans gold deposit, it can be demonstrated conclusively that gold was introduced during a late tectonic event, and is therefore of epigenetic nature.

The Mt. Morgans BIF-hosted gold deposit is situated some 40 km west-southwest of Laverton in the northeastern Eastern Goldfields Province, on the western limb of the moderately south-southeast plunging Mt. Margaret anticline, the major structural element in that area. Most recent estimations of the measured-indicated resources are in the range of 6.245 Mt at 3.42 g/t Au (22 t Au, = 0.72 million oz). This figure means that the Mt. Morgans gold mining operation has the largest gold resources in the Leonora–Laverton area, followed by Granny Smith (20 t Au, = 0.66 million oz), and the Lancefield gold deposit (8 t Au, = 0.26 million oz).

From the hangingwall to the footwall, the dominant host-rock lithologies at Mt. Morgans comprise: 1) massive tholeiitic meta-basalts and minor sheared derivatives [carbonate-chlorite schists], 2) the mine-sequence, essentially composed of several horizons of discontinuous, lensoid bodies of mixed facies BIF [the principal host to gold mineralisation] in a "matrix" of variably foliated rhyolites, and 3) sheared komatiitic peridotite, now present as talc-carbonate-chlorite schist. The Mt. Morgans BIF horizons trend about 10 to 15 degrees oblique to the strike of BIF to the north and south. Structurally, four deformation events can be distinguished. Indirect evidence implies that the earliest deformation was a shearing event, developing a D_1 fabric parallel to lithological layering. The second deformation produced the major Mt. Morgans shear zone (D_2), with a strong foliation slightly oblique to D_1. A north-northeast to south-southwest trending shear/fault set (D_3) intersects D_2 at a moderate angle, and is interpreted to be directly related to gold mineralisation. The latest stage of deformation (D_4) is defined by a subhorizontal fracture set, commonly intruded by lamprophyres and intermediate dykes.

At Mt. Morgans it can be shown convincingly that gold has been introduced into the originally oxide-(+carbonate) facies BIF at a late stage of the structural evolution, and is therefore epigenetic. There are a number of lines of critical evidence supporting this interpretation: 1) the close spatial relationship between crosscutting structures (D_3) and high-grade gold mineralisation, which is similar to volcanic-hosted gold deposits, 2) sulphidation of BIF horizons and associated gold occurrence related to crosscutting structures and diffuse quartz-carbonate veining, 3) chlorite [mainly ripidolite] and carbonate [dominantly siderite] alteration of gold-bearing BIF, 4) base-metal to gold ratios [$Au/Ag<7$, $Cu/Au<8$, $Zn/Au<19$], similar to those of volcanic-hosted gold deposits, compared to volcanogenic massive-sulphide ores or exhalative sediments with Cu/Au and Zn/Au ratios in excess of 10000:1, 5) Pb-Pb model ages of ore-related sulphides of about 2.65 Ga, which are similar to volcanic-hosted gold deposits, and 6) textures indicating the replacement of magnetite by pyrite along grain boundaries and in fractures during sulphidation processes. Although additional information is provided for all the critical evidence mentioned above, this contribution emphasises the replacement textures of magnetite by pyrite, which can be demonstrated on a variety of scales. At hand specimen scale, pyrite occurs along late fractures in individual magnetite bands, as well as a direct replacement of magnetite at contacts with quartz-(+carbonate) veins. In thin section, it can be demonstrated that;

- i) pyrite is selectively developed at the contact of chert- and magnetite bands, with disseminated magnetite in the adjacent chert band,
- ii) pyrite occurs as fracture fillings in magnetite and along grain boundaries between magnetite grains, and
- iii) magnetite occurs as inclusions in pyrite, but pyrite inclusions in magnetite are absent. Microtextures detected with the scanning electron microscope (SEM) indicate that coarse-grained pyrite overgrows individual thin magnetite layers, locally preserving these enclosed layers.

These observations leave little doubt that gold-related sulphides were precipitated after the chemical sedimentation of the oxide-(+carbonate) facies BIF horizons. The ore-bearing fluids were introduced via structurally controlled channelways (D_3), depositing gold in the physically and geochemically most favourable BIF due to fluid/wall-rock interaction.

The Keith–Kilkenny Lineament: Fault or Fiction?

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The north-northwest to north striking KeithKilkenny Lineament (Williams, 1974) has been recognised with varying degrees of assurance for a distance of almost 500 km in the eastern half of the Eastern Goldfields. The lineament has conventionally been interpreted as the manifestation of a major fault along the eastern edge of a high strain corridor (Keith–Kilkenny Tectonic Zone of Hallberg, 1985). In these terms it would qualify as a possible terrane (in the broad sense used by Swager & others, 1990; 1992) boundary.

Historically, recognition of the Keith–Kilkenny Lineament was almost entirely dependent on the presence of a regional reconnaissance scale (1500 m flight line spacing) aeromagnetic low in the Mount Kilkenny area, southeast of Leonora (Williams & others, 1971; 1976). This was extrapolated northwards using a variety of geophysical and geological features into the vicinity of Mount Keith, south-southeast of Wiluna. The Lineament was traced south from Mount Kilkenny into the Mulgabbie area. Semi-detailed aeromagnetic (400 m flight line spacing) and "ground truth" (approx. 1:25 000 scale) data have recently been acquired for the central sector of the Keith–Kilkenny Lineament (Yerilla, Minerie, Leonora, Weebo, and Wildara 1:100,000 Sheet areas) by AGSO as part of the contribution to the Eastern Goldfields National Geoscientific Mapping Accord Project.

In the north of the area studied (Wildara Sheet), the Lineament correlates with the outcropping, apparently sinistral, Perseverance Fault. The fault can be traced using aeromagnetic data to the south-southeast (Weebo Sheet) where it parallels a poorly outcropping greenstone sequence which curves in from the vicinity of the Darlot Mine area to the north. In this region the Keith–Kilkenny Lineament is not readily correlated with any particular lineament defined by the aeromagnetic data or obvious outcropping greenstone. Moderate to highly magnetised units of the greenstone sequence appear to be dislocated or are, at least, much less continuous along strike than equivalent rocks in the Darlot Mine area. Further to the south-south east (southeast Leonora, Minerie and Yerilla Sheets), the Keith–Kilkenny Lineament correlates with a fault inferred from the aeromagnetic data which parallels the northeastern margin of the greenstone sequence. There is no single lineament which connects this fault, across the greenstone sequence, with the Perseverance Fault to the north-northwest.

Greenstone sequences on the southwest side of the postulated Keith–Kilkenny Lineament (western Yerilla, western Leonora and Wildara Sheets) are not fundamentally different in overall aspect from those on the north-eastern side (eastern Yerilla, Minerie, eastern Leonora and Weebo Sheet areas). Tentative correlations have therefore been made across the Lineament (Rattenbury, this vol).

The Keith–Kilkenny Lineament is thus shown to be a complex feature comprised of faults in the northwest and southeast separated by sub-parallel trending and possibly dislocated greenstones. The Lineament cannot be equated with a single major fault and may well be temporally and genetically composite in origin, as significant parts of the Keith–Kilkenny high strain corridor elsewhere appear to be (Eisenlohr, 1992; Passchier, 1993). The previously perceived continuity of the feature was in large part an artifact of reconnaissance scale data sets. These conclusions considerably weaken any claim for the Lineament to be considered a terrane boundary. The possibility remains that the full width of the Keith–Kilkenny corridor (or some other structure) does represent such a boundary. This possibility is being investigated further.

References

Eisenlohr, B.N. 1992, Contrasting deformation styles in superimposed greenstone belts in the northern sector of the Norseman Wiluna Belt, Yilgarn Block, Western Australia (extended abstract), in *The Archaean terrains, processes and metallogeny*, eds. J.E. Glover & S.E. Ho, University of Western Australia, Geology Department (Key Centre) and University Extension Publication, 22, pp 191-202.

Hallberg, J.A. 1985, *Geology and mineral deposits of the Leonora - Laverton area, northeastern Yilgarn Block, Western Australia.* Hesperian Press, Carlisle W.A.

Passchier, C.W. 1993, The nature of high strain zones in the Laverton - Leonora area, Western Australia. *Australian Geological Survey Organisation Record* 1992/53.

Swager, C.P., Griffin, T.J., Witt, W.K., Wyche, S., Ahmat, A.L., Hunter, W.M., & McGoldrick, P.J. 1990, Geology of the Archaean Kalgoorlie Terrane - an explanatory note, *Western Australia Geological Survey Record* 1990/12.

Swager, C.P.,, Witt, W.K., Griffin, T.J., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J., & Wyche, S. 1992, Late Archaean granite-greenstones of the Kalgoorlie Terrane, Yilgarn Craton, Western Australia, in *The Archaean terrains, processes and metallogeny,* eds. J.E. Glover & S.E. Ho, University of Western Australia, Geology Department (Key Centre) and University Extension Publication, 22, pp 107-122.

Williams, I.R. 1974, Structure and subdivision of the Eastern Goldfields Province, Yilgarn Block, *Western Australia Geological Survey Annual Report* 1973, pp 53-59.

Williams, I.R., Gower, C.F., and Thom, R. 1971, Explanatory notes on the Edjudina 1:250 000 geological sheet, Western Australia, *Western Australia Geological Survey Record* 1971/26.

Williams, I.R., Gower, C.F., & Thom, R. 1976, Edjudina, Western Australia, Sheet SH/51-6 International Index, 1:250 000 Geological Series, *Geological Survey of Western Australia, Explanatory Notes.*

A preliminary genetic model for the base-metal rich Mt Gibson Archaean lode-gold deposits, Western Australia

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The Archaean lode-gold deposits at Mt Gibson are located at the southern tip of the Retaliation belt, the southernmost portion of the Yalgoo–Singleton greenstone belt of the Murchison Province, Western Australia. The deposits are hosted in a greenstone sequence which is dominated by tholeiitic metabasalts and dolerites, with lesser magnesian basalts and quartz-feldspar schists and porphyries, and has been metamorphosed to middle amphibolite facies. Lode-gold mineralisation is contained within the Mt Gibson shear zone, a broad, north to north-north east striking, steeply east-dipping, anastomosing ductile-shear network, and typically occurs as steeply dipping lenses of sulphide quartz-bearing schist hosted predominantly within biotite chlorite altered mafic rocks.

The Mt Gibson gold deposits are anomalous when compared with other Western Australian lode-gold deposits. The sulphide assemblage which accompanies mineralisation typically comprises (in order of decreasing abundance) pyrite, pyrrhotite, chalcopyrite, sphalerite, galena, and bismuthinite. Base-metal sulphides in places reach concentrations sufficient to give grade assays of Pb and Zn of several percent. The Ag to Au ratio is generally approximately 3:1. The deposits also display

- (i) no appreciable carbonate alteration,
- (ii) few discrete quartz veins,
- (iii) predominantly ductile deformation fabrics,
- (iv) pre- to syn-tectonic mineralisation, and
- (v) unusual spessartine-gahnite and cordierite-muscovite bearing assemblages which are intimately associated with the gold mineralisation.

There is strong evidence for a synvolcanic VMS-style mineralising event at Mt Gibson. The unusually high base-metal values, primitive lead-isotopic ratios recorded for galena from the Hornet deposit, and the apparently stratiform nature of the mineralisation and asymmetry of the alteration in the Orion 2 Pit, all suggest a volcanogenic-type hydrothermal system. In addition, the spessartine-gahnite bearing schists, which are coincident with elevated Pb and Zn in both Orion 2 and Hornet, and immediately overlie the ore zone in Orion, are readily interpreted as a metamorphosed, base-metal rich, hydrothermally altered, seafloor horizon: that is, the upper or distal portion of a VMS system. Similarly, the cordierite-muscovite schist unit is probably derived from a strongly chloritic precursor, for example the alteration pipe of a VMS.

It is unlikely, however, that the biotitic (chloritic) alteration envelope associated with gold mineralisation in both Orion and Hornet was produced by the same seafloor alteration event. This style of alteration is typical of that in other shear-hosted, Archaean lode-gold deposits sited in amphibolite facies domains. The less primitive lead-isotopic values recorded for Orion 2 galena may reflect this later event. The timing of this later phase of mineralisation is unusual, however, in that the mineralisation is clearly pre- to early syn-tectonic, whereas most lode gold deposits in amphibolite facies settings are considered to be late syn- to post-tectonic.

In summary, a two-stage genetic model is proposed for the composite base-metal and gold deposits at Mt Gibson: an early seafloor VMS mineralising event and a later overprinting syn-orogenic gold mineralising event. The relative importance of these two events to the distribution of gold on both an individual deposit and mineral field scale is not known at this stage. Likewise, the extent to which structure (the ductile shears) and stratigraphy (the VMS mineralised horizon) control mineralisation is not well understood, although both must be considered to be important.