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Regional oxygen-isotope patterns

Implications for epithermal gold exploration

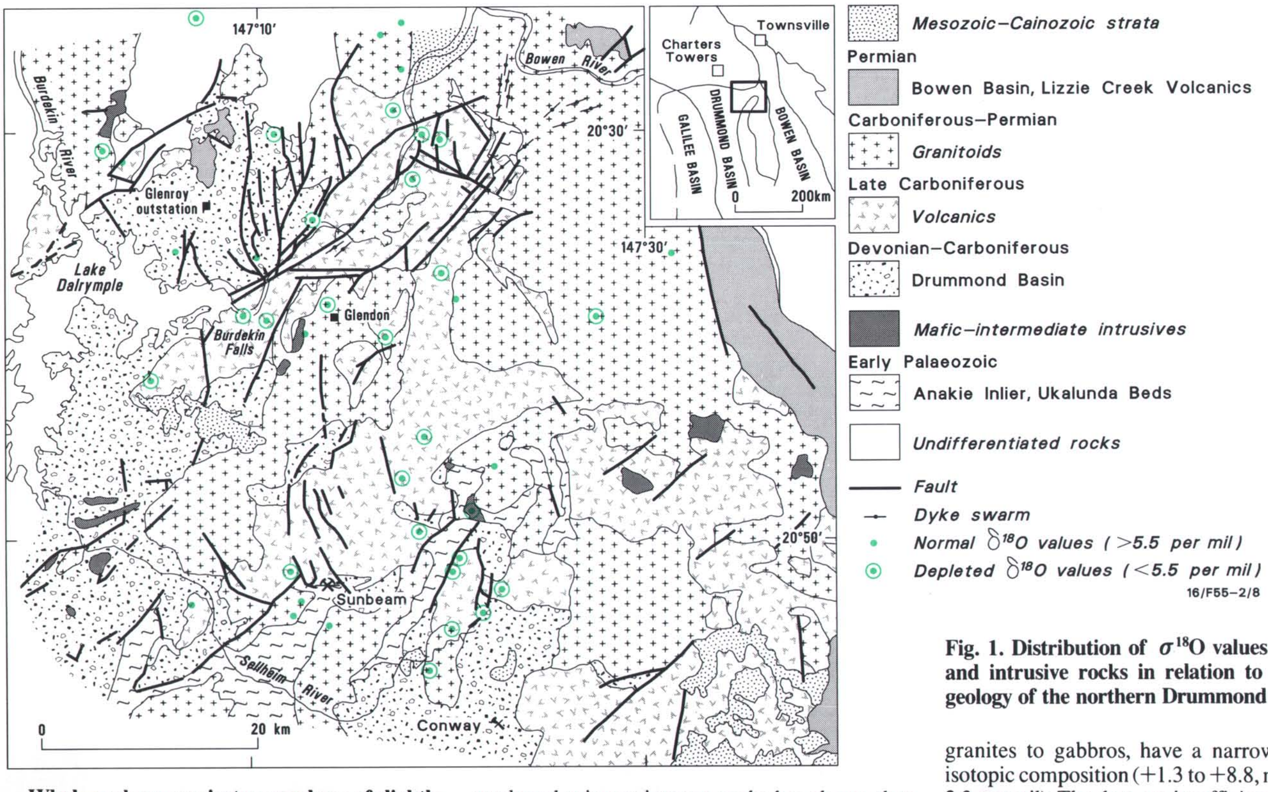

Fig. 1. Distribution of σ^{18}O values for volcanic and intrusive rocks in relation to a simplified geology of the northern Drummond Basin.

Whole-rock oxygen isotope analyses of slightly altered volcanic and intrusive rocks in the Devonian-Carboniferous of the northern Drummond Basin have led to the identification of an area of $^{18}0$ depletion of at least 1500 km^2. The full extent of this depleted area and the mechanism responsible for it are not clear, owing to structural complexity, poor age control, and generally poor outcrop. Since 1984, the northern Drummond Basin has emerged as a significant new epithermal gold province. Its association with a large area of regional $^{18}0$ depletion confirms earlier suggestions of a connection between these regional patterns and the incidence of epithermal districts. This relationship indicates that regional patterns of whole-rock-oxygen isotope depletion may be particularly useful in discriminating those areas which could be prospective for epithermal mineralisation.

A compilation by Taylor (1974: *Economic Geology*, 69, 843–883) of oxygen-isotope data for unaltered primary igneous rocks has shown that they have a typically narrow range, between about +5.5 and +10 per mil relative to Standard Mean Ocean Water (SMOW), providing a reference against which the effects of processes that alter the $\delta^{18}0$ values of igneous rocks can be assessed. Since the late 1960s, there has been an increasing realisation that some volcanic and plutonic rocks are regionally $^{18}0$-depleted relative to 'normal' igneous values. Low-$^{18}0$ meteoric fluids interacting with the rocks at high temperatures are the only plausible means of producing this depletion, because other fluid sources (e.g., magmatic or metamorphic) will either increase or only slightly decrease 'normal' whole-rock igneous values.

Data obtained for 24 relatively fresh volcanic rocks from the northern Drummond Basin (Fig.1) have a wide range of values from -8.2 to + 10.4 per mil; the mean value is +0.7 ± 4.9 per mil. The intrusive rocks (16 samples), which range from granites to gabbros, have a narrower range in isotopic composition (+1.3 to +8.8, mean +5.8 ± 2.3 per mil). The data are insufficient to provide a proper analysis for individual rock units, but they show that volcanic rocks within the Drummond Basin sequence and those extruded during the Late Carboniferous are isotopically depleted. Pyroclastic rocks and lavas are equally depleted, but both are more depleted in general than the intrusive rocks. Although some intrusive rocks are also abnormally low in $\delta^{18}0$, the majority have near normal values. The depleted area coincides closely with the present outcrop distribution of volcanic and intrusive rocks, and is consistent with field observations that suggest the source region for the Late Carboniferous volcanic units was in the northeastern sector of the mapped area (McPhie & others, 1990: *in* Pacific Rim Congress 90, *Australasian Institute of Mining and Metallurgy, Melbourne*, 2, 465–471).

The literature suggests a number of mechanisms, all requiring hydrothermal meteoric water interaction, to achieve this depletion. The possib-

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lity that low-^{18}O magmas (resulting from the assimilation of ^{18}O-depleted material and/or isotopic exchange between meteoric water and the magma) were emplaced and erupted in the northern Drummond Basin during the Palaeozoic cannot be discounted. However, the data are more easily explained, and appear to be more consistent with large-scale interaction of meteoric water with cooling intrusive and extrusive rocks. The observation that volcanic units are generally more ^{18}O-depleted than the intrusive rocks does not accord with depletion occurring at the magmatic stage, although locally a comagmatic intrusive and extrusive suite could be ^{18}O-depleted. Rather, it suggests that the volcanic rocks — being more porous and permeable — interacted and exchanged isotopically with heated meteoric water to a greater degree than the intrusive rocks.

Evidence of hydrothermal alteration and therefore isotopic exchange may be minor or completely absent, if hydrothermal interaction occurs at very high temperatures or, in the case of low-^{18}O magmas, the minerals directly crystallise from the melt. For example, Hemley & Jones (1964: *Economic Geology,* 59, 538-569)) showed that, in the presence of quartz, the stability fields for K-feldspar, sericite, kaolinite, and pyrophyllite are a function of temperature and fluid chemistry (specifically the K^+/H^+ cation ratio). At high temperatures and high K^+/H^+ ratios, K-feldspar will be the stable phase.

If subsolidus interaction occurs between meteoric groundwater (with an initial δ^{18}O value of -10 per mil) and a cooling volcanic pile (at temperatures above 300°C), water:rock ratios close to unity are capable of producing the observed whole-rock ^{18}O depletion. This water: rock ratio is geologically reasonable, although it represents a minimum value and could be much higher locally.

Implications for epithermal gold mineralisation

Stable-isotope data have demonstrated conclusively that hydrothermal fluids derived from meteoric water have played a dominant role in the genesis of epithermal gold deposits. Characteristically, host rocks to epithermal deposits are ^{18}O-depleted as a result of isotopic exchange involving these meteoric fluids (Field & Fifarek, 1985: *Reviews in Economic Geology,* 2, 99-128).

The association of extensive whole-rock ^{18}O depletion in the northern Drummond Basin with an area recently recognised as being highly prospective for epithermal gold provides further evidence of a relationship seen in younger epithermal districts. O'Neil & Siberman (1974: *Economic Geology,* 69, 902-909) first observed that many Tertiary epithermal deposits in the USA occur within areas that have undergone regional oxygen-isotope depletion. This relationship suggests that regional patterns of whole-rock oxygen-isotope depletion may be particularly useful in discriminating those areas which could be prospective for epithermal mineralisation. However, it should be noted that because epithermal deposits typically form within 1000 m of the surface, their preservation will depend on the level of erosion. Thus an area which appears favourable on the basis of isotopic data might be unprospective because the level of erosion is too great.

Other areas of extensive Permo-Carboniferous volcanism in northeast Queensland where epithermal gold prospects have not been realised might warrant closer attention on the basis of regional oxygen-isotope data. One such area is the Featherbed Volcanic Complex, which is over 400 km northwest of the Drummond Basin and about 100 km due west and inland from Cairns. Although regional oxygen-isotope data available for this very large complex are limited at this stage, they suggest that a strip of regionally ^{18}O-depleted rocks of at least 30 km^2 extends northwestwards from Petford. Six samples from this area have δ^{18}O values between -1.0 and +3.9 per mil (mean $+ 1.7 \pm 1.9$). This region, notable for its W-Mo and base-metal mineralisation, does not appear to have been deeply eroded; it might therefore have potential for previously unrecognised epithermal gold.

For further information, contact Drs Greg Ewers, Doug Mackenzie, Brian Oversby, or Doone Wyborn (Minerals & Land Use Program) at BMR

The 'Tumut Trough' is no more

The Tumut region, containing the Tumut and Jindalee Blocks, comprises the southern portion of the Tumut Synclinorial Zone, a fault-bounded belt of Ordovician to Silurian volcanics and flyschoid metasediments in the southeastern Lachlan Fold Belt (LFB), southeastern New South Wales (Fig. 2). Understanding the tectonic history of this region is vital in any account of the development of the LFB. The main reason for this is the presence of an interpreted Silurian ophiolitic suite (e.g., Coolac Serpentinite) in association with flysch, both of which are unique to this part of the LFB. Elsewhere, Silurian deposition was characterised by bimodal volcanism in basins separated by shallow-marine sedimentation and subaerial volcanism on intervening highs (Cas, 1983: *Geological Society of Australia, Special Publication* 10). Considerable interest has also centred on the Gilmore Fault Zone, which is a major crustal feature forming the eastern margin of the Wagga Metamorphic Belt (WMB). The zone extends for hundreds of kilometres, and appears to be the locus of gold mineralisation in a variety of geological settings.

The unique characteristics of the Tumut region have stimulated a variety of proposed tectonic models. Most of these models incorporate the *'Tumut Trough',* a palaeogeographic feature which was thought to be floored — at least in part — by oceanic crust and which was the site of a thick accumulation of flysch. Closure of this 'trough' would necessarily have involved subduction and/or obduction, and consequently plate tectonic models have prevailed (e.g., Crook, 1980: *Journal of the Geological Society of Australia,* 27, 215-232). With the objective of understanding the tectonic development of the Tumut region by resolving structural and stratigraphic problems, geological investigations were carried out by BMR and the Australian National University between May 1986 and May 1989. Major results of the study, including seven geological maps, have been recently published (Stuart-Smith, 1990a: *BMR Record* 1990/78; 1990b: *Australian Journal of Earth Sciences,* 37, 147-167; 1990c: *Journal of Structural Geology,* 12, 621-638), and are summarised below.

Rocks in the Jindalee Block form two distinct domains: Cambrian-Ordovician basement, and Ordovician-Silurian sedimentary and volcanic cover. These two domains are separated by a sharp discontinuity, marking an abrupt change in rock type, structure, metamorphic grade, and deformational style. The cover has undergone only one major penetrative deformation, during the Siluro-Devonian, involving subgreenschist-facies metamorphism and upright folding. In contrast, the basement also underwent at least two older deformations involving greenschist-facies metamorphism, and contains distinct high-strain zones subconcordant with the basement-cover contact. The high-strain zones, characterised by a ubiquitous south-southeast-trending mineral lineation, record a discontinuous history of ductile followed by brittle behaviour — consistent with an extensional origin. The structural and metamorphic discontinuity separating basement from Ordovician–Silurian cover is characterised by widespread cataclasis and alteration, and is interpreted as a major detachment fault associated with Early Silurian lithospheric extension (Fig. 3).

Ordovician-Silurian cover within the Tumut Block comprises two major tectonostratigraphic sequences: Ordovician-Early Silurian quartz-rich to quartz-intermediate flysch and volcanics; and an overlying fossiliferous Early-Late Silurian volcanic sequence. Rhyolite within the older sequence has yielded a U-Pb zircon age of about 428 Ma. Previously both of these sequences were regarded as forming part of the 'Tumut Trough'. However, arenites from the two sequences are compositionally distinct, and differences in clinopyroxene phenocryst compositions from mafic volcanics in both sequences reflect different tectonic environments. Both tectonostratigraphic sequences were meridionally folded during the Siluro-Devonian Bowning Orogeny. An earlier deformation —characterised by thrust-faulting, east-west recumbent folding, and later local coaxial upright folding — has affected only the older, flysch sequence. This earlier deformation is compared to the Benambran Orogeny, which affected Ordovician metamorphics of the WMB, and is tightly constrained to about 425 Ma. Fold characteristics of this deformation are indicative of thin-skinned intraplate transpressional deformation, rather than classical collision tectonics as envisaged by some workers for the Benambran Orogeny here and elsewhere in the LFB.

The Gilmore Fault Zone is a long-lived imbricate fault system separating the WMB from the Tumut Synclinorial Zone. Structures within it indi-

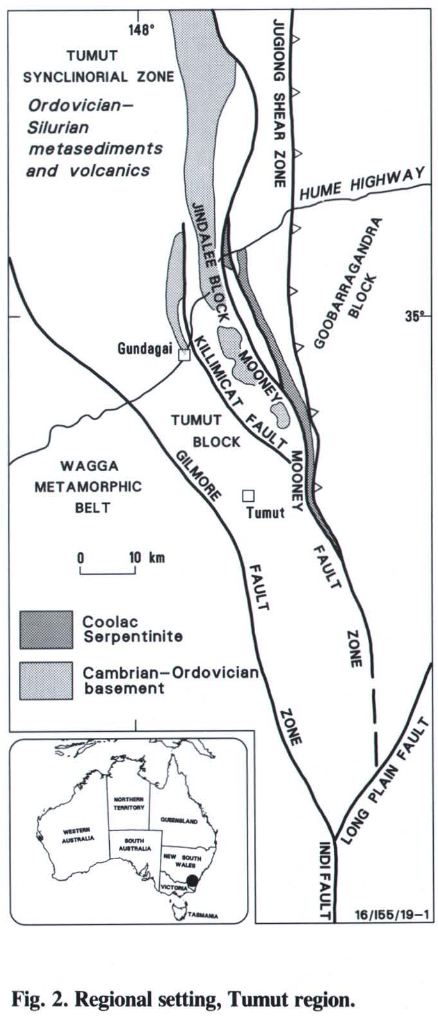


Fig. 2. Regional setting, Tumut region.

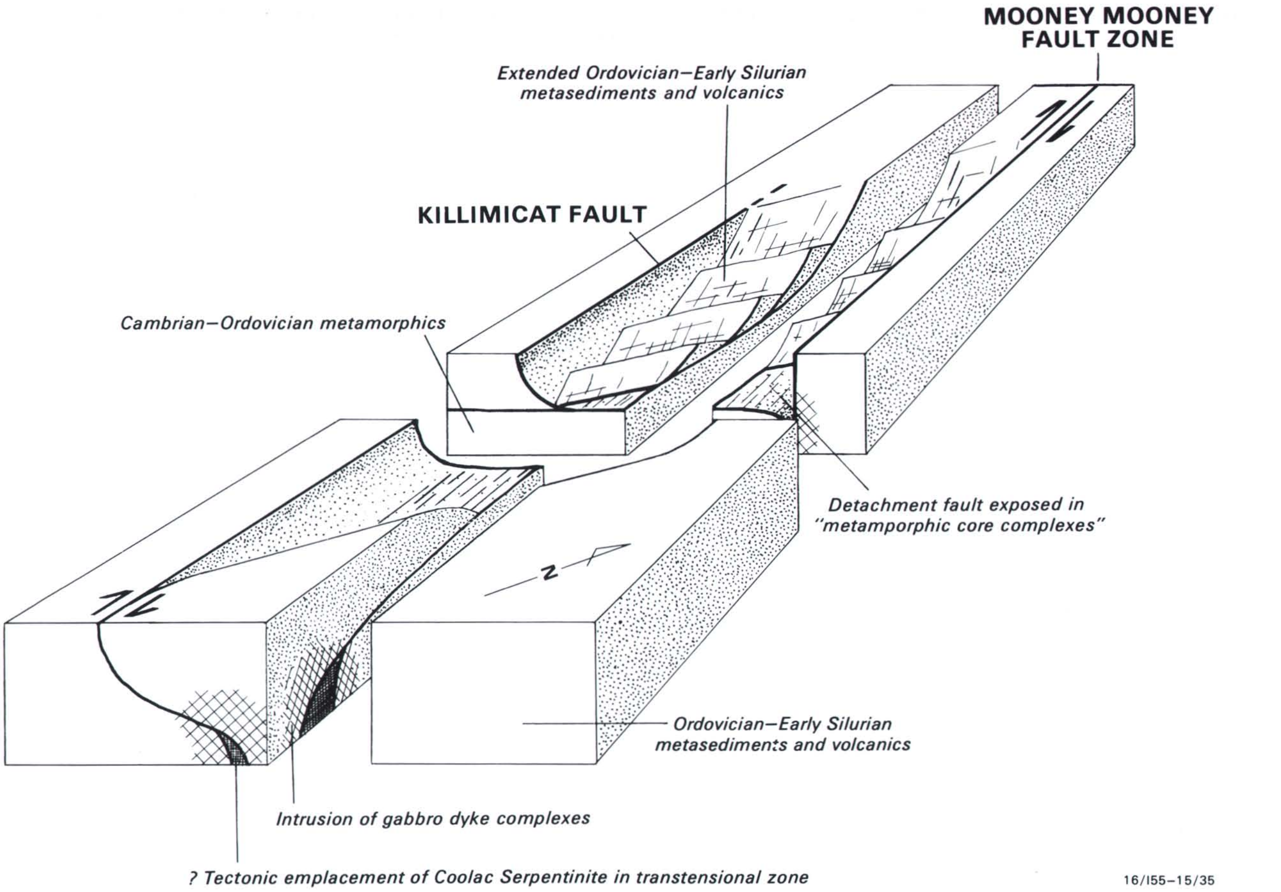


Fig. 3. Schematic block diagram of the pull-apart model of Early Silurian formation of the Tumut Basin.

cate dominantly sinistral transpressional movements during regional deformation in the Siluro-Devonian and mid-Devonian and/or Carboniferous. The movements, in response to lateral compression, resulted in the WMB being thrust over the Tumut Block. In addition strike-slip movement can be inferred during regional deformation and subsequent extension in the Early Silurian. Common structural and metamorphic histories, and lithological correlation of rock units straddling the fault zone, indicate that this feature does not represent a terrane boundary in either the Late Ordovician or Silurian as suggested by some previous workers. Differences in geophysical expression and crustal composition across the zone can be explained by the zone being a reactivated basement fault linked to a mid-crustal detachment.

The Mooney Mooney Fault Zone, containing an extensive ultramafic belt known as the Coolac Serpentinite, forms the eastern margin of the Tumut Synclinorial Zone. The ultramafic rocks, together with mafic volcanics and intrusive gabbroic rocks, have been previously interpreted as early Palaeozoic oceanic crust, dismembered and obducted during Siluro-Devonian deformation. However, a more complex history involving several periods of movements is evident. The ultramafic rocks and Early Silurian volcanics are intruded by Early Silurian gabbro dyke complexes and Late Silurian granodiorite. These intrusive relationships indicate that the ultramafic rocks occupied more-or-less their present structural position before the Siluro-Devonian deformation. The ultramafic rocks therefore cannot represent oceanic crust obducted during the Siluro-Devonian deformation, thus invalidating previous tectonic models for the region based on this interpretation. They probably represent either Early Silurian or Cambrian–Ordovician mantle-derived material emplaced within a strike-slip fault zone during Early Silurian oblique extension (Fig. 3).

The concept of an Early Silurian 'Tumut Trough' is rejected. Instead Early–Late Silurian rocks form a pull-apart basinal sequence (the Tumut Basin, Fig. 3) up to 2500 m thick. The Silurian history of the Tumut region, previously considered unique in the LFB, is little different from other basins of a similar age throughout the LFB.

For further information, contact Dr Peter Stuart-Smith (Minerals & Land Use Program) at BMR.

Depositional age of volcanic precursors of the 'Potosi' gneiss, Broken Hill Group

The nature and depositional age of the Broken Hill Group have been longstanding problems of Broken Hill geological research and exploration. This economically important package of rocks lies approximately in the middle of the roughly 7-km-thick stratigraphic sequence that comprises the Early to Middle Proterozoic Willyama Supergroup reviewed by Stevens & others (1988: *Precambrian Research,* 40/41, 297–327). The sequence consists predominantly of highgrade regional metamorphic rocks and minor granitic intrusives. The depositional age of the Broken Hill Group is vitally relevant to any correlation and exploration models, because the 300-Mt Ag-Pb-Zn Broken Hill orebody is stratabound in this unit. There have been several attempts to correlate rocks in the relatively small and isolated Broken Hill Block with Proterozoic terranes of central and northern Australia, but, until now, convincing geochronological information has been lacking.

Nearly all previous geochronological work in the Broken Hill Group has been confined to multiply deformed, polymetamorphic granulite-facies rocks in or near the 'mine sequence'. Although previous correlations have been based on many detailed lithological, stratigraphic-structural, geochemical and/or geochronological investigations, they have remained ambiguous and often contentious, largely due to complexities of deformation and high-grade metamorphism that have severely modified primary isotopic and other geochemical parameters.

The work summarised here focuses on rocks of lower metamorphic grade, and uses this as a basis for interpretation of new and previous data from higher-grade terranes. We have endeavoured to resolve some of these issues by means of ion-microprobe (SHRIMP, located in the Research School of Earth Sciences, Australian National University) and conventional U–Pb analyses on zircons identified as having crystallised in felsic volcanic precursors to gneisses familiarly known to many as the 'Potosi' gneiss. This is a distinctive quartzofeldspathic, garnet-bearing unit which passes laterally into metasediments containing the Broken Hill orebody. These rocks are laterally extensive, have relict textures characteristic of explosive silicic volcanic eruptions, and compositions consistent with a rhyodacitic precursor. Zircons in these rocks consist largely of zoned euhedral to subhedral slender grains, also consistent with a pyroclastic volcanic origin.

Detailed mapping by the Geological Survey of New South Wales (e.g., Willis & others 1983: *Journal of the Geological Society of Australia,* 30, 195–224; Stevens & others, 1988), and supporting textural, field, and geochemical evidence from collaboration with Dr Bill Laing (James Cook University of North Queensland), provide the basis for the present geochronological investigations. This mapping has shown the existence in the Broken Hill Group near Yanco Glen, about 40 km north of Broken Hill, of lower-metamorphic-grade areas, where volcanic textures and the primary morphology and isotopic integrity of igneous zircon are best preserved. In addition, these units (Parnell Formation and Hores Gneiss) are mappable southwards into higher metamorphic grades near the city of Broken Hill, where metamorphic monazite and new zircon growth are recognisable alongside corroded relict zircon and provide a likely means of determining the timing of the major high-grade event(s).

New U-Pb zircon results

Conventional, multi-grain U-Pb zircon analyses are discordant and and non-linear, hence precluding precise age interpretation by this method. However, ion-microprobe U-Pb work quantifies this complex pattern, and defines a major magmatic population in the Hores Gneiss and Parnell Formation near Yanco Glen, Southern Cross, and Broken Hill, at 1680-1690 Ma. This age is interpreted as that of zircon crystallisation, and hence the eruption and depositional age of this part of the Broken Hill Group.

The coherency of these U-Pb zircon ages provides clear evidence that volcaniclastic precursors of the Hores Gneiss and Parnell Formation lithologies were deposited no earlier than 1690 Ma ago. The preserved integrity of this age, and the preservation of discrete zircon inheritance patterns (1780 Ma, 1860 Ma, and older), suggest that the U-Pb systems in these magmatic zircons have borne little or no effect from later metamorphism. As some of these rocks may be immature volcanogenically derived sediments, the 1690-Ma age and the spread of older zircon ages could represent material inherited from reworked older provenance terranes. However, the relict volcanic textures, morphology of the zircons, rim-core relationships, and consistent strength of the principal age peak in each of the samples, favour the interpretation that 1690 Ma is the magmatic/depositional age of the sequence. It is most unlikely that these were arkosic precursors derived from a terrigenous granite-greenstone terrane, as expounded by Wright & others (1987: *Geology,* 15, 598-602).

This newly determined age of deposition for the Broken Hill Group provides a firmer chronological tie between the Broken Hill Block and other Early Proterozoic terranes in northern Australia. There may be close temporal links, and hence much better correlation from Broken Hill to the Mount Isa and McArthur Groups, and this tantalising possibility and analytical challenge is soon to be addressed with continuing SHRIMP work on the appropriate tuffs.

A further bonus from this Broken Hill study has been the determination of the age of zircon overgrowths (1600 ± 8 Ma) formed during granulite-facies metamorphism. These selvedges, up to 50 m wide, have a 'rounded' appearance that was incorrectly cited by Wright & others (1987) as evidence of a clastic sedimentary origin for the gneiss's precursor. This 1600-Ma age for the high-grade metamorphism is confirmed by U-Pb ages on monazite also of metamorphic origin, and is some 60 Ma younger than previously thought. It is possible that the 1600-Ma regional metamorphism at Broken Hill was part of a major crustal event in this part of Australia. Widespread plutonism of this age is now well documented to the west of Broken Hill in the Olary Block, in subcrop north of the Olary Block, in the northern Gawler Block, and in northern Stuart Shelf granites.

Conclusion

As a result of this geochronological study we have taken a few more steps to reposition pieces of the jigsaw for Australia's Early Proterozoic evolution:

- the zircon morphology and age distribution reveal something of the nature of the 'Potosi' gneiss lithologies in the Broken Hill Group, namely a significant volcaniclastic component;
- we now know the depositional age of the Broken Hill Group, 1680-1690 Ma;
- there is a tantalising apparent age correlation between this and the other major Proterozoic Ag-Pb-Zn deposits in Mount Isa and McArthur River; and
- the high-grade metamorphism is close to 1600 Ma, much younger than hitherto believed, and is part of a major magmatic event in this part of the continent.

For further information, contact Dr Rod Page (Minerals & Land Use Program) at BMR on (06) 249 4261.

Stratigraphy of the Pul Pul Rhyolite, South Alligator Valley Mineral Field

The Pul Pul Rhyolite is the middle member of the El Sherana Group, a sequence of rift-related volcanics and related sedimentary rocks (1860 Ma) formed during late orogenesis in the Pine Creek Inlier. Its stratigraphy was initially studied in an attempt to locate volcanic vents, or determine its proximity to vents and to evaluate the feasibility of a magmatic origin for the mineralisation of the South Alligator Valley Mineral Field. As no vents were located, the original aims were not realised. However, a crystal-rich facies identified at the top of the sequence was interpreted to represent the product of pyroclastic flows entering water, disintegrating, and transforming into water-supported mass-flows. The preservation of such a facies is extremely rare, not only in Australia but internationally. Further work is being carried out on this mate-

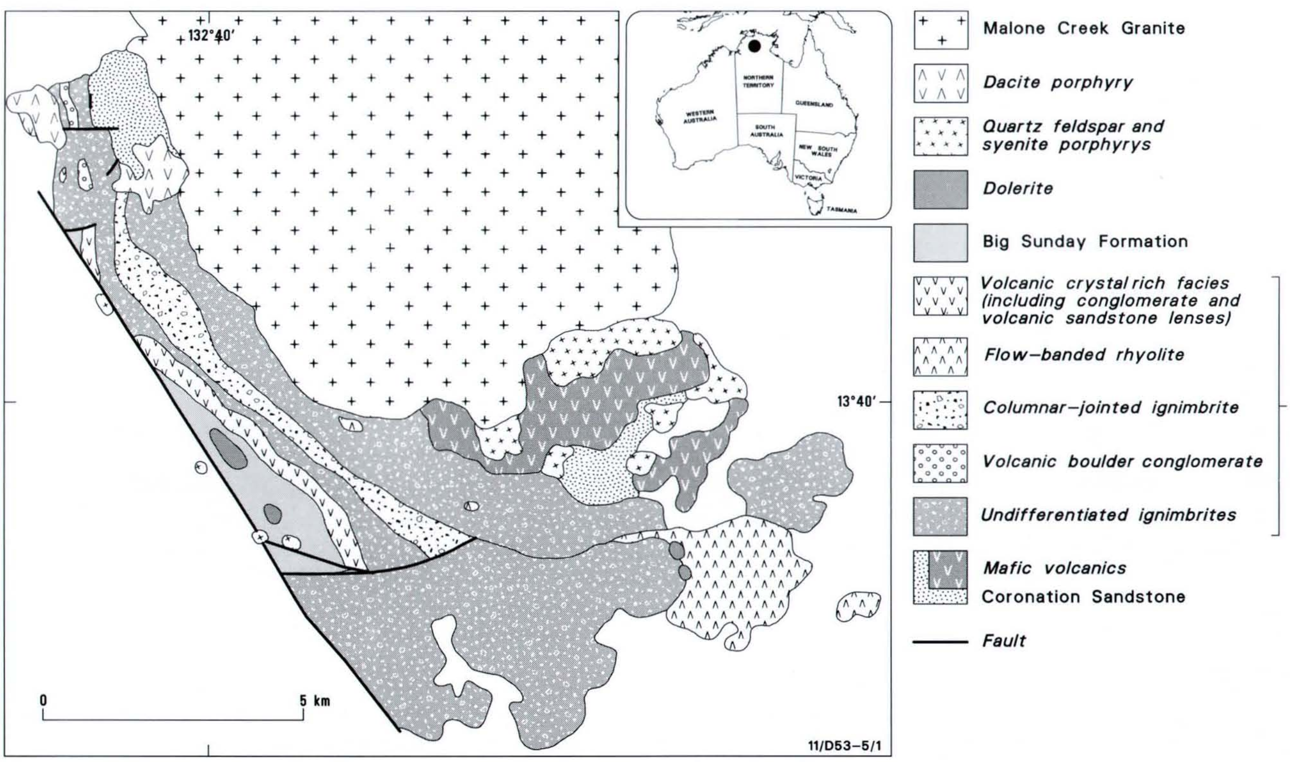


Fig. 4. Simplified stratigraphy and distribution of units of the Pul Pul Rhyolite.

rial to verify this interpretation. Upon verification, an exposure on the South Alligator River illustrating the facies will be recommended to the Australian Heritage Commission for nomination as a geological monument.

Relationships

The Pul Pul Rhyolite was studied in an area south of the Malone Creek Granite. The nature of its contact with the underlying Coronation Sandstone was not resolved; where exposed, this contact is complicated by faulting. The Pul Pul Rhyolite is conformably overlain by the Big Sunday Formation.

The Malone Creek Granite and the Pul Pul Rhyolite have a spatial relationship which suggests that they constitute a caldera complex in which the granite intrudes the volcanic pile. The ignimbrites are also intruded by quartz-feldspar and syenite porphyries which may be of the same generation as the Malone Creek Granite, and by dolerite pods and dykes.

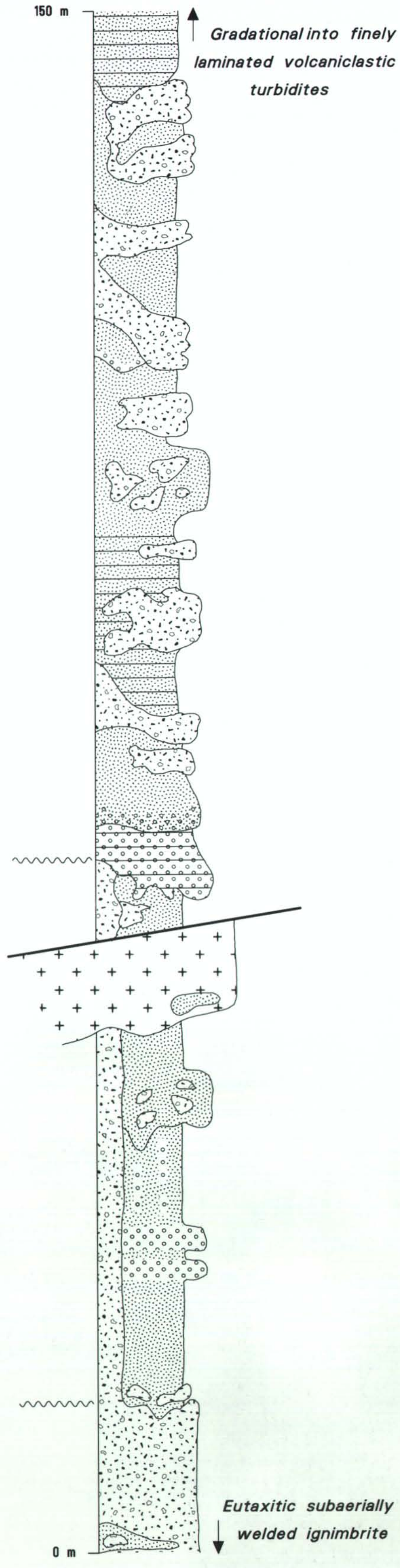
Lithology

The Pul Pul Rhyolite (Fig. 4) is dominated by quartz-feldspar rhyolitic ignimbrites. The ignimbrite succession, ca 500 m thick, is massive and undifferentiated, apart from several distinct facies described below. The undifferentiated ignimbrites are variably welded, as defined by a clear eutaxitic texture of flattened pumice clasts. Variation in the degree of welding is defined by variable degrees of pumice attenuation, and by development of columnar jointing. Of the lithic components, dolerite is the most common; others include quartz-feldspar porphyry, vein quartz, quartz sandstone (?Coronation Sandstone), and basement-derived metapelite/metapsammite. The ignimbrites contain discontinuous zones of lithic-clast concentration (representing the bases of separate pyroclastic flows), and pumice concentration. The composition and size of lithic clasts are variable throughout the succession.

In general the lithic horizons in the ignimbrite pile contain low to moderate concentrations of lithic clasts (up to 20%). They are consistent with basal lithic concentration zones of layer 2b of ignimbrite depositional facies models (Cas & Wright, 1988: Volcanic successions, modern and ancient, *Allen & Unwin)*. However, one lithic layer ca 20 m thick is clast-supported, having clasts up to 2 m in maximum dimension. It is either a ground layer (the deposit of a highly fluidised head of a high-velocity pyroclastic flow), which could form any distance from a vent, or a lag fall breccia — the result of collapse of an eruption column — which forms no more than 3-4 km from a vent.

One unit ca 200 m thick provides a marker horizon in the middle of the succession. It is columnar-jointed, indicating that it extruded as a single eruption, and has markedly attenuated small pink fiamme and compaction layering. Its crystal and clast content (5-10%) is much lower than that of the underlying and overlying ignimbrites (20-30%), and lithic clasts are confined to small dolerite fragments (1-2 cm). Microscopic textures representative of explosive volcanism, such as shards and wispy attenuated pumice fragments, are preserved. The unit is generally underlain by a basal lithic concentration zone of layer 2b which passes gradationally into the main columnar-jointed body. In one place, it is underlain by a flow-folded rhyolite of the same composition which may be a coherent lava flow, but the flow-folding may have formed during rheomorphism (secondary mass-flowage of the ignimbrite during welding).

The only coherent unit in the volcanic succession is a glassy flow-banded rhyolite lava which overlies the ignimbrites in the southeast. A thick ridge of the rhyolite lava is massive, has a spherulitic texture, and contains no phenocrysts, indicating that it extruded above liquidus temperature — a very rare occurrence.



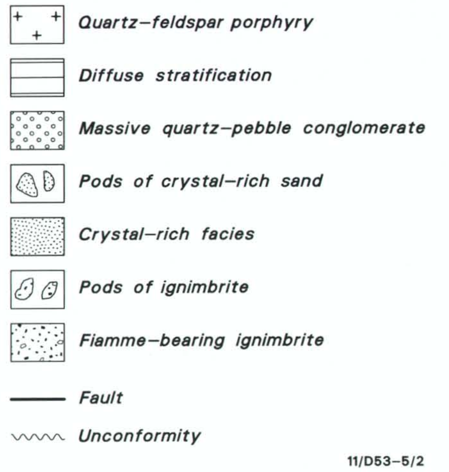


Fig. 5. Schematic section through the top of the Pul Pul Rhyolite succession, South Alligator River (GR468887-892, Stow 1:100 000 Sheet area).

The top 200 m of the ignimbrites hosts conglomerate and volcanic sandstone lenses (Fig. 5) which probably represent fluvial channels formed during the intervals between emplacement of ignimbrite flow units. They contain vein quartz, dolerite clasts, angular volcanic quartz and feldspar, metamorphic quartz, chert, and other lithic fragments, indicating a mixed basement and contemporaneous pyroclastic source. The channels have many features of fluviatile sedimentation, such as fining-upward sequences, diffuse planar bedding, and cross-stratification.

A crystal-lithic-rich volcanic sandstone 30-100 m thick forms a laterally extensive unit at the top of the Pul Pul Rhyolite. Apart from rare diffuse stratification, it is massive.

Origin of the crystal-rich facies

The crystal-rich facies at the top of the formation formed as a single mass-flow unit, similar in nature to a turbidite, but is far too thick to be of this origin. It is dimensionally comparable to subaerial ignimbrites, but is anomalous in being so crystal-rich and ash-matrix poor. Whereas subaerial ignimbrites are matrix-supported and have up to 35% crystals (unless ash winnowing has occurred), this facies has 80% crystals. Such thick, massive crystal-rich units are known only from subaqueous successions of juvenile volcaniclastics. The crystal-rich facies, located at the transition of subaerial ignimbrites and subaqueous lake sediments (overlying Big Sunday Formation), probably represents pyroclastic flows entering water, triggering phreatic explosions and ash-winnowing; more ash would have been washed out of the body as it became a water-supported mass-flow.

This model of pyroclastic flows entering water, disintegrating, and transforming into water-supported mass flows is best illustrated in a superb stretch of exposure across strike in the South Alligator River (GR 468887-892, Stow Region 1:100 000 Geological Sheet; Fig. 4) where the facies is somewhat thicker, suggesting a possible palaeovalley.Here the crystal-rich facies at two levels contains very irregular 'wispy' clasts of ignimbrite, and very diffusely bounded pods of ignimbrite occur randomly throughout it. The pods represent patches of ignimbrite which remained intact during phreatic eruption. Conglomerate and volcanic sandstone of similar composition to those in the nearby fluvial channels are mixed in with the slurry of ignimbrite and crystal-rich sandstone, and probably represent shoreline detritus caught up in the mass-flow.

Point counting will be carried out on the ignimbrites and the crystal-rich facies to test this model by determining whether the sandstone could be derived directly from the ignimbrite pile by ash winnowing. If this interpretation is correct, this exposure is most unusual; the only other known location where such features may be preserved is the Ordovician of the Welsh Basin, United Kingdom (Dr Ray Cas, Monash University, personal communication, 1990).

For further information, contact Ms Liz Jagodzinski (Minerals & Land Use Program) at BMR.

The felsic metamorphic/igneous core complexes hosting the Giles Complex

The Giles Complex, part of the western Musgrave Block in central Australia, is one of the world's largest basic-ultrabasic layered igneous complexes. It comprises numerous layered mafic intrusions, which were emplaced in the late Mesoproterozoic during granulite metamorphism at a depth of about 20 km in the Earth's crust. The rocks hosting the Giles Complex are felsic granulites of sedimentary and possibly felsic volcanic parentage, and are accompanied by migmatites and granitoids. An understanding of the relationships between the layered intrusions and the felsic granulite-migmatite-granitoid associations is essential in unravelling the history of the Giles Complex. In this article we report preliminary results of geological mapping of felsic granulite units in the Tomkinson Ranges in the west of the Musgrave Block (Fig. 6).

Geology

Felsic igneous/metamorphic core complexes consisting of granulite and partly migmatised granulite occur immediately north of Mount West, around Mount Aloysius, and at the western end of the Champs de Mars (Fig. 6). The Champs de Mars area (Fig. 7) is the best example of the core complexes, and is located between two large blocks of layered basic-ultrabasic rocks of the Giles Complex — the Hinckley Gabbro to the north and the Michael Hills Gabbro to the south. Steep, south-dipping thrust-faults cut the rocks in this area, and postdate all events except the unmetamorphosed dolerite dykes (Pharaoh, 1990: *BMR Record* 1990/5, p. 21) and pseudotachylite vein networks (Glikson & Mernagh, 1990: *BMR Journal of Australian Geology & Geophysics*, 11, 509-519).

Descriptions of rock units

The **felsic granulites** are thinly layered and composed generally of quartz, feldspar, pyroxene, and magnetite; garnet is abundant in some,

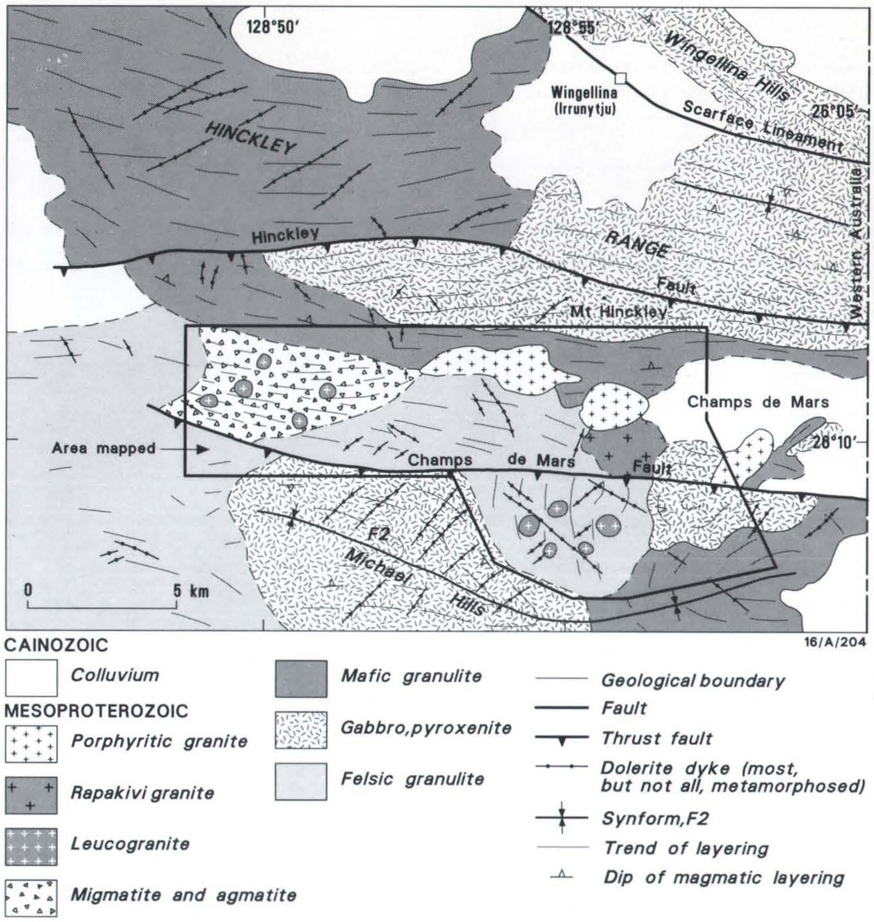


Fig. 7. Geological sketch map of the Champs de Mars area. Distribution of leucogranite is diagrammatic only.

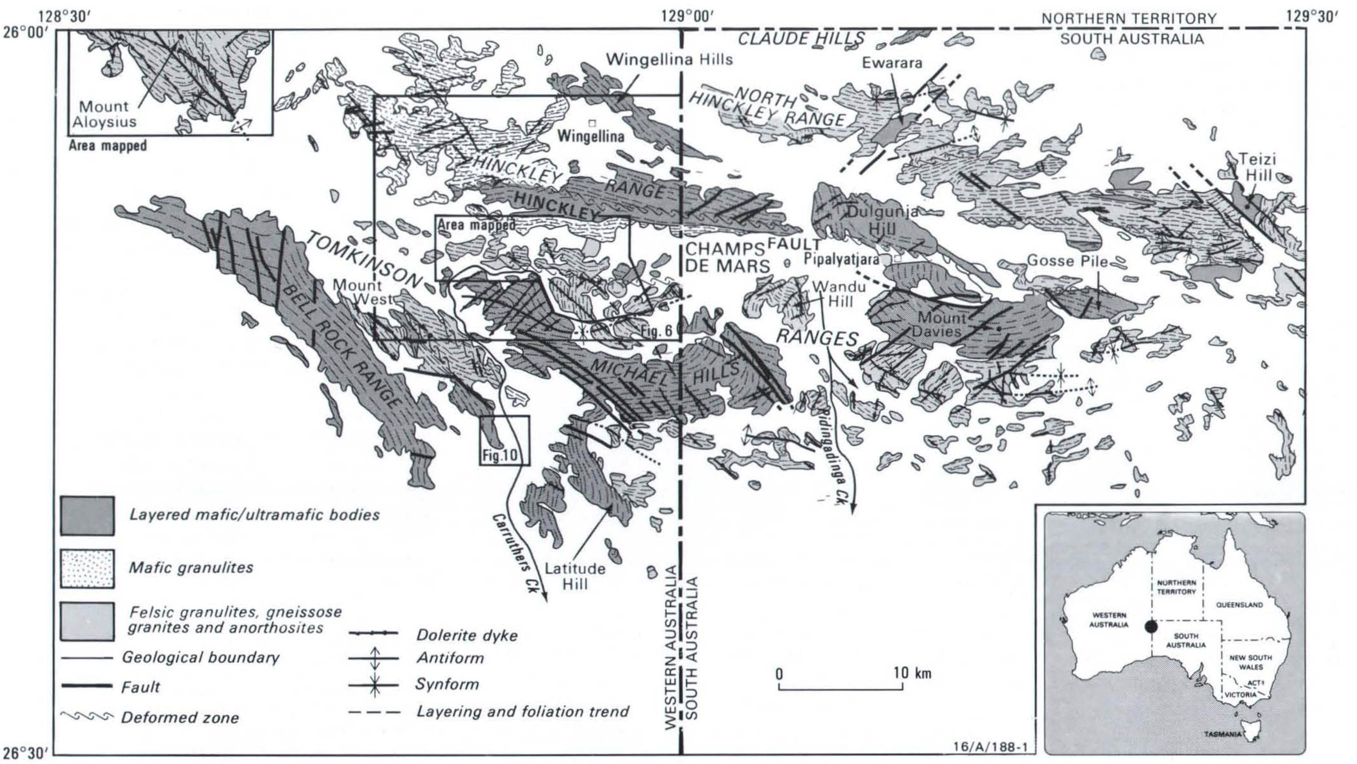


Fig. 6. Giles Complex and environs, Tomkinson Ranges, central Australia.

and magnetite-quartz granulite (metamorphosed banded iron formation) grading to quartzite is common. Layering is almost everywhere discontinuous and of metamorphic and/or transpositional origin, but bedding is preserved in places (e.g., Fig. 8). Hence, the granulites represent metamorphosed shallow-water arkose, feldspathic sandstone, pelite, and banded iron formation, or alternatively metamorphosed felsic volcanics with minor psammitic and pelitic interbeds (Gray, 1978: *Journal of the Geological Society of Australia,* 25, 403-414).

Westward, the felsic granulite grades to **migmatite;** compositional differences between layers become more pronounced; layers are less regular in shape and commonly bifurcate; and light quartz-feldspar layers coarsen and are bordered by dark mafic selvedges. Hence, the layers in the migmatite result from metamorphic differentiation superimposed on metasedimentary or metavolcanic layers. The migmatite layers in many places break up and form **agmatite**, comprising light quartz-feldspar cutting and fragmenting the dark layers (Fig. 9). This grades into **streaky granitoid** laden with dark xenolithic remnants and thin schlieren.

Small irregular elongate bodies of **mafic granulite** within the felsic granulites may be offshoots from the layered mafic intrusions (*BMR Research Newsletter* 10, 4-6; 12, 18-20); the mafic rocks are recrystallised and contain abundant phlogopite and rare pyrite. The main intrusions of the Giles Complex are in places extensively metamorphosed to mafic granulite at their margins, and in the Hinckley Gabbro throughout much of the mass itself.

Fig. 8. Cross-bedding in granulite-facies quartzite, Mount Aloysius area. Scale 15 cm long.

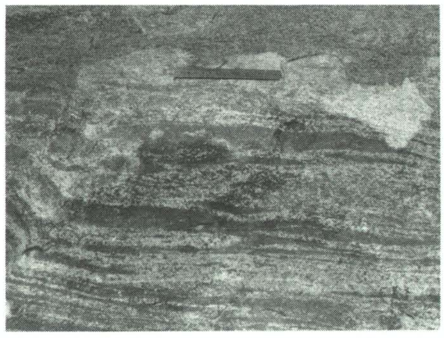


Fig. 9. Migmatite transitional to agmatite, Champs de Mars area. Scale 15 cm long.

Other granitoid varieties are present:

- Weakly foliated **leucogranite** blebs, ranging in extent from a few metres to a few hundred metres, are located in and contain rare xenoliths of felsic granulite.
- **Rapakivi granite** forms an extensive body in the south of the area, and contains the mantled feldspars typical of this rock. Xenoliths in the granite also contain mantled feldspar porphyroblasts, which suggests growth of the mantled feldspars in the solid state.
- **Porphyritic granite,** with feldspar phenocrysts exhibiting a marked platy parallelism, is the most abundant granitoid, and in several places is transitional from felsic granulite through a zone of feldspar-blastic granulite to true granite. Granite dykes intrude mafic granulite along the southern margin of the Hinckley Gabbro.

Dolerite dykes intrude all the above rocks, mostly as two intersecting sets, one striking northwest, the other northeast; cross-cutting relationships show that the northwest set is the older. Some bear pyrite, and most are recrystallised to phlogopite-bearing mafic granulite. The dykes are little deformed for the most part, but are commonly broken and boudinaged, and in a few places are tightly to isoclinally folded. Some are apparently unmetamorphosed, and emit hydrogen sulphide when broken.

Deformation

The earliest structures observed are centimetre to metre-size tight to isoclinal folds in felsic granulite — the F1 folds of Nesbitt & others

(Continued on page 15)

Environmental mapping in BMR

Cainozoic deposits, landforms, and vegetation in the Tomkinson Ranges

BMR's dual emphasis on National Geoscience Mapping Accord (NGMA) projects and on environmentally oriented studies has been combined within the framework of the western Musgrave project. Thematic Mapper (TM) and Geoscan imagery, 1:20 000 colour aerial photographs, and detailed ground observations of Cainozoic deposits, landforms, and vegetation patterns are being applied in order to define a range of environmental associations in the Tomkinson Ranges, which straddle the border between South Australia and Western Australia.

TheTomkinson Ranges (Fig. 6) constitute a series of ridges and inselbergs which occupy an east-west belt about 120 km long and 40 km wide in the Great Victoria Desert. The pristine nature of the region, where indigenous flora and fauna are preserved owing to a lack of pasture and grazing, has been highlighted by earlier regional mapping surveys (Daniels, 1974: *Geological Survey of Western Australia, Bulletin* 123). This is despite the arid nature of the terrain, where annual rainfall is as low as 200 mm and springs are scarce. The survey has the following objectives: (1) systematic classification, mapping, and documentation of landforms, vegetation, and fireburn patterns; (2) investigation of the relationships between Cainozoic deposits, landforms, and vegetation; and (3) tests of the applicability of remote-sensing techniques for correlations between band reflections and ground-truth for soil-vegetation-fireburn patterns.

The results of field mapping, assisted by remotely sensed data and photo-interpretation, will be presented on a 1:100 000 environment map (with 1:50 000 insets) showing features similar to those illustrated in Figure 10.

Topography

About 40 per cent of the Tomkinson Ranges comprises elevated ridges such as the Hinckley Range (up to 1014 m ASL). The elevation of the surrounding plains diminishes through a series of terrace steps about 50 m high from about 700 m in the northeast to 550 m in the southwest. Plains include minor dune fields averaging about 10 m high — for example, between Mount Aloysius and Bell Rock Range, and in the area between Claude Hills and Teizi Hill (Fig. 6). Drainage patterns emanating from the ridge-valley areas loose their identity in the plains. The longest stream beds, Carruthers Creek and Pidingadinga Creek, drain southwards for over 25 km before terminating in flood plains. Streams draining northwards from the ridges are far shorter, forming only small alluvial fans 1 to 2 km from the ridges.

Classification of landforms and Cainozoic deposits

Landforms and Cainozoic deposits in the Tomkinson Ranges are classified as follows:

playa plain (PLY)	colluvial fan and
flood plain (FLO)	screen (COL)
alluvial plain (ALP)	ferricrete (FC)
alluvial fan (ALF)	calcrete (CC)
ancient channel (ACH)	silcrete (SC)
sandplain (SAN)	duricrust (DU)
dunes (DUN)	rockpile (RP)
pediment(PED)	bedrock (B)

Plains are characterised by playas (in the form of claypans) up to several hundred metres wide. The playas generally abut the southern sides of outcrops, or develop along the courses of minor streams. Alluvial fans, alluvial plains, and flood plains occur mostly south of the Hinckley Range -Mount Davies belt, a feature related to the general southerly slope of the valleys and plains.

Two ancient channels occur in the Tomkinson Ranges: the major one is the prior western channel of Carruthers Creek (Fig. 10); the other issues from the southeastern Michael Hills. Silting of both has caused floodwaters to spread southeastwards into adjacent depressions in the plains, where new south-flowing channels were formed.

Sandplains and dunes dominate the plains on the north side of the Tomkinson Range, and penetrate into the area between Mount Aloysius, Hinckley Range, and Bell Rock Range, The dominant southeasterly dune trends of the Great Victoria Desert are deflected around the Tomkinson Ranges, with the result that northern dunes show little alignment, and intermontane dunes generally conform to bounding ridge orientations. Ring and rounded dunes are commonly associated with rocky outcrops. Isolated outcrops may be surrounded by extensive pediments, indicating advanced water and wind erosion. Dissected ridges are flanked by scree and colluvial fans, which are especially common around granite outcrops.

Duricrusts are widespread. Ferricrete associated with calcrete occurs mainly north of the Hinckley Range-Dulgunja Hill belt, and is the host to lateritic nickel. Large areas of calcrete occur east of Michael Hills. They are up to several metres thick in creek terrace sections, which include thin silcrete interbands. Silcrete may be also associated with ferricrete, and has contributed to the formation of chrysoprase deposits

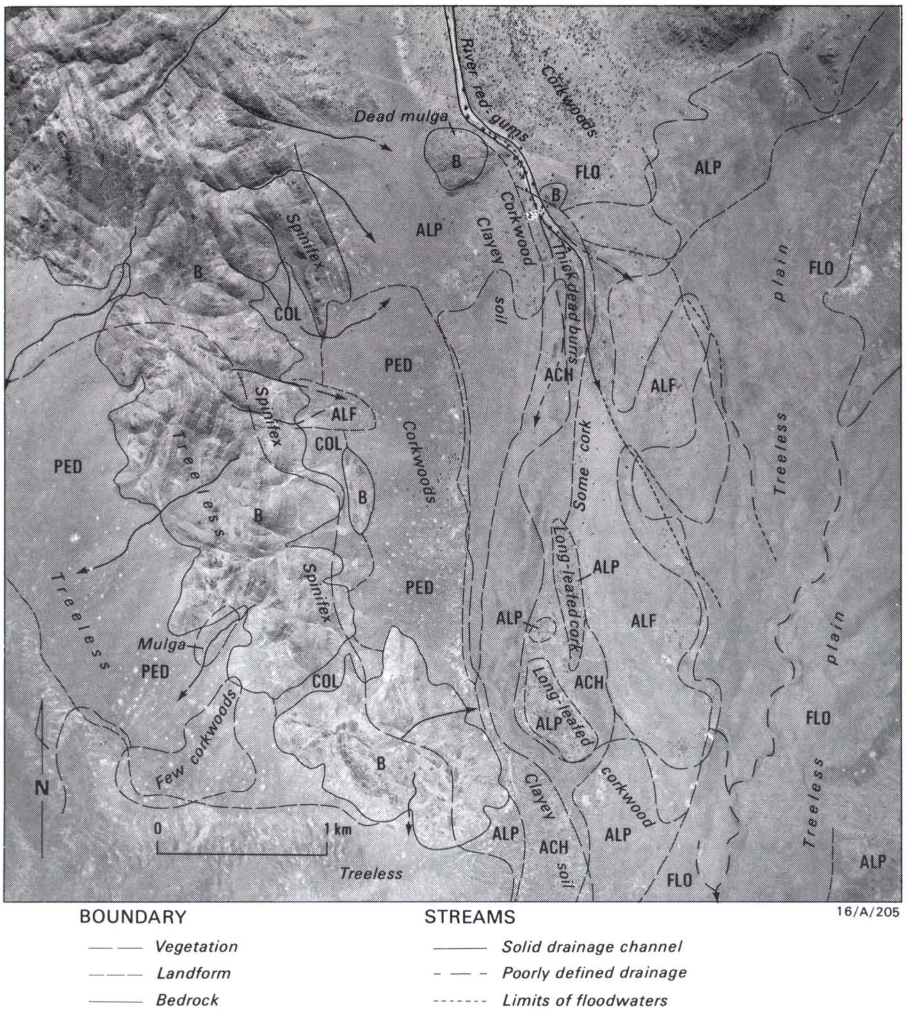


Fig. 10. Airphoto of part of the Tomkinson Ranges (photographically reduced run 32/052 of 9/5/87; for location, see Fig. 6) with an overlay outlining the types of features that will be illustrated on a 1:100 000 environmental map. It shows part of the ancient channel (ACH) of Carruthers Creek and the limits of more recent sheet-flooding southeast of it. Letter symbols are decoded in a list in the text.

above lateritised ultramafic rocks around Wingellina, Pipalyatjara, and other localities.

Vegetation patterns

Plants belonging to 130 genera and species grow in the Tomkinson Ranges. Some have associations with specific rock and soil types. Thus, *Acacia aneura* (mulga) grows on most alluvial plains, but particularly on red soils, and on rocky hill slopes and in places on calcrete. The genus *Hakea* (corkwood) mingles with open mulga, but generally prefers slightly higher ground, such as pediments and alluvial fans. *Eucalyptus camaldulensis* (river red gum) is rooted in or lines major stream beds, while *E. terminalis* (bloodwood) lines lesser stream beds or mingles with corkwoods on alluvial fans or pediments. *E. oleosa* (giant mallee) commonly provides dense cover on well exposed calcrete.

Two species of *Melaleuca* (tea-tree) are of particular environmental importance; they grow within creek beds between headwaters and places where the creeks debouch on to plains. Three species of *Triodia* (spinifex) are of the greatest ecological importance; they generally occupy specific environments, including interdunal valleys, basic and ultrabasic bedrock outcrops, and calcrete.

With few exceptions, spinifex does not grow on granitic outcrops. Species of *Thryptomene* (desert heath), *Cassia*, *Eremophila* (desert fuchsia), and *Grevillea* usually occur on sand dunes.

Of the above species mulga and spinifex are by far the most widespread, occurring over roughly two-thirds of the terrain. Much of the remaining area consists largely of treeless plains with grass cover.

Remotely sensed data and photo-interpretation

Correlations between Thematic Mapper and Geoscan imagery, and ground observations of surface deposits and vegetation, were carried out on 20 selected 1:20 000 airphotos. The remotely sensed imagery allows effective discrimination of (1) areas of calcrete; (2) stream beds characterised by an abundance of heavy minerals (i.e., magnetite); (3) ferricrete-rich terrains; and (4) vegetational variations between shrub, mulga, and spinifex-dominated domains. Fireburn and regrowth areas show clearly.

The study included observations of some of the outstanding problems of bush degradation caused by feral animals, human intervention and bushfires. Rabbits entered the area over 100 years ago and have populated calcareous outcrops and soils in plague proportions, resulting in degradation and disappearance of mulga in many areas. Herds of camels have roamed over the area since the beginning of the century, stripping branches off corkwood, mulga, and grevillea. Fires, both accidental and induced, have swept the region repeatedly.

The mapping and documentation of landforms, Cainozoic deposits, and vegetation, and a forthcoming hydrogeological study, will provide a basis for coping with these problems and for assessing natural and water resources in the Tomkinson Ranges and other parts of the Musgrave Block.

For further information contact Mr Erwin Feeken, on telephone (06) 2303565, or Drs Andrew Glikson or Alastair Stewart (Minerals & Land Use Program) at BMR.

Book review

Igneous petrology

A classification of igneous rocks and glossary of terms, edited by R.W.LeMaitre; 1989; Blackwell Scientific Publications, Melbourne; xi, 193 pp, 18 figs., 13 tables, 3 append., 1 chart; ISBN 0 632 02593 X ; $A62.

This book contains the recommendations of the International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Igneous Rocks, which are based on 20 years of discussions among no less than 417 participating igneous petrologists worldwide (including several from BMR).

In the first, and major, section of the book, classification schemes for essentially all igneous rocks are proposed. Although most of these have already been published elsewhere, they are now brought together and complemented by an extensive glossary, bibliography, and wall chart. Separate classifications are presented for pyroclastic rocks and tephra, carbonatites, lamprophyric rocks, melilitic rocks, charnockitic rocks, plutonic rocks, and volcanic rocks. Each classification is based on at least one diagram or table, which is also included on the wall chart. Modal classifications are used wherever possible, but clast size and composition are used for pyroclastic rocks. The basic classification of plutonic rocks is based on the QAPF (quartz-alkali feldspar-plagioclase-feldspathoid) diagram, and additional schemes are given for gabbroic and ultramafic rocks. Volcanic rocks for which a mineral mode can be determined are similarly classified using the QAPF diagram, whereas fine-grained or glassy volcanics for which only chemical analyses are available use a TAS ($Na_2O + K_2O$ versus SiO_2) diagram. If neither is available, a 'field' classification is proposed. There are further subdivisions into low-K, medium-K, and high-K volcanics and comenditic and pantelleritic rocks, and there is a separate chemical classification of 'high-Mg' volcanics (picrite, komatiite, meimechite, and boninite).

The second section of the book consists of a comprehensive glossary of 1586 petrographic terms, including those recommended by the Subcommission, as well as a large number considered to be redundant. It forms an invaluable guide to the plethora of obscure local or trivial names which have been used over the years, and which are still encountered in the literature. The final section is an extensive bibliography of 787 references.

The IUGS scheme represents a praiseworthy attempt to produce a comprehensive classification of igneous rocks which can be used by all petrologists. Most petrologists will have their own ideas on igneous nomenclature and will not necessarily agree with all the recommendations. For example, the classification of lamprophyres is not entirely satisfactory in this reviewer's opinion, because virtually all mafic dyke rocks other than dolerites (= microgabbros) would be covered by this term, which includes any such rock with significant biotite and/or amphibole (not necessarily as phenocrysts). Perhaps a chemical classification, like that proposed for the volcanic analogues, would have been preferable.

Of course, no classification scheme will please everyone, and this is as close to a consensus as is ever likely to be achieved. As such it deserves to be widely used. Even if the IUGS classification is considered to be inappropriate or in need of modification for particular rocks, it should at least be referred to in publications so that other petrologists can better identify the rocks being described. The book should be on the bookshelf of every igneous petrologist.

Reviewed by Dr John Sheraton (Minerals & Land Use Program), BMR

National Geoscience Mapping Accord

Preliminary results of the Kimberley-Arunta project

The objectives of the recently initiated Kimberley-Arunta project are: to determine, through systematic mapping, the nature, timing, and distribution of significant geological events in and between the east Kimberley, The Granites-Tanami, and west Arunta areas of the North Australian Craton; to determine the extent of prospective basement beneath superficial cover; to describe styles of mineralisation that can be used as predictive exploration models; and to provide mineral resource assessment information necessary for land-use decisions.

During the 1990 field season, BMR geologists carried out detailed mapping in GORDON DOWNS* (D.H. Blake, R.G. Warren), east Kimberley region; and in MOUNT DOREEN (D.H. Blake) and HERMANNSBURG (R.D. Shaw, R.G. Warren, M. Owen) Arunta Block. The aims were:

- GORDON DOWNS — commence detailed mapping of the Halls Creek 1:100 000 Sheet area in collaboration with geologists of the Geological Survey of Western Australia (GSWA) T.J. Griffin and I.M. Tyler, who — continuing eastwards from a major mapping project in the west Kimberley — concentrated their efforts in adjoining MOUNT RAMSAY (Angelo and Dockrell 1:100 000 Sheet areas), to the west:
- MOUNT DOREEN — map in detail, with geologists of the Northern Territory Geological Survey (NTGS) C. Edgoose and D.N. Young, the basement rocks north of the Ngalia Basin (Vaughan, Doreen, and Yuendumu 1:100 000 Sheet areas); and
- HERMANNSBURG — review and revise recent detailed geological mapping by BMR and university researchers in order to produce a second-edition 1:250 000 geological map.

1. Halls Creek area, east Kimberley

Summary of 1990 fieldwork

Colour airphotos at 1:25 000 scale taken in July 1990 by the Department of Lands Administration (WA) supported the fieldwork.

The previously mapped 'Sophie Downs Granite' (Fig. 11) appears from our mapping to be unrelated to the very extensive batholithic Bow River Granite. It was previously regarded as equivalent to the Bow River Granite and intrusive into the Halls Creek Group (Ding Dong Downs Volcanics, Saunders Creek Formation, Biscay Formation, and Olympio Formation). However, contacts between the Halls Creek Group and 'Sophie Downs Granite' are either sheared or unconformable; no intrusive relationship between the two is apparent. The unconformable relationship is well documented in the north of the Sophie Downs Dome, where sandstone of the Saunders Creek Formation — containing quartz pebbles and granophyre cobbles — overlies the 'Sophie Downs Granite'. The 'Sophie Downs Granite' is generally a foliated recrystallised microgranite, in contrast to the mostly non-foliated and much coarser Bow River Granite, and is possibly subvolcanic. It is commonly granophyric in the Sophie Downs Dome, but is coarser-grained in some outcrops in the McClintock Range. Felsic volcanic rocks have been identified in areas previously mapped as 'Sophie Downs Granite' in the Sophie Downs Dome; these may be equivalent to the Ding Dong Downs Volcanics.

Much of the outcrop of Woodward Dolerite shown on existing maps is either exaggerated, or comprises basaltic lava flows and associated pyroclastic rocks which commonly have a carbonate-rich matrix. These rocks are typical of the Biscay Formation.

Intensely sheared to mylonitic rocks are characteristic of the contact between the 'Sophie Downs Granite' and Ding Dong Downs Volcanics north of Bulara well, and between the 'granite' and Saunders Creek Formation northwest of Esaw Bore, in the south of the Dockrell 1:100 000 Sheet area (Fig. 11). Three phases of deformation have been recognised here. D1 is characterised by a layer-parallel foliation, as well as the development of mylonites. D2 consists of tight to isoclinal upright folds with subhorizontal axes; an S2 axial-plane crenulation cleavage is well developed. D1 and D2 predate intrusion of the Bow River Granite, and may be related to a thrust event which shear criteria in the mylonite indicate was directed to the south. Sinistral movement on the Halls Creek, Angelo, and Woodward Faults (D3) postdates intrusion of the Bow River Granite; D2 structures are progressively reorientated in the vicinity of the faults, and a second crenulation cleavage (S3) has developed.

The Tickalara Metamorphics northwest of the Angelo Fault include medium to high-grade cordierite-rich migmatitic rocks. This material is present as inclusions in the Bow River Granite. To the southeast of the Angelo Fault, rocks are low to medium-grade, consistent with the metamorphic pattern described by Gemuts (1971: *BMR Bulletin* 107).

The McIntosh Gabbro and Bow River Granite northwest of the Angelo Fault have a complex outcrop pattern dominated by granitoid rocks surrounding small areas of medium to coarse-grained mafic rocks. Gabbro is more prominent in the north. Some contacts are typical of granitoid magma intruded into mafic and metasedimentary country rock, but contact relationships also include net-veined complexes (Fig. 12) between felsic and mafic intrusive rocks; these complexes are considered to be indicative of liquid—liquid relationships (e.g., Blake, 1981: *BMR Journal of Australian Geology & Geophysics*, 6, 95–99).

According to David Blake, these relationships

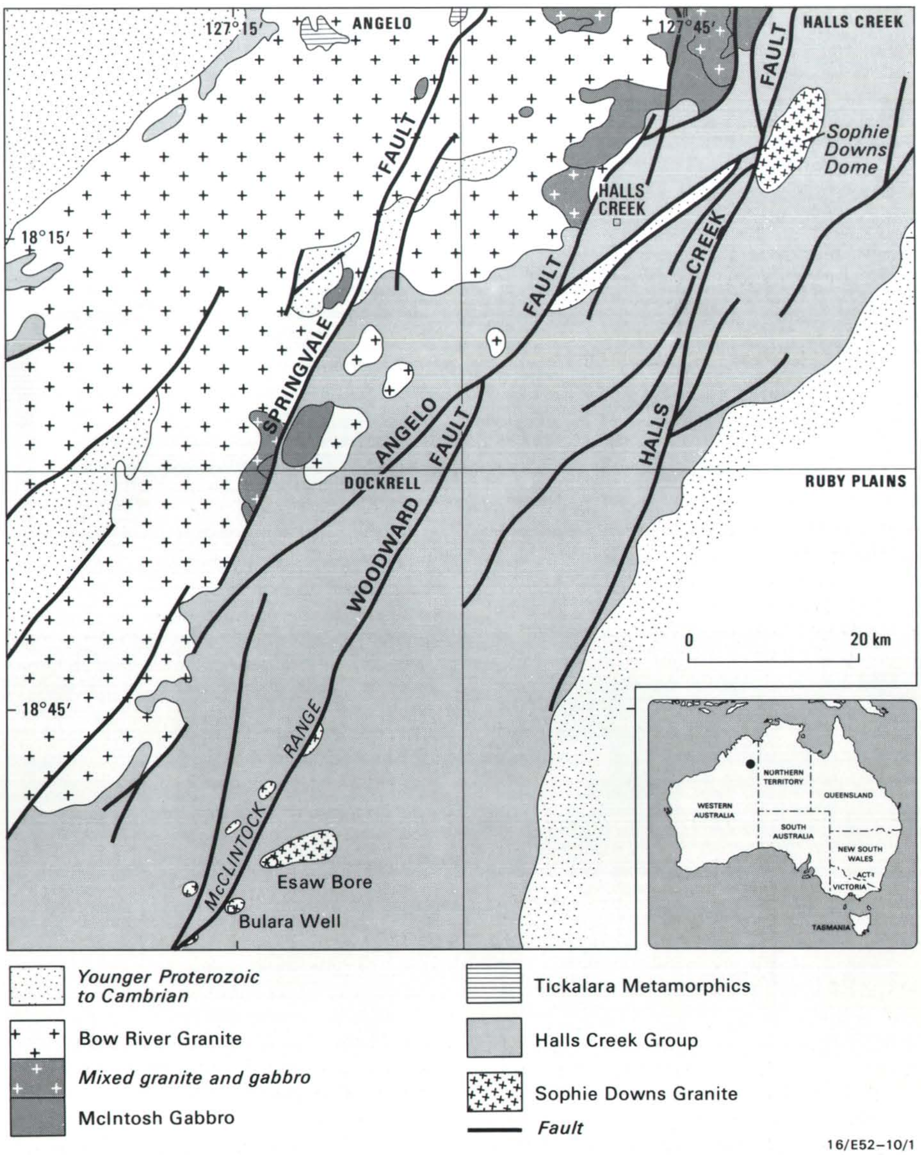


Fig. 11. Main geological units in the Angelo, Dockrell, Halls Creek, and Ruby Plains 1:100 000 Sheet areas (simplified after Dow & Gemuts, 1969: *BMR Bulletin* 106).

*Names of 1:250 000 Sheet areas are printed in capital letters in this article.

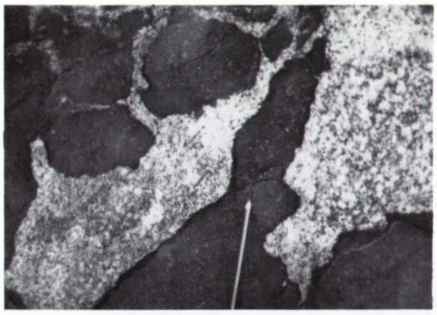
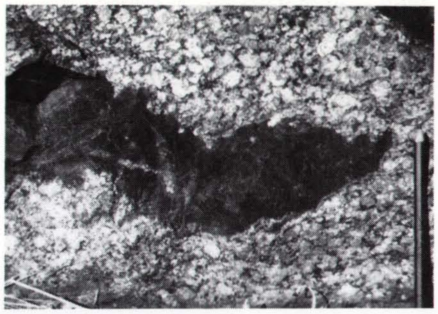



Fig. 12. Net-veined complexes of the Bow River Granite and McIntosh Gabbro in the Halls Creek 1:100 000 Sheet area. Pillow-like mafic inclusions in porphyritic granite 7 km northwest of Halls Creek (left). Mafic inclusion with cumulose/crenulate contact in porphyritic granite 14 km north-northwest of Halls Creek (right).

could imply the following sequence: the Bow River Granite was emplaced into deformed rocks of the Halls Creek Group; contact aureoles developed; gabbro intruded both units before the earlier intrusive had cooled significantly; and the large volumes of mafic magma caused partial melting of the hot granite to form the net-veined complexes, and of nearby hornfels to form the swirly migmatitic rocks characteristic of the high-grade Tickalara Metamorphics. Should this be substantiated by future mapping, much of the high-grade metamorphism represented by the Tickalara Metamorphics could be of contact type (as, for example, suggested by Gemuts & Smith, 1967: *Explanatory Notes* for GORDON DOWNS), and would therefore postdate (rather than being part of) the regional D2 deformation.

Implications for future work

The 1990 field season has highlighted some of the problems which need to be addressed during the term of this project.

- The 'Sophie Downs Granite' is either basement to the Halls Creek Group — and therefore the oldest rock in the east Kimberley — or it is simply a subvolcanic equivalent of the felsic component of the Ding Dong Downs Volcanics. Isotopic dating is proceeding; preliminary BMR age data indicate that the Ding Dong Downs Volcanics are 1900 Ma (U-Pb zircon, R.W. Page; T_{CHUR}^{Nd} model age, S.-S. Sun) and the 'Sophie Downs Granite' is no older than 2000 Ma (T_{CHUR}^{Nd} model age, S.-S. Sun).
- The Biscay Formation and the Woodward Dolerite will have to be remapped in order to establish their distribution.
- Correlating units of the Halls Creek Group across the Angelo Fault-Halls Creek Fault system has yet to be validated.
- Previous work, together with our initial fieldwork, indicates that the complex structural and metamorphic history of the Halls Creek Group needs to be carefully documented to help resolve the relative timing of deformation, metamorphism, and igneous intrusion.
- Rocks previously mapped as Tickalara Metamorphics, McIntosh Gabbro, and Bow River Granite will have to be re-examined in detail in order to determine their doubtless complex metamorphic and intrusive history.

The work to date indicates that significant revision of the Early Proterozoic stratigraphy and tectonic history in the east Kimberley might be required.

For further information, contact Dr David Blake (Minerals & Land Use Program) at BMR, or either Dr Tim Griffin or Dr Ian Tyler at the Geological Survey of Western Australia, Perth

2. Arunta Block north of the Ngalia Basin: MOUNT DOREEN

The MOUNT DOREEN mapping has indicated the following sequence of major events.

1. Deposition of the Lander Rock beds — a widespread but poorly defined, thick unit of mainly turbiditic greywacke and siltstone — and possibly Patmungula beds, which consist largely of silty sandstone. The Lander Rock beds tentatively include in the west (south of a major fault) a unit of more siliceous clastic sedimentary rock. Contemporaneous magmatism is represented by mafic lavas and intrusives in the turbiditic beds, a lens of porphyritic felsic volcanics in the western more-siliceous unit, and felsic tuff in the Patmungula beds. The Lander Rock beds in the Vaughan Sheet area are lithologically similar to, and probably contiguous with, the Tanami Complex of The Granites-Tanami region to the northwest, and hence could be correlatives of the 1880-Ma-old Halls Creek Group of the east Kimberley and Warramunga Group of the Tennant Creek Inlier; future U-Pb zircon dating of felsic volcanics should resolve these uncertainties.

2. Deformation and metamorphism. The Lander Rock and Patmungula beds were tightly folded and cleaved about upright east-west-trending axial planes, and regionally metamorphosed. If these beds are similar in age to the Halls Creek and Warramunga Groups, this tectonism may be related to the 1870-Ma-old Barramundi Orogeny of northern Australia. The metamorphism was mainly greenschist facies, but in the Lander Rock beds locally ranged up to granulite facies, with migmatite development, especially in the east. Changes from low to high-grade rocks are abrupt, and in one locality appear to coincide with a synmetamorphic intrusion of garnet-bearing granite. The granulite metamorphism does not appear to be a regional-scale deep-seated event; rather, it seems likely to have been a localised low-pressure contact effect.

3. Intrusion in the far northwest of porphyritic granophyre (perhaps before event 2), and possibly of even-grained biotite granite to the south.

4. After uplift and erosion, deposition of the Reynolds Range Group: ridge-forming quartz sandstone at the base overlain by less clean sandstone, siltstone, some carbonates, and a band of basaltic lava. This group, exposed in the far northwest, is a possible correlative of the 1830-1800-Ma-old Hatches Creek Group unconformably overlying the Warramunga Group in the Tennant Creek Inlier to the northeast.

5. Folding of the Reynolds Range Group into a major east-west-trending syncline, which is near isoclinal and upright to overturned (to the north), accompanied by low-grade (greenschist-facies) regional metamorphism.

6. Intrusion of granite — voluminous porphyritic biotite and muscovite-biotite granites in which feldspar phenocrysts commonly have dimensions of several centimetres — across folds in the Lander Rock beds and Reynolds Range Group.

7. Intrusion of mafic dykes, which might include correlatives of the 900-Ma-old Stuart Dyke Swarm exposed in the Arunta Block to the east.

8. Start of Ngalia Basin sedimentation. The first sediments to be deposited, those of the Vaughan Springs Quartzite, are correlated with the ?850-Ma-old Heavitree Quartzite of the Amadeus Basin to the south.

9. Alice Springs Orogeny, 400-300 Ma ago. Extensive faulting and shearing of the Proterozoic rocks north of the Ngalia Basin took place during this orogeny. Most of the faulting was close to east-west, subparallel to earlier structural trends. Granite emplaced during event 6 invariably shows microscopic evidence of strain and some recrystallisation effects probably caused by the orogeny. Greenschist-facies metamorphism evident in all mafic dykes might also be of this age.

For further information, contact Dr David Blake (Minerals & Land Use Program) at BMR, or Ms Christine Edgoose or Mr Dave Young at NTGS, Alice Springs.

3. HERMANNSBURG (towards a second-edition map)

Since the first edition of the Hermannsburg 1:250 000 geological map was published in 1968, important geological studies have considerably revised the level of knowledge in the Sheet area, which has been largely covered by 1:100 000 preliminary maps. Work is in hand to revise and update the compilation sheets used to produce these 1:100 000 maps, and to prepare compilation sheets for the whole 1:250 000 Sheet area, incorporating the results of additional studies.

An important outcome of recent work is an overview of the Redbank Thrust Zone (RTZ) — in association with geochronological studies — as a fundamental terrane boundary within this part of the Arunta Block (Fig. 13). Geochemical studies, now at an early stage, are helping to further constrain tectonic models.

Tectonic development interpreted from geochronological studies

Stratigraphic and deformational history either side of the RTZ in HERMANNSBURG (Fig. 13) is quite different. North of the RTZ (in the Central Province), layered meta-igneous complexes dominated by mafic granulite, but including felsic igneous rocks and minor metasediments, were deformed, metamorphosed, and intruded by syntectonic granites. U-Pb dating of these granites suggests that the main regional deformation and granulite metamorphism peaked at about 1760-1750 Ma (Table 1).

By contrast, to the south of the RTZ (in the Southern Province), metasediments overlie a granitic basement which, near Glen Helen, has yielded a U-Pb age of about 1660 Ma. This granitic basement is younger than the youngest succession of the Northern Province (Fig. 13), which is intruded by 1730-Ma granites in the Reynolds Range region (Clarke & others, 1990: *Journal of Metamorphic Petrology*, 8, 65-88). The metasediments south of the RTZ were intruded by small plutons of megacrystic granite, not yet dated, before being unconformably overlain by the Chewings Range Quartzite (Teyssier & others, 1988: *Precambrian Research*, 40/41, 157-173).

The main regional Chewings deformation south of the RTZ has been established by Rb-Sr dating at about 1600Ma (Marjoribanks & Black, 1974:

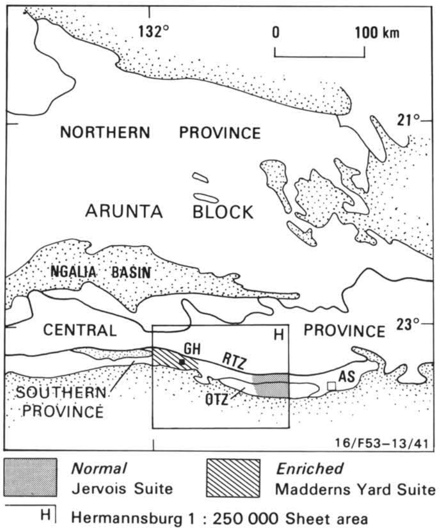


Fig. 13. The three provinces in the central Arunta Block, and the distribution of felsic suites in HERMANNSBURG. GH — Glen Helen homestead; AS — Alice Springs; RTZ — Redbank Thrust Zone; OTZ — Ormiston Thrust Zone.

Journal of the Geological Society of Australia, 21, 291-299). Mapping HERMANNSBURG in 1990 has shown that much of the regional foliation south of the Chewings Range belongs to this 1600 Ma event — not to the Devonian-Carboniferous Alice Springs Orogeny as previously thought. Evidence for northward transport during Chewings deformation, as previously proposed (Teyssier & others 1988), is limited as the dominant strain of the Chewings event is coaxial.

New Rb-Sr geochronology suggests that the RTZ initially underwent thrusting at about 1500-1400 Ma. Much later a major thermal event, centred south of the RTZ, produced widespread migmatisation and anatectic granites. Pegmatites, dated by both U-Pb and Rb-Sr methods at about 1140 Ma immediately north of the RTZ, provide the most reliable temporal estimate of this thermal event, which otherwise had only a minor effect north of the RTZ.

$^{40}Ar/^{39}Ar$ geochronological studies (by Dr R.D. Shaw in conjunction with Dr P. Zeitler of Lehigh University, Pennsylvania, and Dr I. McDougall of the Research School of Earth Sciences, Australian National University) suggest that movement on an imbricate thrust wedge, centred on the Ormiston Thrust Zone (OTZ) to the south of the RTZ, continued until as late as 300 Ma. The zone of greenschist mylonites whose present position marks the RTZ was passively upthrust, together with the Central Province (Fig. 13), by movement on this younger imbricate thrust zone. The Rb-Sr and U-Pb geochronological results have been documented by Drs Shaw and Black for publication in the *Australian Journal of Earth Sciences*.

For further information, contact Dr Russell Shaw or Dr Lance Black (Minerals & Land Use Program) at BMR.

Table 1. Tectonic events HERMANNSBURG

Central Province	*Southern Province*	*Age (Ma) (Method[1,2,3])*
Uplift	Imbricate thrusting, OTZ	300-350[3] Alice Springs Orogeny
Greenschist mylonite formation in RTZ	Greenschist mylonite formation in RTZ	350-400[2]
Pegmatite intrusion	Migmatite formation	1140[1,2,3]
High-grade mylonite formation in RTZ		1400-1500[2,3] Ormiston Event
	Regional coaxial strain, minor thrusting	1600[2] Chewings Event
	Deposition of Chewings Range Quartzite	
	unconformity	
	Granite intrusion	
	Sediment deposition	
	?unconformity	
	Granite intrusion	1660[1]
Granitoid emplacement folding, migmatisation		1760-1750[1] Strangways Event
Deformation of layering		
Accumulation of mafic + felsic igneous rocks		

Geochronological method: [1]U-Pb, [2]Rb-Sr, [3]$^{40}Ar/^{39}Ar$.

Table 2. Major suites of felsic igneous rocks in the Arunta Block

Suites	*Components units*, Distinguishing characteristics
Normal type	
Alarinjela	*Dneiper and Copia Granites, Alarinjela Complex, Ali Curung Complex, Strangways Metamorphic Complex* K/Rb 150-220, Sn 4-10, profile corresponds closely to envelope for the Alarinjela Complex
Harverson	*Harverson Granite, Aloolya Gneiss, Mount Airy, Yaningidjara, and Anmatjira Orthogneisses* K/Rb 90-180, Sn > 5, high Cr, V, & Ni, profiles may show slightly high REE, U
Napperby	*Napperby Gneiss, Boothby and Ngalurbindi Orthogneisses* Generally similar to the Harverson Suite, lower in Cr
Jervois	*Jervois and Queenie Flat Granites, Atneequa Granitic Complex, Casey Bore granite, Burt Bluff Gneiss, Jennings Granitic Gneiss, part Jessie Gap gneiss, possibly Bruna Gneiss* High K/Rb (>150-300), low Sn, high Ba at low SiO_2, slightly high REE
Kintore	*Unnamed intrusive and extrusive units in the Ehrenburg and Kintore Ranges* Differs from the Jervois Suite in lower Al_2O_3, TiO_2, & Li, otherwise very similar
Enriched type	
Jinka	*Jinka, Mount Ida, and Mount Swan Granites, Pgk*
Ennugan	*Ennugan Mountains Granite (Pgp* of Stewart & others, 1980: *BMR Record* 1980/63) High Sn
Barrow Creek	*Barrow Creek Granite* High Li, Cs
Madderns Yard	*Madderns Yard and Teapot Granites, felsic gneiss west of Papunya, possibly Stuart Bluff granite* Low Sn, high Ba
Microgranites	*small bodies of sugary or porphyritic granite near the margins of the Ngalia Basin* High Th, U, Pb, cf. Ennugan Mountains Granite
Flat-profile type	
	Atnarpa Igneous Complex, Alice Springs Granite, part Jessie Gap gneiss Low incompatibles, Sr high, Y low, mode with plag > Kf

Geochemical classification of the felsic rocks

A preliminary assessment of geochemical data for the felsic rocks in HERMANNSBURG collected before the 1990 field season showed that two distinct suites are apparent south of the RTZ. Comparison and correlation with suites already recognised elsewhere in the Arunta Block has implications for tectonic models for the evolution of the region.

A reference geochemical classification for Arunta Block felsic rocks

The BMR PETCHEM database contains about 750 published and unpublished analyses of rocks from the Arunta Block. Geochemical signatures of most of the felsic igneous rocks in the Arunta Block can be assigned to one of three classes (Fig. 14). Two have typical Proterozoic characteristics, being Sr-depleted and Y-enriched; the third has a flat profile (e.g., Alice Springs Granite, Fig. 14) with high Sr and low Y. The Sr-depleted, Y-enriched classes subdivide into a normal Proterozoic type (e.g., Alarinjela Suite); and a high-U, enriched type (e.g., Jinka Suite).

Both normal and enriched types have the general geochemical characteristics of Sr-depleted felsic magmas — in particular, a high content of incompatible elements. Broadening of the peaks at Th and U may reflect mobility of these elements during metamorphism. The reference envelope for the Jinka Suite (Fig. 14) shows the more exaggerated composite profile of the enriched type, reflecting higher U, Th, K, Rb, REE, and Y relative to the normal type. High REE and Th are reflected by allanite or monazite in the mode. The fluorine content may be high enough to give visible fluorite in hand specimen. Relative enrichment in Rb leads to lower K/Rb in the enriched types.

Distinct suites (Table 2) can be delineated within both normal and enriched classes, using XY plots (e.g., Harker diagrams, ratio plots) and ternary plots to show subtle chemical variations. The distribution of suites by area may have important time-tectonic significance, particularly if the subtle variations that distinguish the suites are the consequence of different sources. Regional variations among the enriched granites mimic those found in the normal types in the same areas, suggesting an evolutionary link between the types. The normal and enriched types are widely distributed, occurring in all three tectonic zones; the flat-profile type occurs mainly in the eastern part of the Central Province and in the Southern Province.

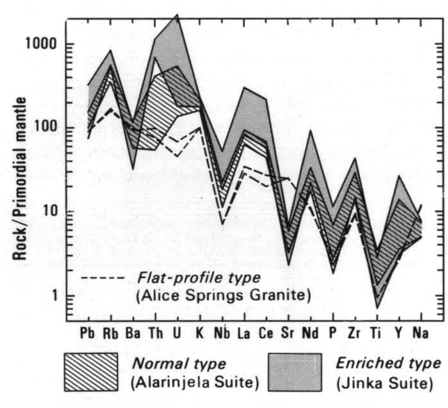


Fig. 14. Multi-element plots of normal, enriched, and flat-profile types of felsic igneous rocks. The normal and enriched types are represented by the envelopes of data for the Alarinjela and Jinka Suites respectively. The flat-profile type is illustrated by spidergrams for the Alice Springs Granite.

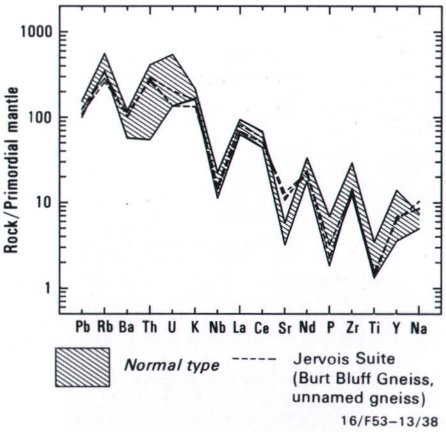


Fig. 15. Spidergrams for samples of the Jervois Suite in HERMANNSBURG relative to the reference envelope for the normal (Alarinjela Suite) type.

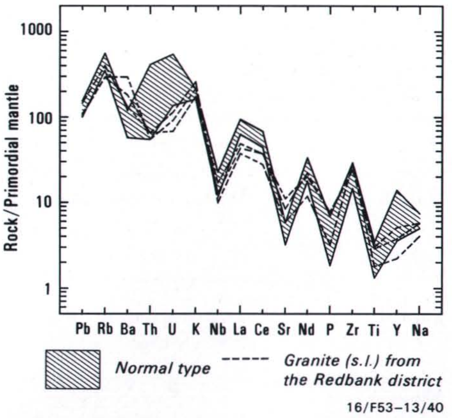


Fig. 17. Spidergrams for samples of felsic rocks from the Redbank area north of the RTZ relative to the reference envelope for the normal (Alarinjela Suite) type.

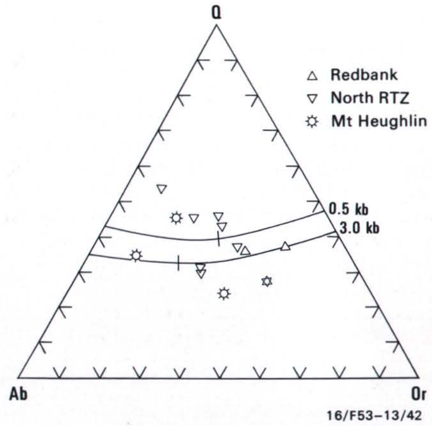


Fig. 18. Plot of normative q, or, and ab, with the 0.5 and 3-kbar curves (Tuttle & Bowen, 1958: *Geological Society of America, Memoir* 74), for felsic rocks from the Redbank area, the Mount Heughlin massif (5 km north of Glen Helen homestead), and elsewhere north of the RTZ. Some are of probable igneous parentage; the most quartz-rich, which also has high normative corundum, has been modified by sedimentary processes.

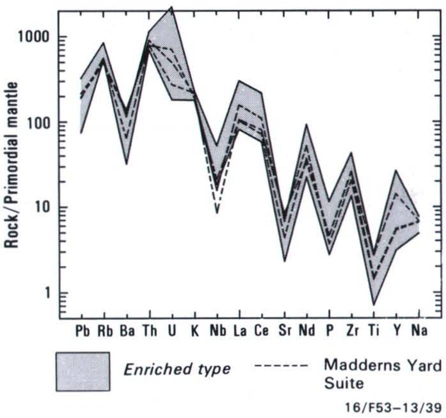


Fig. 16. Spidergrams for samples of the Madderns Yard Suite relative to the reference envelope for the enriched (Jinka Suite) type.

Felsic rocks in HERMANNSBURG

In the eastern part of the Southern Province in HERMANNSBURG, the Burt Bluff Gneiss and megacrystic orthogneiss south of the Chewings Range have chemical signatures typical of the normal type (Fig. 15). They have the relatively high Ba and Ga/Al and low Sn characteristics of the Jervois Suite, of which they are a westward continuation. Though poorly constrained by age determinations, present data suggest that the Jervois Suite was emplaced ca 1750 Ma.

A newly recognised suite of enriched felsic rocks, the Madderns Yard Suite (Fig. 16), occurs in the Southern Province in the west. It includes the Madderns Yard Granite, comprising large dykes and small bosses of fine-grained leucogranite intruding deformed and migmatised volcanics; the Teapot Granite near Mount Zeil; granitic basement dated as 1660 Ma (Table 1) east of Glen Helen homestead; and probable fine-grained metavolcanics from west of Papunya, in adjacent MOUNT LEIBIG. The suite has low Sn, and high Ba, similar to the Jervois and Kintore Suites to the east and west. High REE, Th, and U are contained in allanite; monazite is less common.

The few analyses of felsic rocks from north of the RTZ do not fit the patterns seen south of the RTZ (e.g., Fig. 17), and confirm field observations that some are plagioclase granites. Some of the felsic rocks appear to have a sedimentary component (Fig. 18). No granite of the flat-profile type has yet been recognised in HERMANNSBURG.

Economic implications

Enriched granites, such as those in the Madderns Yard Suite, are the probable source for the uranium deposits in the Late Devonian sedimentary rocks of the Ngalia and Amadeus Basins, and potential sources for uranium deposits in Tertiary and Quaternary sediments. Drainage from the Madderns Yard Suite into the Dashwood and Derwent River systems floods out in the northwest of HERMANNSBURG; abandoned drainage channels indicate that the flood-out water previously reached the salinas south of the Hann Range. If, as appears probable, the water moves into closed groundwater basins in this region, then these may be trapping uranium extracted from the Madderns Yard Suite.

For further information, contact Dr Gladys Warren (Minerals & Land Use Program) at BMR.

AWAGS — towards an 'aeromagnetic risk' map of Australia, and a basis for regional magnetic field surveys

Fifty-seven recording stations comprising the Australia-Wide Array of Geomagnetic Stations (AWAGS) were used to record natural variations of the geomagnetic field at one-minute intervals between November 1989 and July 1990. Preliminary results are giving unprecedented insight into the large-scale magnetic induction properties of the crust (reflecting its subsurface electrical conductivity structure), and the effect this has on the accuracy of base-stations used for correcting aeromagnetic surveys. AWAGS is also giving us a more detailed picture of the diurnal pattern of field variations over Australia than has hitherto been possible. Several airborne and satellite survey activities are taking advantage of this for mapping the regional magnetic field over the continent.

Aeromagnetic surveyors must contend with the temporal (diurnal) variations of the geomagnetic field, and the complications arising from the heterogeneous nature of crustal induction effects that distort the diurnal variation on a local as well as a regional scale.

AWAGS is a magnetometer array study designed to address these problems. It is the first continent-wide experiment of its kind ever undertaken. The array provides a detailed picture of how the diurnal pattern and transient disturbances vary across the continent and how they evolve with time. It can be used to look downwards to probe the large-scale electrical conductivity structure of the continent, or upwards to investigate the current systems that are responsible for external contributions to the geomagnetic field. In addition the array data provide excellent diurnal control for regional airborne and satellite magnetic surveys.

A knowledge of the induction properties of the crust can be used to identify regions subject to large (or small) variability in the diurnal field variation. Hence it is possible to construct contour maps depicting the errors inherent in using a base-station for making corrections to aeromagnetic survey data. This concept of an 'aeromagnetic risk' map of Australia is being developed through AWAGS.

Fieldwork

The AWAGS stations, which include four permanent magnetic observatories (Fig. 19), were deployed over the whole continent at an average spacing of about 275 km. Three components of the field, together with temperature and time, were recorded at one-minute intervals. In addition a north-south line of instruments was maintained from Darwin through Alice Springs to Adelaide for a full 12-month period in order to

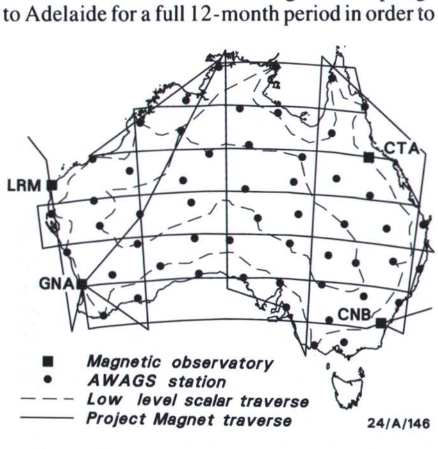


Fig. 19. Station locations for AWAGS, permanent magnetic observatories, track lines for the low-level scalar traverses, and track lines for the new high-level Project Magnet vector traverses.

achieve complete seasonal information about undisturbed diurnal (Sq) patterns of geomagnetic variation.

Design and development of the magnetometers was carried out at Flinders University. Each instrument package is completely self-contained, and comprises an orthogonal set of three Kelvin-Hughes fluxgates, control electronics, a solid-state memory card for logging the data, and a battery pack. The magnetometer is housed in a PVC cylinder, 16 cm diameter and 68 cm long, and can run unattended for four months with a one-minute sampling rate. Instruments are buried to achieve temperature stabilisation, and can be tested, reprogrammed and interrogated in the field using a portable PC.

The instruments performed very successfully; the data recovery rate exceeded 85%. Data losses were due mainly to premature battery failure and to the disappearance of two instruments.

Induction results

Induction effects can be represented conveniently by 'Parkinson' induction vectors that are computed for a particular periodicity of the field fluctuations during an interval of high disturbance. In broad terms, the induction vectors should point towards an electrical conductor. They are small either directly over the conductor, or far away from the conductor. The lengths of the vectors reflect the strength of the induction effects, which relate to both the scale and electrical conductivity of the conducting region.

So far only a cursory analysis of the AWAGS data for induction effects has been completed. It shows that major distinct zones of electromagnetic induction behaviour can be identified. Induction vectors (Fig. 20) can be grouped into three regions:

- a coastal region, in which the vectors point towards the conducting oceans (the 'coast-effect') and decrease in amplitude away from the coast:
- a central craton region, and its northwards extension, in which the induction arrows are small and randomly directed in the centre but — towards the rim of the craton — point outwards from the centre: and
- an intermediate region (shaded in Fig. 20), in which the induction arrows are either small or point towards the central craton and away from the coast.

The northern margin of the shaded area apparently represents an Australia-wide conducting path — the intercratonic conductive zone — which traverses the eastern Canning Basin, the Officer Basin south of the Musgrave Block, and the western margins of the Eromanga and Carpentaria Basins. Within the main crystalline basement areas, induction effects are moderately subdued, apart from the well defined coast-effect. Work is in progress to delineate the conductor path in more detail by incorporating the results from previous small-scale array studies.

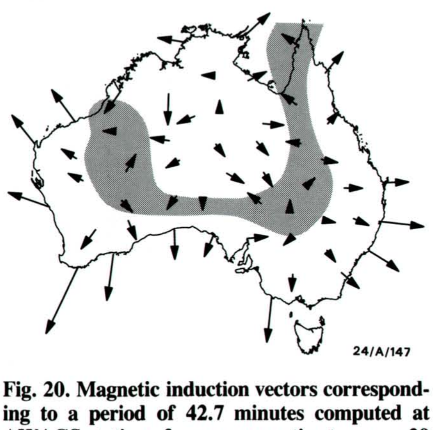


Fig. 20. Magnetic induction vectors corresponding to a period of 42.7 minutes computed at AWAGS stations from a magnetic storm on 29 December 1989. Areas where the induction vectors show large variability in size and direction are characterised by heterogeneous induction properties, and are therefore liable to large base-station errors.

'Aeromagnetic risk' maps of Australia

Because few areas in Australia are free from induction effects (cf. Fig. 20), there are few areas where the assumption of spatial homogeneity of the fluctuating field — extensively applied in aeromagnetic data reduction — holds in detail.

Anyone deploying base-stations for aeromagnetic (or marine) survey work needs to have a feel for the differences between the diurnal signal at a base-station and the corresponding signal at a remote survey point. The AWAGS study provides the first country-wide basis for generating this base-station error information, allowing the possibility of drawing a contoured 'aeromagnetic risk' map of Australia. In fact a set of maps will be required because the base-station error, as a function of distance away from the base-station, is expected to be frequency-dependent.

The induction arrows (Fig. 20) are not directly related to base-station errors, but nevertheless do provide a crude 'aeromagnetic risk' map. The figure delineates areas where large base-station errors can be expected (high variability between induction vectors), and areas where they are going to be small (short or uniform patterns of arrows).

AWAGS-related surveys

Several important developments in regional magnetic field surveying have been timed to take advantage of the opportunity afforded by AWAGS.

Firstly, two low-level traverse circuits were flown around the country in January and February 1990, recording the scalar field (i.e., total intensity) at an elevation of 150 m (Fig. 19). The data will be used for levelling individual aeromagnetic maps to assemble a magnetic anomaly map for the whole of Australia.

Secondly, as part of the US Navy's Project Magnet, a set of traverses was flown across the continent measuring the vector (3-component) field at 20 000 feet (6000 m) elevation (Fig. 19). This data set will lead to a substantial improvement in the accuracy of future regional field models (e.g., the Australian Geomagnetic Reference Field, AGRF).

Thirdly, the US Navy's magnetic-field survey satellite, POGS, was successfully launched on 11 April 1990, and is operating reliably. It is equipped with MAGSAT instrumentation, although it does not have sufficiently accurate attitude control to give good vector data. The AWAGS array will provide one of the best ground-truth data sets for the satellite. POGS data will also be used in future AGRF models.

For further information, contact Dr Charles Barton at BMR, or Dr Francois Chamalaun, School of Earth Sciences, Flinders University of South Australia.

New K—Ar constraints on the onset of subsidence in the Canning Basin

Recent K-Ar dating and structural mapping have enabled BMR and the Geological Survey of Western Australia to delineate and date the latest deformational stage in the King Leopold Orogen, to the north of the Fitzroy Trough of the Canning Basin. The dates have been determined for schists selected from both contractional shear zones, and rocks metamorphosed to the lower greenschist facies during the final deformation in the basement. They suggest that the basement-deforming event started in the Cambrian and continued until the latest Cambrian to earliest Ordovician (ca 500 Ma). This contractional deformation is slightly older than the earliest known Early Ordovician (latest Tremadoc) sedimentary rocks in the Canning Basin, and explains the lack of Cambrian rocks in the northern part of the basin.

Introduction

In 1988, BMR commenced a multidisciplinary project to review the evolution of the Canning Basin. This work is concentrated around 640 km of deep seismic data recorded in 1988, and adopts the technique of seismic stratigraphy to refine geological understanding of the basin.

In order to clarify the age of the last compressional event that affected the basement to the Fitzroy Trough, a program of age determination and structural mapping was instigated. Before the work started, the consensus view was that the last major deformation to affect the King Leopold Orogen was about 600 Ma (e.g., Bennett & Gellatly, 1970: *BMR Record* 1970/20). We consider that this date is too old because the poor precision of the isochrons and high initial ratios suggest a lack of isotopic equilibrium in the dated samples.

The Fitzroy Trough (Fig. 21) is a deep, composite set of complex half-grabens formed during two or more extensional events in the Ordovician and in the Devonian. Later deformation in the Jurassic produced open folds with east-northeast-trending axes, many of which are truncated by steep faults established during earlier Palaeozoic rifting.

Results from BMR88.03 deep seismic profile in the Fitzroy Trough (inset in Fig. 21) suggest that the Phanerozoic sedimentary section might attain a thickness of 15-17 km. As the ages of the sedimentary rocks in the deeper parts of the trough are completely unknown, it has been speculated that Cambrian rocks, which occur in all the surround ing contemporary basins, might occur there too. Outside the trough, sedimentary rocks as old as latest Tremadoc are known from Samphire Marsh 1 well in the southeast of the basin (McTavish & Legg, 1976: *in* Bassett, M.G., Ed., The Ordovician System, *Proceedings of a Palaeontological Association Symposium, Cardiff, Wales).*

Geological setting

The structural development of the exposed basement and Proterozoic successions in the King Leopold Orogen and adjacent Oscar and Pillara Inliers of the Lennard Shelf has been re-examined by Tyler & Griffin (1990: *Journal of Structural Geology,* 12, 703—714). They recognised a D$_1$ event of localised high strain and a D$_2$ folding event that predate the main phase of granite intrusion in the mid-Proterozoic. A much later D$_3$ event, here called the Yampi Event, involved folding and formation of complex north-directed shear systems. A D$_4$ event, here termed the Precipice Event, involved southwest-directed folding and thrusting in the Precipice Fold Belt, at the southern margin of the Kimberley Basin. The dominant structural feature in the Precipice Fold Belt is the Inglis Fault, which follows the contact between the 1880-1840-Ma Hooper Complex of the King Leopold Orogen and the 1840-1760-Ma Kimberley Basin succession. Within the Precipice Fold Belt, the D$_4$ axial-plane cleavage can be traced through the unconformity separating the Kimberley Basin succession from overlying Late Proterozoic glacigene rocks, which it must postdate.

Intensely foliated schist zones in the southern King Leopold Orogen and inliers to the south, regarded as high-strain zones active at the close of the D$_4$ Precipice Event, include the south-dipping,

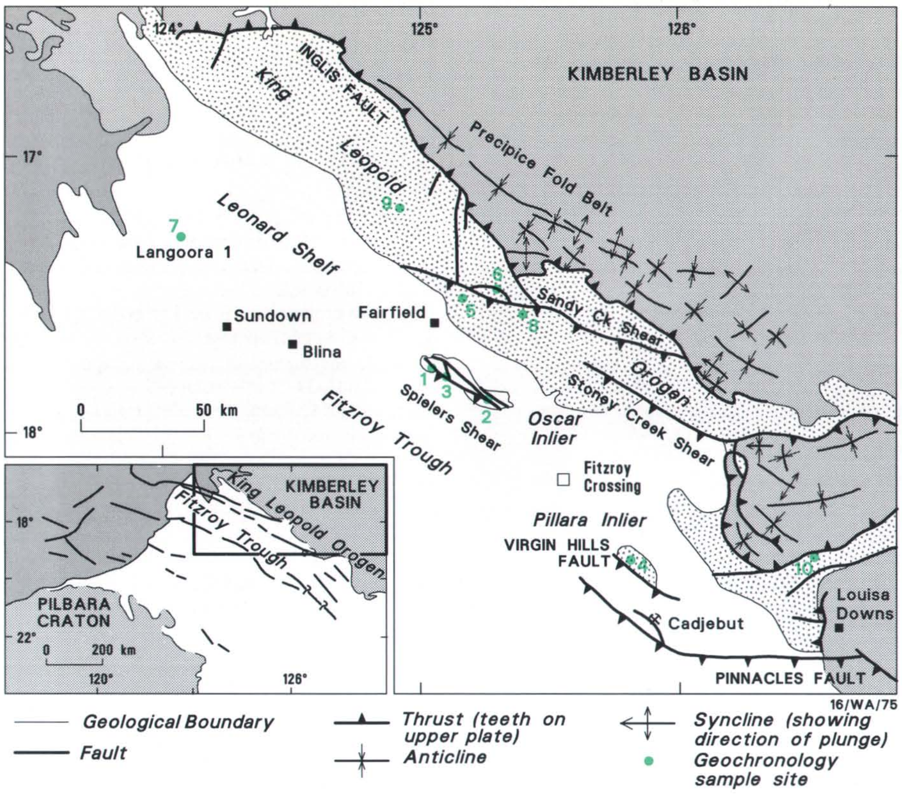


Fig. 21. Main structural features at the northern margin of the Canning Basin. BMR seismic profiles are shown as dashed lines in the inset.

mylonitic Spielers and Stoney Creek Shear Zones, and localised shears along the southern margin of the Pillar Inlier (Fig. 21). A weak fabric asymmetry in these shear zones suggests fault movements involving limited north-directed thrusting. Thus, various thrusting directions are indicated.

South of Louisa Downs homestead (Fig. 21), northeasterly faults assigned to the Precipice Event also cut the Early Cambrian Antrim Plateau Volcanics (Dunn, P.R., 1963: *BMR Explanatory Notes* SD/53—14.).

New geochronological results

K-Ar dates (Table 3) from 10 different localities (Fig. 21) in the Lennard Shelf and King Leopold Orogen have been determined. A sample selected from site 10 to monitor the time of initial plutonism yielded an age of 1725 Ma. Samples selected from sites 8 and 9 to estimate the time of metamorphism accompanying the D_3 Yampi deformation yielded ages of about 1475 and 1000 Ma respectively. The ca 700-Ma biotite K-Ar age for site 6, within a reactivated segment of the Sandy Creek Shear Zone, might represent either a period of renewed movement and local isotopic resetting of the earlier D_3 Yampi deformation in the Sandy Creek Shear Zone, or partial resetting of a D_3 Yampi isotopic signature.

Two ages, for sites 1 and 4, of 532 ± 3 and 557 ± 8 Ma are considered to provide a guide to the time of regional phyllitic cleavage formation.

In the Oscar Inlier, two muscovite samples, from widely separated exposures of phyllonitic mylonite and of deformed and tilted schist within the Spielers Shear Zone (sites 2 and 3), yielded Late Cambrian K-Ar ages of 504 ± 4 and 514 ± 4 Ma respectively. Muscovite from a north-trending schist zone showing post-crystallisation microfolding (site 5) gave an age of 506 ± 4 Ma. Similarly, deformed actinolite-biotite schist from basement core in Langoora 1 well, near the northwest margin of the Lennard Shelf (site 7), gave a slightly younger age of 473 ± 3 Ma.

Although these results are of a reconnaissance nature, the consistency of K-Ar mineral ages from widely distributed deformed zones points to a major period of fault movement in the latest Cambrian to earliest Ordovician. This deformation is similar in age to the Delamerian Orogeny in the Adelaide Geosyncline (Parker, 1986: *Ore Geology Reviews,* 1, 203-212).

Implications for timing of basin initiation

The latest Cambrian contractional deformation, evident in the basement at the northern margin of the Canning Basin, also probably extended into the Fitzroy Trough. The age of deformation in the Paterson Orogen to the south of the Canning Basin, although poorly constrained (Myers: *Geology,* 18, 537-540), could be of a similar age to the deformation that we have documented to the north of the basin. If this latest Cambrian deformation extended under the basin, it could explain why the Canning Basin apparently lacks Cambrian sedimentary rocks, because much of the basin region would have been elevated by crustal shortening in the latest Cambrian. Since the oldest trilobite faunas are of latest Tremadoc age (i.e., ca. 485 to 490 Ma, Webby & Nicoll, 1989: *BMR Record* 1989/32), subsidence and deposition in the Fitzroy Trough can be constrained to have started in the Early Ordovician, possibly between about 505 and 490 Ma.

Table 3. Potassium-argon results

Site	Sample 8909-	Lithology	Age $\pm 1\sigma$ (Ma)
1	1077A Muscovite	Schist	532 ± 3
2	1004 Muscovite	Phyllonitic mylonite	504 ± 4
3	1056 Muscovite	Deformed schist	514 ± 4
4	1012 Biotite	Adamellite	557 ± 8
5	1039B Muscovite	Schist	506 ± 4
6	1043B Biotite	Schistose gneiss	700 ± 8
7	1091 Hornblende	Schist	473 ± 3
8	1049 Biotite	Deformed tonalite	1475 ± 12
9	1026 Biotite	Deformed Granite	999 ± 9
10	1018 Biotite	Diorite	1725 ± 17

For further information, contact either Dr Russell Shaw at BMR, Canberra; Drs Tim Griffin or Ian Tyler at the Geological Survey of Western Australia, Perth; or Dr Alan Webb of AMDEL, Adelaide.

New insights to the structural evolution of the Coen Inlier

Recent (1990) mapping and associated studies by BMR and the Queensland Department of Resource Industries (QDRI) in the Proterozoic Coen Inlier (Cape York) have produced a better understanding of the complex chronology of deformation and metamorphism, which has important implications for structurally controlled gold mineralisation.

The Coen Inlier (Fig. 22), located in far north Queensland, comprises essentially Proterozoic Coen, Sefton, and Holroyd Metamorphics, and Siluro-Devonian granites of the Cape York Peninsula Batholith (CYPB; Willmott & others, 1973: *BMR Bulletin* 135). The metamorphics range from sub- to low-greenschist siltstone, sandstone, and slate to upper amphibolite sillimanite gneiss, schist, and quartzite. The Sefton Metamorphics also contain quartz-hematite schist at Iron Range.

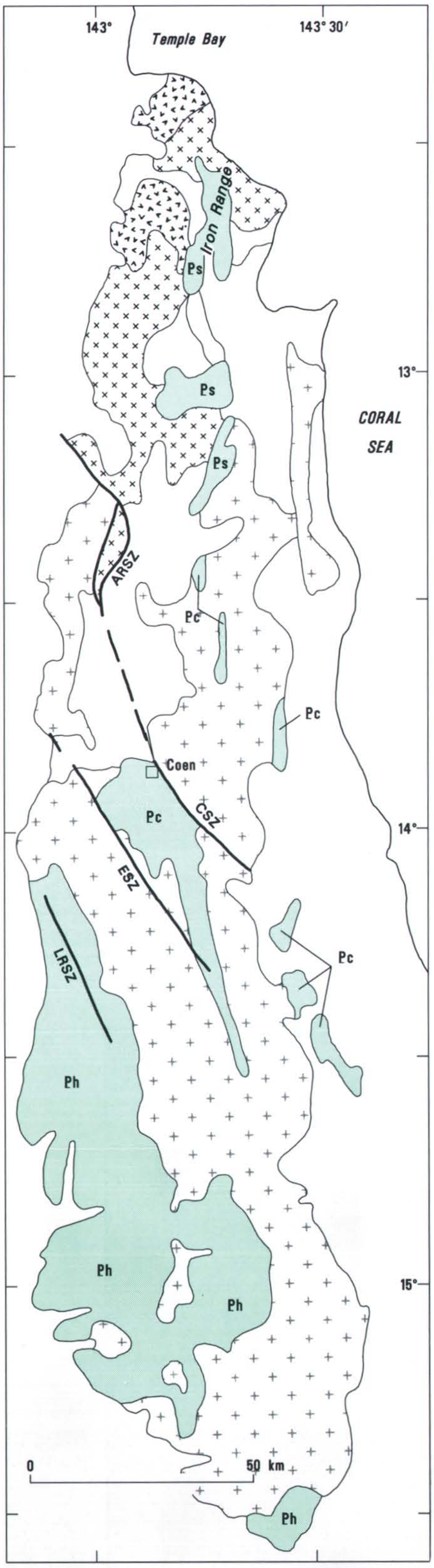
Structures

F_1 folds are commonly tight to isoclinal, gently east-plunging, upright and have an axial-planar S_1 shistosity with local associated shallow lineations (Fig. 23A). In many areas, S_1 is transposed by D_2 to a north-northwest-trending subvertical orientation.

Prograde metamorphic climax is associated with D_1, shown by common sillimanite (now pseudomorphed by retrograde muscovite) and kyanite (reported for the first time).

F_2 folds are upright, asymmetric, have variably plunging chevron-like hinge zones and a well developed steeply dipping north-northwest-to-north-trending S_2 crenulation cleavage (Fig. 23B, D). Mesoscopic folds are common, while macroscopic folds are generally confined to the Holroyd and Sefton Metamorphics. They plunge gently and have large amplitude-to-wavelength ratios. D_2 structures overprint some of the granites of the CYPB. Retrogression is associated with M_2 metamorphism.

Major ductile shear zones are common in the Coen Inlier; many of them have a spatial relationship with gold mineralisation. For example, the Coen Shear Zone (CSZ), and associated Archer River Shear Zone (ARSZ, Fig. 22) have a combined strike length of 150 km, and a number



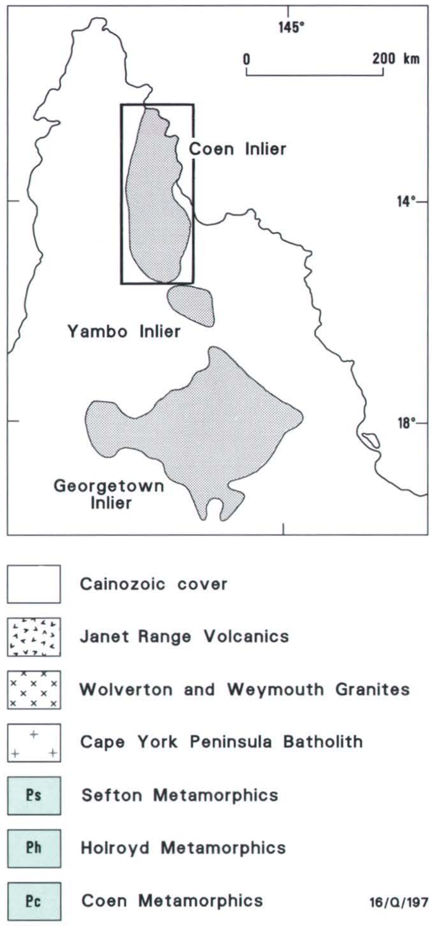


Fig. 22. Simplified geological map of the Coen Inlier showing the distribution of the main metamorphic units. Major shear zones include the Archer River (ARSZ), Coen (CSZ), Ebagoola (ESZ), and Lukin River (LRSZ) Shear Zones.

of old workings lie along or adjacent to this. The 100-km-long ESZ also hosts a number of gold workings. A well developed restraining bend and strike-slip duplex are developed north of the Archer River. New BMR aeromagnetic data define the western edge of the inlier, and show that the shear zones are truncated against a magnetically featureless area (interpreted as granite).

These shear zones are discrete en-echelon belts up to 3 km wide, and have well developed C-S mylonites (Fig. 23E, F), all of which display a sinistral-west-over-east sense of shear. Mylonites dip steeply, on average to the east-northeast (86° to 067), and presently define oblique-slip normal shear zones. Stretching lineations on S_m pitch moderately to steeply north-northwest (average 65° to 333).

An intense L-S tectonite fabric (D_m) is visible in many steeply dipping rhyolite dykes along the CSZ and ESZ. These are commonly invaded by subparallel steeply dipping quartz veins, and a costean southwest of Coen reveals that the quartz vein and rhyolite dyke are folded by F_2 and overprinted by S_2. This demonstrates that at least one generation of quartz veins is not composed of simple linear bodies.

Most of the shear zones appear, however, to be rectilinear (a function of post-D_2 reactivation), and the mylonitic foliation is locally a composite of at least two generations of movement (all sinistral-west-over-east). The timing of shear-zone development is post-D_1, because mylonites overprint granites that cross-cut S_1 (Fig. 23D). Mylonites are also clearly overprinted by the north-south-trending S_2 crenulation cleavage with an S-shaped asymmetry viewed north (Fig. 23E). This crenulation of 'S_{ml}' is itself strongly transposed into a second generation of mylonitisation with a sinistral sense of shear. The S-shaped asymmetry and steep plunge of $F_2^{\ m}$ folds (Fig. 23E) suggest maintenance of the sinistral shearing with reduced dip-slip movement. They also point to progressive deformation, where foliations were formed and being deformed within an active shear zone. The implications are that, like the quartz veins, the ductile shear zones could be macroscopically folded (e.g., in the Holroyd Metamorphics), and that possible associated gold mineralisation might be 'down F_2-plunge' in areas not previously considered. Future work should investigate this possibility.

Open to tight F_3 folds and a (less well developed) S_3 crenulation cleavage are common in the Holroyd and Sefton Metamorphics and to a lesser extent in the 'shearing-dominated' Coen Metamorphics. These are typically mesoscopic, upright, easterly to northeasterly trending structures (Fig. 23C). Rare low-angle F_4 axial surfaces with shallow easterly plunges overprint D_3 structures.

Structural correlations with the Georgetown Inlier

A number of inferences can be made where the orientations of structural elements in the Coen Inlier appear to conform with those in the Georgetown Inlier, to the south, as they do for D_1 and D_2, which are assumed to be synchronous respectively in either inlier. The Coen Inlier, however, has a D_1 climax and D_2 retrogression as well as pre-and post-D_2 ductile shearing. In the Georgetown Inlier, D_1 and D_2 were prograde events (probably not separated by a long period of quiescence) which are older than 1550 Ma (Ian Withnall, QDRI, personal communication 1991), and D_3 was a period of retrogression and ductile shearing (the absolute timing of which is in doubt). D_2 structures overprint some of the granites of the CYPB, and raise doubts about the Siluro-Devonian intrusive ages (Cooper & others, 1974: *Journal of the Geological Society of Australia*, 22, 285-310) if D_2 was synchronous in both inliers. In the Georgetown Inlier, D_2 is cross-cut by 1550-Ma granite and the 1550 Ma Croydon Volcanics are undeformed (Ian Withnall, personal communication 1991).

It should also be noted that the Nd model ages for the Coen Metamorphics are within the range of other north Australian Proterozoic inliers (T^{Nd} between 1940 and 2130 Ma; McCulloch, 1987: *American Geophysical Union, Geodynamic Series*, 17, 115-130), and inherited U-Pb zircon ages in Siluro-Devonian granites in the Coen Inlier record major Proterozoic thermal events (Lance Black, BMR, personal communication 1991).

What next?

The main belt of the Coen Metamorphics is now mapped at 1:100 000 scale. A *BMR Record* and accompanying 1:100 000 map of the CSZ and Ebagoola Shear Zone (ESZ) will be available soon. The 1991 priority is the completion of the six 'hard-rock' 1:100 000 Sheet areas of the Ebagoola 1:250 000 Sheet area (SD/54-12) including the main Holroyd metamorphic belt, whose southern extent also crops out in the Hann River 1:250 000 Sheet area (SD/54-16).

For further information, contact Dr Richard Blewett at BMR (Minerals & Land Use Program) at BMR, or Mr Friedrich von Gnielinski (Geological Survey; Regional Mapping Program) at QDRI.

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(1970: *Special Publication of the Geological Society of South Africa*, 1, 547-564), and the F1F folds of Pharaoh (1990). The folds have a range of orientations, although axes are generally subhorizontal. These folds are transected by a generally east-west striking, steeply dipping grain-flattening foliation (S2); the foliation cuts obliquely through the folds and granulite layers, and also affects the granitoids and in places the earlier dolerite dykes. The foliation is broadly parallel to, and therefore correlated with, the axial planes of the major folds of the region, classified as F2 by Nesbitt & others, and as F2F by Pharaoh. A third episode of folding (F3 of Nesbitt & others; F2M of Pharaoh) is inferred from changes in strike of the grain-flattening foliation, implying steep axes; F3 fold hinges were seen at only one locality in the Mount Aloysius area, however, and the strike changes elsewhere may equally well have some other cause, such as kinking or faulting.

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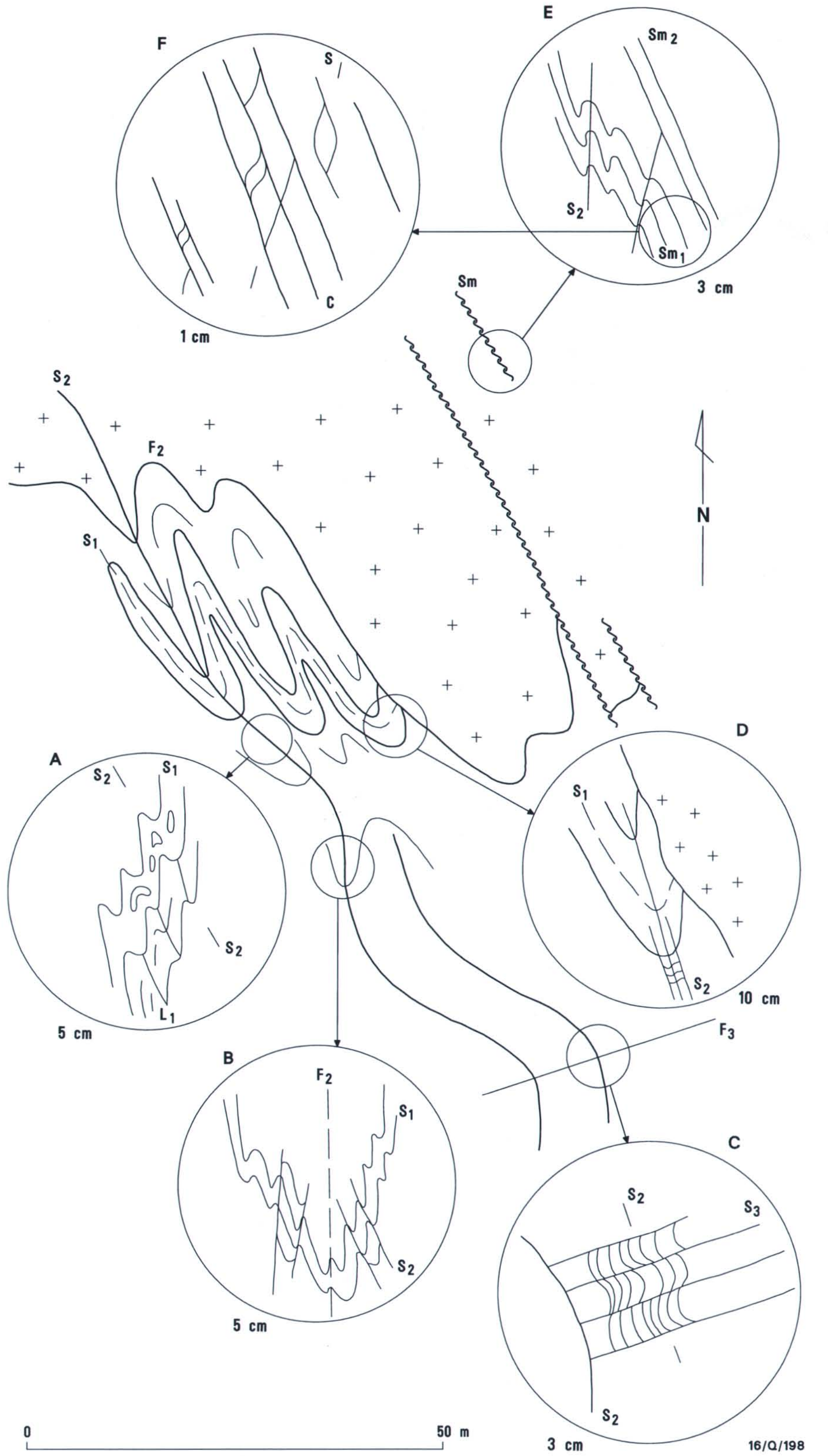

Fig. 23. Schematic fabric element sketch for the Coen Inlier. A: Sillimanite bunches and L_1 lineations overprinted by an asymmetric S_2 crenulation cleavage. B: S_2 overprint of S_1. C: S_3 crenulation of S_2. D: S_1 overprinted by S_2 and cross-cut by granite. E: S_2 overprint of mylonitised (S_{m1}) granite which is overprinted by a second generation of mylonite (S_{m2}). F: Typical C-S fabrics in a sinistral ductile shear zone. S_{1-3} — foliation generation from 1 to 3; F_{1-4} — fold generation from 1 to 4; L_1 — lineation associated with the first generation; M_{1-2} — metamorphic generations 1 and 2; S_{m1-2} — mylonite C-plane generations 1 and 2.

(Continued from page 15)

The last major structural event was high-angle thrust-faulting along the Champs de Mars and Hinckley Faults. The faults strike east-west, and shear-sense indicators — such as small asymmetric folds and S-C planes in mylonite — consistently indicate an upthrown southern block and minor dextral displacement. The faults form zones of mylonite up to several tens of metres wide, and are overprinted by networks of pseudotachylite. Some mylonites and major cross-joints are locally epidotised.

Geological history

The geological history of the felsic core complexes is interpreted as follows:

- Deposition of arkose, pelite, quartzite, and pebbly sandstone, or alternatively extrusion of felsic volcanics with lesser interbedded amounts of these sedimentary rocks, possibly at 1327 ± 7 Ma in the Champs de Mars area, and at 1564 + 13 Ma around Mount Aloysius (Rb-Sr regional whole-rock isochrons; Gray, 1978).
- Transport of the sediments and volcanics to about 20 km depth in the crust, possibly by burial and/or faulting.
- Tight to isoclinal F1 folding.
- Regional metamorphism of quartz-feldspar sediments and/or felsic volcanics to granulite facies, formation of migmatite and agmatite in felsic granulite, local melting forming granitoid blebs and intrusives.
- Intrusion of mafic magma bodies of the Giles Complex during waning of granulite metamorphism.
- Intrusion of early dolerite dykes.
- Major F2 folding about approximately east-west-trending axes of felsic granulites and Giles Complex intrusions and early dolerite dykes in response to approximately north-south compression, imparting steeply dipping grain-flattening and recrystallised fabric.
- Open F3 folding (or kinking) with steep axes, in response to compression — possibly oriented east-west.
- High-angle thrust-faulting.
- Intrusion of late dolerite dykes containing pyrite and hydrogen sulphide.

The work outlined above has shown that granite formed abundantly throughout the Tomkinson Ranges by dry partial melting and migration of migmatitic neosome during granulite metamorphism, and that the melts so formed intruded at least one of the Giles Complex layered intrusions. As the Giles Complex was intruded during the waning of the granulite metamorphism (*BMR Research Newsletter,* 12, 19), it follows that mafic intrusion, metamorphism, and partial melting were contemporaneous, and so may have been genetically related. Future work in the Champs de Mars area will include isotopic study of the felsic granulites aimed at establishing the provenance of their sedimentary precursors, the times of granulite metamorphism, migmatisation, and melting, and the time(s) of crystallisation of the various granitoids and dolerite dyke sets.

For further information, contact Drs Alastair Stewart or Andrew Glikson (Minerals & Land Use Program) at BMR.

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