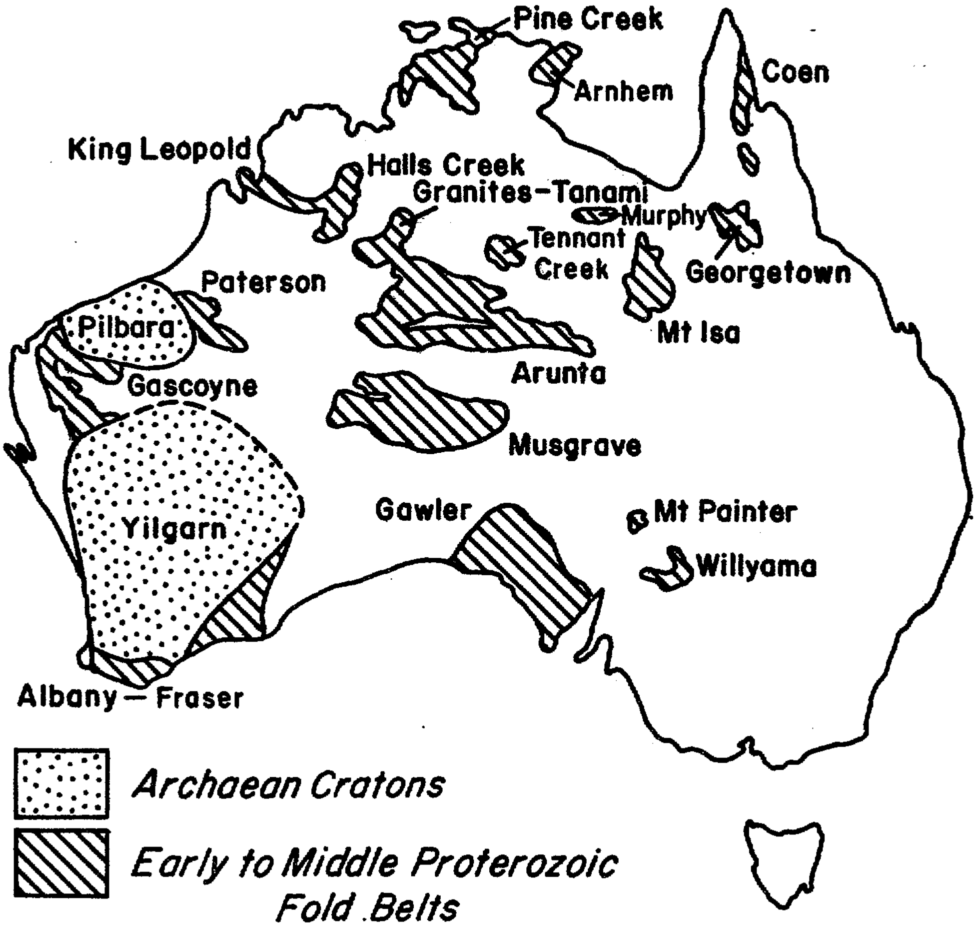
TECTONICS AND GEOCHEMISTRY
OF
EARLY TO MIDDLE PROTEROZOIC FOLD BELTS



PROGRAM AND ABSTRACTS
7-14 AUGUST 1985
DARWIN AUSTRALIA

BMR RECORD 1985/28

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TECTONICS AND GEOCHEMISTRY
OF
EARLY TO MIDDLE PROTEROZOIC FOLD BELTS

DARWIN, N.T., AUSTRALIA

7-14 AUGUST, 1985

PROGRAM AND ABSTRACTS

SPONSORED BY:

IGCP Projects -
Proterozoic fold belts
Proterozoic geochemistry

ILP, WG3 -
Proterozoic lithospheric evolution

ORGANIZED BY:

Bureau of Mineral Resources

Northern Territory Geological Survey

Geological Survey of Western Australia

TECTONICS AND GEOCHEMISTRY OF EARLY TO MIDDLE PROTEROZOIC FOLD BELTS

PROGRAM

WEDNESDAY 7 AUGUST

1530-1540: Welcome to Conference

1540-1620: Opening Address - An overview of Proterozoic Tectonics - A. Kroner

1620-1700: Tectonic evolution of the Pine Creek Geosyncline and contiguous terranes, Northern Territory - R.S. Needham, P.G. Stuart-Smith, and R.W. Page

1700-1740: Geochemistry and mineralisation of the Pine Creek Geosyncline, Northern Territory - P.G. Stuart-Smith, R.S. Needham and L.A.I. Wyborn

1800- : BBB (beer, barbecue and bull) session

THURSDAY 8 AUGUST

REGIONAL TECTONICS OF EARLY TO MIDDLE PROTEROZOIC PROVINCES - I: AUSTRALIA

0830-0910: Tectonic process in the Early to Middle Proterozoic of northern Australia - M.A. Etheridge, R.W.R. Rutland and L.A.I. Wyborn

0910-0950: Tectonic development of the Proterozoic Mount Isa Inlier, northwest Queensland - D.H. Blake

0950-1030: Tectonic interpretation of the Margin of the Early Proterozoic southern Litchfield Province, Northern Territory of Australia - R.H. Findlay, D.L. Dundas, C.J. Edgoose, G.M. Fahey, J.E. Fahey, and B.A. Pietsch

1030-1100: Coffee break

1100-1140: Structure and stratigraphy of the Proterozoic of the Olary Block, South Australia - G.L. Clarke, J.P. Burg and C.J.L. Wilson

1140-1220: Tectonic development of the Gawler Craton, South Australia - A.J. Parker and R. Flint

1220-1300: Tectonic evolution of the Georgetown Inlier, Queensland - J.H.C. Bain

1300-1400: LUNCH

GEOCHRONOLOGY AND ISOTOPE GEOCHEMISTRY

1400-1440:	Isotopic record of Proterozoic crustal events in northern Australia - R.W. Page
1440-1520:	U-Pb and Rb-Sr geochronology of Proterozoic supracrustals in the vicinity of the Harts Range Ruby Mine, Arunta Inlier, central Australia - G.E. Mortimer, J.A. Cooper and P.R. James
1520-1550:	Coffee break
1550-1630:	U-Pb geochronology of the Trans-Hudson orogen in northern Saskatchewan, Canada - W.R. van Schmus, M.E. Bickford, J.F. Lewry and R. MacDonald
1630-1710:	Geodynamic interpretation of chemical and isotopic data on granitoids from mid-Proterozoic orogenic belts, Sweden - M. Wilson

FRIDAY 9-SATURDAY 10 AUGUST:- FIELD TRIP TO PINE CREEK AND KATHERINE

SUNDAY 11 AUGUST

REGIONAL TECTONICS OF EARLY TO MIDDLE PROTEROZOIC PROVINCES - II: THE AMERICAS

0900-0940:	Accretion of western and central North America during the Proterozoic - K.C. Condie
0940-1020:	Archaen basement inliers in two Early Proterozoic orogens in Canada: Their structural position and geotectonic significance - P.F. Hoffman
1020-1050:	Coffee break
1050-1130:	Ancient "massifs" in the Proterozoic mobile belts of Brazil - B.B. de B. Neves, M.C. Neto, and U.G. Cordani
1130-1210:	New geodynamic concepts regarding the crustal evolution of NE Brazil - R. Caby
1210-1250:	The Barro Alto Complex of central Brazil - R.A. Fuck, O.H. Leonardos, J.C.M. Danni and M. Winge
1250-1400:	LUNCH

REGIONAL TECTONICS OF EARLY TO MIDDLE PROTEROZOIC PROVINCES - III: EUROPE, AFRICA AND ASIA

1400-1440: Precambrian development of the Baltic Shield - R. Gorbatschev

1440-1530: Pan-African crustal evolution in the Nubian segment of northeast Africa - A. Kroner, R. Greiling, T. Reischmann and R.J. Stern

1530-1550: Coffee break

1550-1630: The Mozambique orogenic belt of northern Kenya - R.M. Key and T.J. Charsley

1630-1710: Tectonic evolution of Proterozoic in North China Platform - Sun Dazhong and Lu Songrian

1710-1750: Indian Rift Valleys as the sites of former orogenic belts - J.J.W. Rogers, E.J. Callahan, T. Chacko, S.M. Naqvi, C.A. Powell and P.T. Stroh

MONDAY 12 AUGUST

GEOCHEMISTRY AND PETROLOGY

0900-0940: Geochemistry and origin of a major Early Proterozoic felsic igneous event of northern Australia and evidence for substantial vertical accretion of the crust - L.A.I. Wyborn

0940-1020: Geochemical and Nd isotope study of late Archean to Middle Proterozoic mafic volcanic rocks in northern Australia - S-s Sun and M.T. McCulloch

1020-1050: Coffee break

1050-1130: Geochemical patterns in a Lower Proterozoic basic granulite-gneiss suites, southwestern Arunta Inlier central Australia: evidence of deep crustal partial melting - A.Y. Glikson

1130-1210: The geochemistry of mafic-ultramafic associations from the Harts Range - W. Sivell

1210-1250: Composition, age and tectonic setting of volcanic rocks in the central Bushmanland Group, Western Namaqua Province, Southern Africa - D.L. Reid, H.J. Welke, P.J. Betton and A.J. Erlank

1250-1400: LUNCH

1400-1440: Petrogenesis of a Proterozoic late orogenic plutonic complex from E. Greenland - J. Tarney

1440-1520: Geochemical differentiation of the lithosphere and upper mantle in the gravity field of the earth - A.A. Beus

1520-1550: Coffee break

1550-1630: Partial melting during granulite metamorphism - A mechanism for control of fluid composition B.J. Hensen and R.G. Warren

1630-1710: Aspects of metamorphism in the Harts Range Block of the Arunta Inlier, Northern Territory - R.L. Oliver, R. Lawrence, B.D. Goscombe, D.G. Bowyer and P. Ding.

1710-1750: Metamorphism in the Hall's Creek Mobile Zone - R. Allen

TUESDAY 13 AUGUST

STRUCTURAL GEOLOGY/STRATIGRAPHY

0900-0940: Displacement and strain within the nappe sequences of the Harts Ranges, Central Australia - P.R. James, P. Ding, L. Rankin and G. Scales

0940-1020: Central Australian orogeny and Himalayan comparisons - K.A. Plumb

1020-1050: Coffee break

1050-1130: Structural-stratigraphic relations of the Proterozoic metasediments in the vicinity of the Broken Hill mine, Aggeneys, South Africa - D. Strydom and A.E. Schoch

1130-1210: Stratigraphic interpretation of highly deformed and metamorphosed metasediments of central Bushmanland, Namaqua Mobile Belt, South Africa - H.E. Praekelt

1210-1250: Deformation in a flat-lying Proterozoic shear belt: Colonsay, N.W. Scotland - M. Bentley

1250-1400: LUNCH

METALLOGENESIS AND MINERAL DEPOSITS

1400-1440: Structure of the Bushveld Complex, South Africa, as derived from geoelectrical sounding data - J.H. de Beer and R. Meyer

1440-1520: Stratiform polymetallic ore environment, Ashburton Basin, Western Australia - G. Doust

1520-1550: Coffee break

1550-1630: Mount Isa copper and lead-zinc-silver ores: Coincidence or co-genesis? - P.J. McGoldrick and R.R. Keays

1630-1710: The Mary Kathleen U-REE deposit, Queensland: Age and origin of mineralisation from Sm-Nd systemataics - R. Maas, M.T. McCulloch, R.W. Page, and I.H. Campbell

1710-1750: Distribution of Zambian gold occurrences in the Zambian part of the Zambezi Mobile Belt - A.S. Sliwa

WEDNESDAY 14 AUGUST

0900-1200: DISCUSSION SESSION

POSTER DISPLAYS

Allen, R. - Geochemistry of the volcanic rocks of the Halls Creek Mobile Zone, East Kimberley Western Australia.

Clarke, G.L. - Deformation sequence in the Rayner Complex, Macrobertson and Kemp Land, East Antarctica.

Glikson, A.Y. - On the origin of Proterozoic craton-mobile belt patterns, with reference to Australian Lower-Middle Proterozoic terrains.

Parker, A.J., Rickwood, R.C., Baillie, P.W., McClenagham, M.P., Boyd, D.M., Freeman, M., Pietsch, B.A., Murray, C. and Myers, J.S. Precambrian mafic dyke swarms of Australia.

Plumb, K.A. - Proterozoic orogeny worldwide - diachronous, random or episodic.

Winsor, C.N. - Evidence of three weak folding events within the Irregully Formation at Irregully Gorge, Bangemall Basin, Western Australia.

In addition, displays of 1:100,000 and 1:250,000 maps from Australian Early to Middle Proterozoic terranes will be mounted at the lecture centre.

REGIONAL METAMORPHISM IN THE HALLS CREEK MOBILE ZONE,

EAST KIMBERLEY, WESTERN AUSTRALIA

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The Lower Proterozoic orogenic belts of the Halls Creek subprovince are polymetamorphic terrains. Overprinting criteria indicate a number of regional metamorphic events which can be correlated with different deformations. The NNE trending Halls Creek Mobile Zone ranges in grade from greenschist in the south to granulite in the north. Dow and Gemuts (1969) recognised two periods of folding with associated metamorphism and mapped three metamorphic zones. This regional work has been modified and expanded. Five metamorphic zones are mapped. A cylindrical metamorphic belt is indicated, higher grade zones plunging south under lower grade zones. This interpretation differs from Hancock and Rutland (1984), who perceive metamorphic grade in the Halls Creek Mobile Zone as fault controlled. Four periods of deformation are recognised, and peak metamorphic temperatures occur progressively later with increasing grade. Regional metamorphism in the East Kimberleys commenced syntectonically with the first period of folding. The paragenetic sequence of mineral nucleation and growth in relation to deformational events is presented hereunder for metapelites in the five mapped zones.

Upper Greenschist - Lower Amphibolite Zone.

In low grade areas west of the Halls Creek Fault, D1 folds are the most obvious structural element. In the McClintock ranges an isoclinal overturned F1 fold with restored amplitude of 30 km has been refolded by D2 with the development of a schistosity overprinting an earlier layer parallel fabric. Both S1 and S2 are defined by musc-bio. However S1 is the regional schistosity, and S2 overprints only in the core of the major D2 structure closing south. Thus peak metamorphic conditions are pre-D2.

The Lower Sillimanite Zone.

The tectonothermal history of rcoks from the Lower Sillimanite Zone has been described and illustrated elsewhere (Allen, 1982) and is briefly recapitulated below. Four fold events have been delineated with structures and fabrics recognisable at a variety of scales.

D1 No folds of D1 generation are recognised at amphibolite grade or higher. However, there is good evidence for the presence of a heavily overprinted S1.

1. The layer parallel fabric in the hinges of D2 folds is very strong in rocks of appropriate composition.
2. This early fabric is associated with metamorphic minerals e.g. garnet.
3. S2 is a crenulation cleavage implying a strong pre existing anisotropy of probably tectonic origin.
4. Porphyroblasts wrapped by S2 sometimes display a rotational Si, finer than and discontinuous with S2.
5. D2 folds a tectonic fabric in some igneous rocks.

D2 This is a complex event which has generally developed in two stages.

D2a Widespread, mesoscopic folds fold S1. This event is associated with extensional tectonism. Recumbent folds verge east and west from the orogenic core, and a widespread elongation lineation is developed. S2, axial plane to these folds, is the regional schistosity in high grade areas. It is generally well developed and easily recognised, and provides the datum from which structural and metamorphic events are put into a relative time scale.

D2b This deformational event is associated with shearing along the base of D2a folds, transposition, and widespread, though locally discrete, mylonitization. It registers initiation of, and major movement on, the Halls Creek Fault system.

D3 Structural effects of this deformation are upright macroscopic folds and E-W crenulations. New phases are not nucleated at this grade during D3. This event is associated with major E-W faulting involving both the East and West Kimberley, with movement on (initiation of ?) the Little Gold Fault, the Osmond Fault and the Sandy Creek Shear, with major uplift of the Southern block, and/or downfaulting of the Northern block.

D4 Upright macroscopic and mesoscopic folds trend NNE in the sillimanite grade areas. A D4 crenulation is widely developed in meta-pelitic rocks, however a regional schistosity is not associated with this event in rocks of any grade west of the Halls Creek Fault. This is a period of compressional folding with fold axes plunging generally shallowly to NNE or SSW. No major overthrusting has been documented.

Metapelitic rocks from this zone show the following sequence:-

M1 Garnet cores with rotational Si, and staurolite relics in optical continuity in the core of M2 garnets or plagioclase.

M2a Biotite (S2 schistosity), syntectonic garnets and fibrolite.

M2b Muscovite replacing biotite and fibrolitic sillimanite.

M2c Euhedral, randomly oriented, andalusite and staurolite overgrowing fibrolite. Staurolite nucleates in muscovite, or on biotite or garnet.

Peak temperatures of ca. 500-550°C were recorded during M2a.

Upper Sillimanite Zone

In the Upper Sillimanite Zone effects of D3 become more obvious. Air photos clearly show two "granitic" plutons just south of the Ord River, with S2 folded by this event and refolded by D4. Migmatites become a quite common feature with coarse grained biotite defining selvidges of leucosomes. The knotted schists have a stong S2 with garnet porphyroblasts up to 1cm in diameter, and well defined sillimanite. Thin sections of pelitic rocks from this area frequently show two generations of sillimanite, the earlier fine grained and syntectonic with D2a, and a later coarse grained sillimanite replacing the S2 biotite. There is no development of retrograde mineral phases overgrowing S2 (as in the Lower Sillimanite Zone). Peak metamorphic temperatures of 600° - 650°C registered during M2c, later than in the Lower Sillimanite Zone. There is no obvious metamorphic effect of D4 at this grade.

The transitional Granulite Zone.

Entry into this zone is defined by the appearance of cordierite in gt-cord-sill gneisses, and the concomitant disappearance of biotite. Cordierite has never been recorded in rocks of lower amphibolite grade in the Halls Creek Mobile Zone. This is most probably a reflection of the iron rich nature of the province evidenced by -

(1) the development of banded iron formation
(2) the common presence (sometimes abundance) in meta-pelites of iron rich phases e.g. staurolite, almandine garnet, and magnetite.
(3) felsic volcanics are consistantly more iron rich than their Cainozoic counterparts (Allen, 1982).

These gt-cord-sill gneisses contain no biotite except as remnant inclusions and no other hydrous minerals. Potassium contents are very low. They are interpreted as restites after migration of $H2O$ and K^+ into early minimum melts. Thus metamorphic conditions at D2a are estimated to be a minimum of $650^{\circ}C$ and 4kb. There is evidence of a further high grade metamorphic event syntectonic with D3. Coarse grained porphyroblastic K-fels-perthite-sill gneisses also appear in this zone. Coronas around cordierite of qtz-sill simplectite with granular magnetite are considered to represent retrograde M4 fabrics. Thornett (1983) has estimated a metamorphic grade of $710^{\circ}C$ and 4kb during the D3 metamorphic peak in the Transitional Granulite Zone.

Granulite Zone.

Thornett also uses a biotite consuming - melt formation reaction as a zone marker. He defines entry into the granulite zone west of the Mabel Downs Granodiorite by the reaction

$$\text{bio + cord + qtz + plag} \longrightarrow \text{gt + K-spar + melt}$$

In two pyroxene granulites, hornblende, which is ubiquitous in the Transitional Granulite Zone to the west, disappears in the granulite zone in the east. Thornett (op cit) estimates peak metamorphic grade at $800^{\circ}C$ and 5 1/2 kb. Neville (1975) also estimated temperatures of $800^{\circ}C$ in the granulite facies rocks east of the Mabel Downs Granodiorite. Two pyroxene granulites and charnockitic granite have been recorded in this area, which lies well within Dow and Gemuts's Zone C (high grade). Hancock and Rutland (1984) have mapped it as Zone 11 (med grade). They indicate metamorphism during D2 at 3-5 kb and 500°-$600^{\circ}C$, and only $400^{\circ}C$ during D3 in Zones II and III.

The Halls Creek Mobile Zone is a high temperature / low pressure terrain. The mineralogical evidence is supported by geothermometry and geobarometry. The lack of kyanite (reported from only one small area of anomalous metamorphic grade), coupled with the occurrence of wollastonite in marbles in granulite facies rocks east and west of the Mabel Downs Granodiorite suggests low pressure. The maximum recorded grade of $800^{\circ}C$ and 5 1/2 kb indicates that the Halls Creek Mobile Zone developed an abnormally high geothermal gradient during orogenesis.

GEOCHEMISTRY OF THE VOLCANIC ROCKS OF THE HALLS CREEK MOBILE ZONE, EAST KIMBERLEY, WESTERN AUSTRALIA.

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Much of the stratigraphic sequence in the Ding Dong Downs Volcanics and the Biscay Formation of the Lower Proterozoic Halls Creek Group consists of intrusive rocks. The presently exposed Ding Dong Downs Volcanics is an interbedded sequence of felsic, crystal-lithic tuffs (some with a vitric component), and amygdaloidal basalts. The Biscay Formation is richly volcanogenic. All four units contain variable thicknesses of tuffs and/or basalts interbedded with sediments. These deformed and metamorphosed rocks of the Halls Creek Group are unconformably overlain (in the East Kimberley) by the post orogenic, dacitic-rhyolitic, vitric-crystal-lithic tuffs and tuffaceous sediments of the Whitewater Volcanics.

The chemistry of the volcanic material is distinctly bimodal with very few samples plotting in the andesite field. Within the two categories of felsic and mafic volcanics, a number of different populations are defined on chemical grounds. The felsic volcanics within the Biscay Fm - the "Corkwood East Suite", the "Wills Creek Suite" and the alkaline suite - form populations discrete from each other and from the felsic Ding Dong Downs Volcanics and the Whitewater Volcanics. All Biscay basalt samples from Units 1, 2 and 4 plot closely together forming a coherent population. The Ding Dong Downs basaltic rocks and samples of pre - or early tectonic dolerite sills form separate, more diffuse groupings.

Not only is there a discontinuity between the felsic and mafic rock chemistry, they follow different differentiation paths indicating that although coeval they are not co-magmatic. The felsic volcanics have chemical characteristics broadly akin to modern calc alkaline felsic volcanics from island arc settings. Differentiation appears to have been controlled by crystallization of plagioclase, magnetite, apatite and zircon (plus ortho-pyroxene in the Whitewater Volcanics). The basic volcanics are all highly evolved tholeiites with chemical characteristics variably suggesting affinity with MORB, ocean floor, or back arc basin basalts, rather than calcalkaline basalts or island arc tholeiites. Extensive fractionation of olivine and pyroxene is indicated. Thus different lines of liquid descent are indicated from probable non-consanguineous parent magmas. (There is no implied suggestion of different tectonic settings).

Comparison with other Proterozoic rocks within Australia indicates a general similarity of volcanic geochemistry between terrains within the Northern Australian Proterozoic province. More general comparison suggests that while some Proterozoic provinces appear geochemically broadly similar to the Northern Australian province, some gross dissimilarities are apparent (e.g. in crystallization controls of basaltic melts). Similarities include bimodality, and the suggestion is offered (tentatively, due to limited data) of iron and scandium enrichment in all Proterozoic felsic volcanic rocks relative to their modern counterparts.

TECTONIC EVOLUTION OF THE GEORGETOWN INLIER, QUEENSLAND

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The Georgetown Inlier is the largest and most complex of the several Precambrian inliers in NE Queensland; it comprises four groups (Etheridge, Langlovale, Croydon, Inorunie) of Early & Middle Proterozoic metasedimentary and metavolcanic rocks intruded by Middle Proterozoic granitoids. The precise age of the principal Precambrian sedimentary cycle (Etheridge Group) remains unknown, largely as a result of its high metamorphic grade and the scarcity of felsic volcanics. Consequently these rocks can be interpreted as belonging to either the first or second cycle of the BMR model of Proterozoic basin evolution, magmatism and orogeny (Etheridge & others, 1984).

The lower part of the Etheridge Group, perhaps representing the rift phase of the model, is characterised by psammitic, commonly carbonate rich sediments deposited on a shallow marine shelf in deltaic and shoreline environments. In the eastern part of the area sporadic lenses of high-Zr ("A type") felsic metavolcanics and metamorphosed stratiform basemetal sulphide deposits are associated with a transition upwards to finer more pelitic sediments with less carbonate. To the west the pelitic sediments are finer and less felspathic. This sequence is overlain by submarine mafic lavas and intruded by mafic dykes and sills. Above it the group is mostly very fine grained quartzose clastic sediment, generally rich in carbonaceous material and with variable but mostly minor carbonate content; it was deposited fairly rapidly in a shallowing shelf environment, and is characteristic of the sag phase of the model. The upper part is characterised by carbonaceous mudclast siltstone and minor supra-tidal sequences containing evaporite minerals and probable stromatolites.

The Langlovale Group lies unconformably on the Etheridge Group and is characterised by a fluviatile sequence at the base grading upwards into a pelitic/psammitic, prograded deltaic turbidite sequence. The subaerial felsic Croydon Volcanic Group - a rhyolitic ignimbrite-dominated sequence confined to a large volcanic subsidence structure and intruded by comagmatic subvolcanic granitoids, unconformably overlies the Langlovale Group. Gold-silver-basemetal-quartz veins are associated with carbonaceous zones in the granite and with fracture systems in the volcanics; tin-bearing greisens are locally developed in and near a late phase of the granitoid. Fluviatile quartzose sediments of the Inorunie Group complete the sequence as preserved.

The abundant "I-type" felsic igneous rocks that characterise the orogenic event separating the two cycles of the model are conspicuously absent in the Georgetown region: either the sequence is cycle 2, or the region does not overlie a zone of pre-1850Ma underplating such as in the Mount Isa region. Tholeiitic mafic igneous rocks are abundant in the Georgetown region, but confined to the lower half of the Etheridge Group, i.e. the eastern half of the region. Geochemical characteristics (especially REE) of the mafic rocks are most like those of mafic rocks in cycle 1 sequences elsewhere. Felsic igneous rocks with "A-type" affinities like those that characterise the second cycle of the model are represented in the Georgetown region only by sporadic development of sphene-bearing, high-Zr, leucogneiss in the Einasleigh Metamorphics. Earliest post deformation granitoids are small trondhjemite bodies dated at about 1550 Ma. Their chemistry and very low initial Sr 86/87 suggest derivation directly from the mantle, or by melting of lower crustal material - possibly Archean basement to the Etheridge Group - probably during the EWAMIN orogeny (D1). The overwhelming majority of Proterozoic felsic igneous bodies in the Inlier are "S-type" granitoids that formed during the JANA orogeny (D2); they are characterised by high K_2O, U, Th, Y, Ce, Nb, etc. A very distinctive and conspicuous unit is the large composite Forsayth Batholith. This body comprises early syn-deformation migmatoids to post-deformation leucogranite. Much of the batholith resulted from the the mixing of two products of anatexis of the Etheridge Group with a more mafic mantle-derived magma. Increased heat flow during the JANA orogeny, possibly following underplating of the crust at about 1500 Ma, led to local anatexis; but emplacement of the mafic magma into the migmatites produced the voluminous melts that formed the Batholith and similar bodies.

The Croydon Volcanic Group, Esmeralda Granite and associated subvolcanic granitoids although "S-type" differ in composition from the Forsayth-type granitoids; they are highly reduced, due to the ingestion of much carbonaceous material at their source or in a near-surface magma chamber, more potassic, more mafic, and they show weak fractionation trends.

The style of deformation is mostly like that in second cycle sequences except that nappe style folding did not occur. The earliest event (D1) is characterised at high levels (west and south) by E-trending tight upright to overturned folds with wavelengths of 1-10km and a strong axial plane foliation. Elsewhere folds were tighter to isoclincal, but strong deformation during subsequent orogenies makes identification of F1 features difficult. A second event (D2), 100 Ma later, formed N-trending tight to isoclinal upright folds with generally much shorter wavelengths, associated small scale folds, and a strong commonly differentiated, crenulation cleavage or schistocity. Deformation intensity diminishes westwards to an area where folds are more open and crenulation cleavage is only locally developed; further west there is little or no folding. Additional episodes of folding have been superimposed on these folds in later Proterozoic and Palaeozoic time.

Although the Croydon and Inorunie Groups are essentially unmetamorphosed, the Etheridge Group is characterised by regional low pressure metamorphism grading from low greenschist in the west to transitional granulite in the east. Extensive migmatisation is associated with the upper amphibolite and transitional granulite zones, and large anatectic granitoid bodies with the middle amphobolite zone. These these migmatites and granitoids formed mostly, if not entirely, during D2; maximum grade reached during D1 was probably lower amphibolite. Granitoid migration to higher levels during D2 resulted in modification of the regional geothermal gradient, and probably in the increasing temperatures during S2 development. Forsayth Batholith, although regionally conformable with the isograds, locally cuts them and D2 folds. Some retrogression of prograde assemblages occurred late or post-D2.

Rb-Sr, Ar39/40, U-Pb zircon dating of the amphibolite grade metasediments and associated granitoids (Black & others,1979;Black & Holmes, in prep) has shown that the first two deformation events were of regional extent and occurred at about 1570Ma (EWAMIN orogeny) and at about 1470Ma (JANA orogeny). Therefore there was no pre-cycle 2 orogenesis. Sm-Nd dating (Black & McCulloch, 1984) provides a lower limit of about 2500Ma. Thus the bulk of the Precambrian metasedimentary rocks of the region (ie the Etheridge Group) are early Proterozoic, between 2500Ma and 1600Ma.

References

Black, L.P., Bell, T.H., Rubenach, M.J., & Withnall, I.W., 1979, Geochronology of discrete structural-metamorphic events in a multiply deformed Precambrian terrain, Tectonophysics, 54, 103-137.

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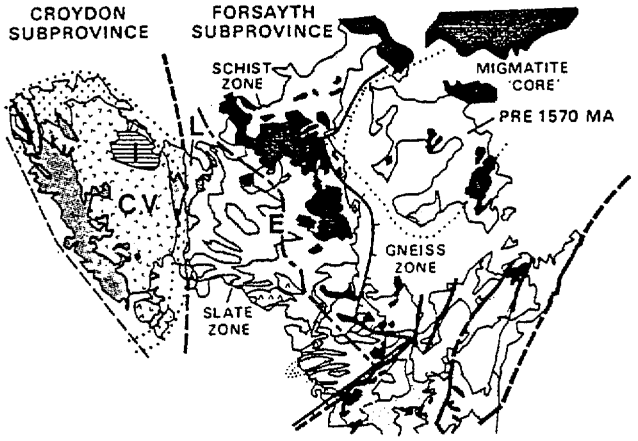

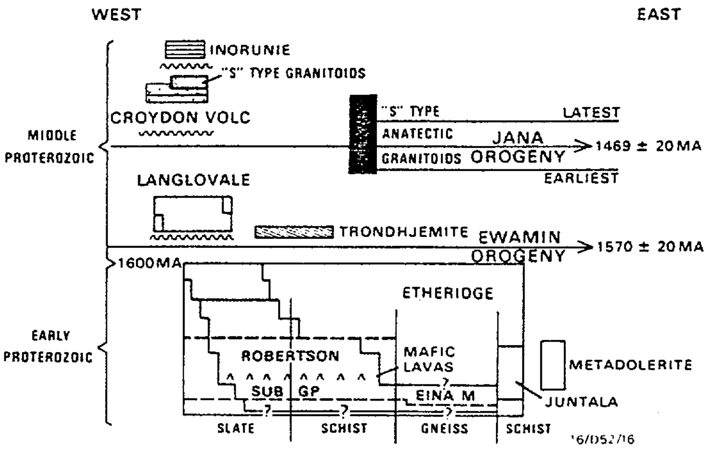

DEFORMATION IN A FLAT-LYING, PROTEROZOIC SHEAR BELT: COLONSAY, N.W.SCOTLAND.

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The Colonsay Group is a 4-5km thick suite of low grade meta-sedimentary rocks, which lie with a sheared unconformity upon gneissic basement. The stratigraphic age of the Group, and the tectonic age of the structures developed in the Group have previously been unclear. New isotopic evidence is presented here which demonstrates a Proterozoic age both for the deposition of the Group, and the age of the earliest penetrative deformation within the Group (D1). This deformation is described below.

LOCATION

The Group is exposed on two islands in the Scottish Inner Hebrides, Colonsay and Islay (fig.1a). Tectonically, the islands are situated near the north-west margin of the Caledonian orogenic belt (of end-Precambrian to Lower Palaeozoic age in Scotland). Additionally, the Group lies in the broad area in which the effects of Grenvillian orogenesis (c.1000Ma) have been identified.

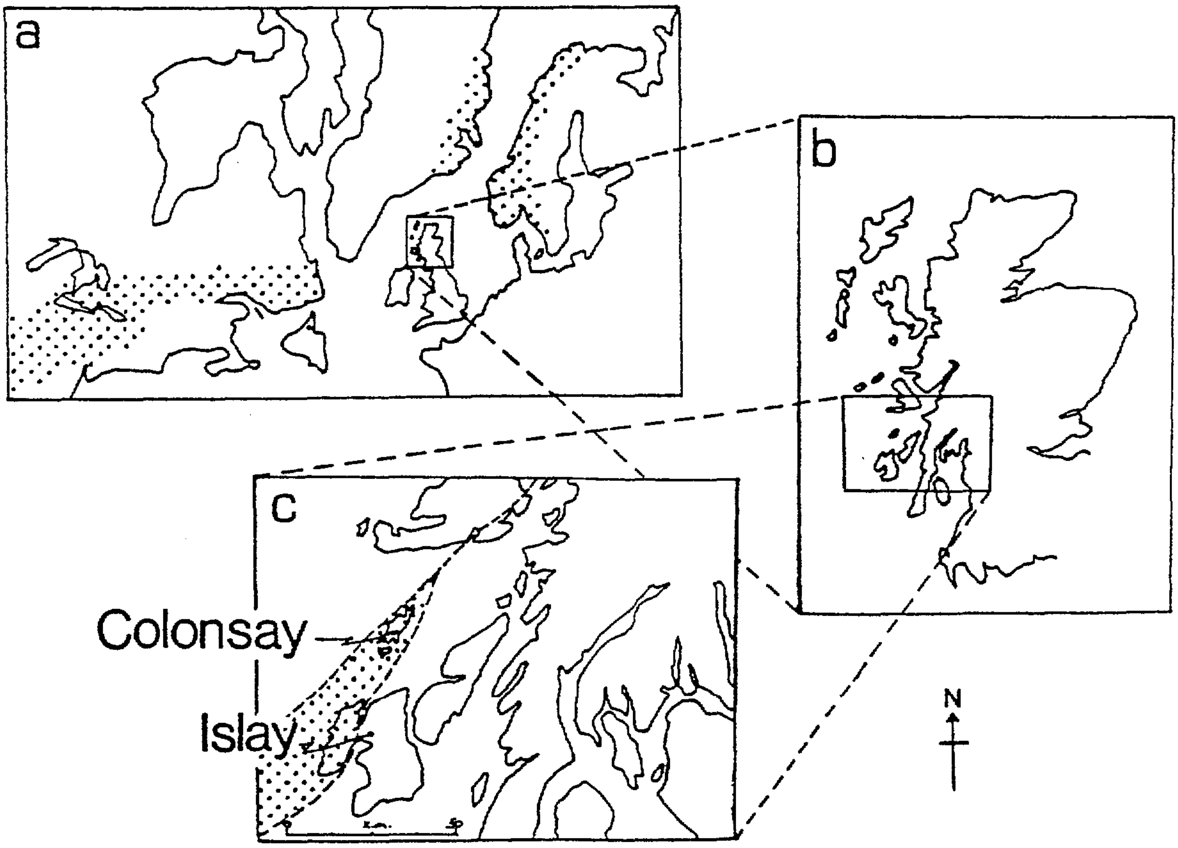

Figure 1 - Location. A: the North Atlantic continents in the mid-Proterozoic (stippled area marks the approximate extent of the Grenville belt),b: the Southern Inner Hebrides, c: the Colonsay Block (stippled area).

On a more local scale (fig.1b,c), the Colonsay Group is isolated both geographically and geologically from the mainland, this isolation being the main limiting factor in determining the age of the Group and the association of the structures exposed on the islands.

AGE CONSTRAINTS

Explosion breccias associated with the emplacement of igneous bodies in the Colonsay Group clearly post-date the earliest penetrative deformation (D1). Samples from the intrusions have been analysed by Rb/Sr, K/Ar and Ar/Ar methods, the results from which indicate an age of emplacement of c.620Ma for the intrusions. This provides a minimum estimate of the age of the earliest structures (D1).

A maximum age for the D1 structures is provided by the basement rocks on which the Colonsay Group sediments are unconformable. Although an isotopic age for the basement is not yet available, the gneisses resemble the Lewisian gneisses of NW Scotland, which underwent high grade metamorphism as late as 1800Ma.

The depositional age of Colonsay Group and the tectonic age of the early penetrative deformation therefore lie within the range c.1800Ma - c.620Ma.

PROTEROZOIC STRUCTURES

The Proterozoic, D1 structures in the Colonsay Group were produced in an environment of heterogeneous sub-horizontal shear. The heterogeneity is expressed as a broad increase in strain up the sequence, and is characterised by the systematic variation of D1 fabrics and folds across the 4-5km stratigraphic sequence.

Fabric development: The S1 fabric is typically weak or absent in the lowest 2km of the sequence (excepting a local strain high close to the cover-basement contact). Approximately 3km up the sequence, a ubiquitous S1 fabric appears, typically oblique to bedding, with S>>L. Higher in the sequence, S1 becomes progressively stronger, closer to bedding and develops a more well-marked linear component, with the local development of an L>>S fabric. Highest strains are reflected in the local development of proto-mylonitic fabrics.

Fold development: D1 folds are generally absent in the lowest stratigraphic horizons of the Group. Higher in the sequence, F1 folds appear in association with S1, the fabric showing a consistently axial planar relationship to the folds. Where S1 is oblique to bedding, F1 occurs typically as open to close asymmetric folds. As S1 approaches parallelism with bedding, the folds become tight to isoclinal and more reclined. In the latter case, the fold axes locally become highly non-cylindrical or sheath-like.

The degree of metamorphism associated with D1 is low, characterised by the widespread development of chlorite. In the more highly strained upper stratigraphic levels of the Group, chloritoid is locally produced.

The sense of shear given by the overturning of the early folds, and the S1/bedding intersection lineation (fig.2) indicate a broad sense of shear to the north, allowing for the subsequent effects of Caledonian deformation.

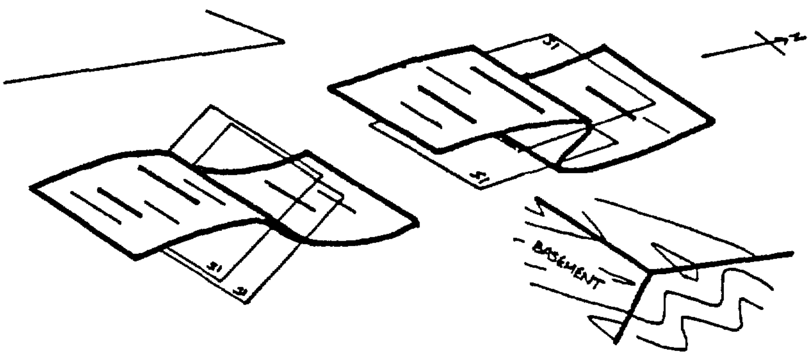

Figure 2. The geometric relationships between the early folds, the S1/bedding intersection lineation (discontinuous faint lines), the mineral lineation (discontinuous bold lines), and the basement inlier in N.Colonsay.

The pronounced mineral lineation, although genetically associated with D1, lies highly oblique to the direction of shear implied by the other D1 structures. The lineation is therefore not a reliable indicator of overall transport direction during D1.

The upward increase in strain, the growth of chloritoid near the top of the sequence, and the northward sense of shear indicated by most of the D1 structures, imply the deformation in the Group may be a response to the northward translation of an overlying body of rocks, now removed.

In N.Colonsay, basement rocks crop out at a high stratigraphic level (approximately 4km from the base of the sequence). Although the basement-cover interface is deformed, a coarse conglomerate, unique within the Colonsay sequence, may be recognised at the contact. Similarly, the depositional environment of the sediments in the 1-2km area surrounding the basement is consistent with the inlier being an autochthonous block, rather than a tectonically emplaced sheet. The presence of autochthonous basement so high in the stratigraphic sequence is a reflection of the highly irregular cover-basement interface which underlies the Colonsay Group. The constrictive effect of shearing ductile cover rocks towards relatively resistant basement blocks such as that in N.Colonsay may explain the discordant behaviour of the linear component of S1.

CONCLUSIONS

The Colonsay Group is a middle or late Proterozoic suite of metasedimentary rocks, deposited on basement of Archaean or Lower-Proterozoic age. The Group was intensely deformed during the Proterozoic in a flat-lying shear belt, probably in response to the northward translation of an overlying nappe, now removed, over an irregular basement surface. The exact timing of this Proterozoic deformation is open to discussion, although the regional setting of the Colonsay Group prompts a correlation with Grenvillian events. If this is so, the Colonsay Group constitutes one of the best preserved Grenvillian terrains so far identified within the Scottish Caledonides.

GEOCHEMICAL DIFFERENTIATION OF THE LITHOSPHERE AND UPPER MANTLE IN THE GRAVITY FIELD OF THE EARTH

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It is known that migration of chemical elements and compounds in the Earth's shells develops under the influence of the Earth's gravity field, being directed to the enhancement of the energy equilibrium within the difference in gravitational parameters of geospheres making up our planet. Taking this into account it is possible to consider the differentiation of the outer shells of the Earth as resulting from the redistribution of the primary mantle substance, the tendency being to achieve a more complete energy equilibrium within these shells.

Mechanisms for this redistribution was not fully understood until recently, especially for the migration of the ionic forms which played an important role in the formation of the zonal lithosphere. Special attention was paid to atomic volumes of elements, but it is impossible to explain many specific features of the differentiation of chemical elements in the Earth on the basis of their atomic volumes alone.

From this point of view specific ionic or atomic volumes, determined in both as mass of the atom and as a measure of the electric field, can provide much more complete information, allowing the behaviour of a particular particle to be assessed during its migration in the gravity field of the Earth.

As shown by Barth (1952), deviations of a system from the state of equilibrium in the gravity field can be described by the following equation:

$$F = PM\ (V_i - V_c)$$

where F is the change in free energy of the system (positive or negative); P is the pressure at a given depth (-h); M is the molecular or atomic mass of the component; V^i is the specific volume of the component; and V^c is the specific volume of overlying rocks. The state of equilibrium is achieved at F = 0. Positive values of F mark the tendency of a component to migrate to the upper, less dense, zones of the Earth's shells; e.g., from the mantle to the crust, or from the "basaltic" layer. This tendency can be realized only if migration of a component is possible; i.e., during rise and migration of melts, solutions and gaseous emanations within the deep zones of the Earth.

In considering gravitational sorting in the migrating liquid phases within the mantle and lower crust, it is necessary to take into account gravitational differentiation along the migration routes of migrating particles such as atoms, ions and various complex compounds.

From this point of view it is necessary to emphasize the special role of compounds, including various complex radicals as well as silicon-oxygen and aluminium-oxygen complexes, which could exist and migrate. These are usually composed of a central atom of amphoteric element or complex-forming metal, surrounded by ligands, represented by oxygen, fluorine, sulphur or carbonate, sometimes forming a rather complicated particle. The specific role of these complexes is the formation of comparatively stable migrating compounds in which a heavy atom of amphoteric element or complex-forming metal is tied up with four or more large light atoms or ligands, creating a mobile complex ion with a comparatively high specific volume. In such a complex particle, ions of ligands with a low ionic density act as "lifters" which, under the influence of the Earth's gravity field, direct the migration of heavy metals bonded in complexes to the upper "granitic" layer of the lithosphere.

The significance of this phenomenon can be emphasized by the fact that all chemical elements having the complex-forming properties are probably transported in melts, water, and pneumatolitic solutions as complex compounds.

Specific volumes of ions and atoms can be calculated using simple equations and assuming that electric fields of ions and atoms have approximately spherical forms. To calculate specific volumes for complex ions it is suggested that additive specific ionic volumes of complexes be used.

As a result, chemical elements are divided into five distinct groups according to geochemical associations existing in the Earth's shells. This corraborates the important role of gravity in the differentiation of chemical elements within the crust and upper mantle.

The application of the suggested model allows some important features related to formation of the composition of outer shells of the globe to be explained.

1. Granitization should be considered as one of the most important features leading to the formation of the continental crust. This process develops as a result of the interaction of mantle-derived overheated hydrous solutions, carrying potassium and silica, and the crustal rocks. Large potassium ions ($V^3/M = 0.152$ cm^3/g) and silicon-oxygen complexes ($V^3/M = 0.141$ cm^3/g) should upset the thermodynamic equilibria within the deep mantle levels. This defines a tendency for these components to migrate with hydrous solutions into the outer shells of the lithosphere where, under the influence of these solutions, the granitization process develops at certain thermodynamical levels. Thus formation of the "granitic" layer can be considered to result from the redistribution of alkalic metals, silica, alumina and some other components between the upper mantle and the crust under the influence of the gravity field of the Earth.

2. Accumulation of heavy complex-forming metals (W, Sn, Ta, Nb, Au and others) within the 'granitic' layer of the lithosphere, and their deficiency in rocks of the 'basaltic' layer and mantle, are fully in line with the gravitational properties of the complex particles, such particles being the most probable forms of transportation for these metals in liquid and gaseous phases.

3. Prevailing relative depletion in the upper mantle of alumina in comparison to silica during fractionation of basaltic magmas can be explained by the larger specific volume of the aluminium-oxygen complex (0.174 cm^3/g) due to the Al-O bonds being larger than the Si-O bonds.

4. Relatively high contents of alkali metals (including K), and also of complex-forming rare metals, in the deepest basic (alkali basalts) and utrabasic (kimberlites picrites) melts originating in the mantle suggest that the continuing redistribution of elements upsets the energy equilibria of deep, undepleted parts of the mantle.

TECTONIC DEVELOPMENT OF THE PROTEROZOIC MOUNT ISA INLIER, NORTHWEST QUEENSLAND

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The Mount Isa Inlier consists of four major supercrustal sequences, numerous I-type granitic intrusives, and many mafic dykes and sills, all Proterozoic. The oldest sequence forms the basement for the three younger sequences, which make up the cover. The basement comprises sialic sedimentary and volcanic rocks which were deformed and metamorphosed, in places being partially melted to form migmatites, at around 1900 Ma. Uplift and erosion of this basement was followed by crustal extension, resulting in basin development associated with rifting and perhaps major strike-slip faulting, and the deposition of the cover sequences, which are more than 10 km thick. Deposition took place in an intracratonic setting, well away from a continental margin.

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The cover sequences were first regionally deformed and metamorphosed between about 1620 Ma and 1550 Ma. Two main deformation events, D_1 and D_2, took place during this period. D_1 resulted in the formation of thrust and fold nappes, with movement directions apparently from the west, north and east, towards the centre of the Inlier. During D_2, an east-west shortening event, kilometre-scale tight upright folds formed elongate basins and domes, and several major vertical shear zones were developed. Regional metamorphism up to upper amphibolite facies accompanied the deformation.

Subsequent Proterozoic deformation events, postdating granite emplacement at around 1500 Ma, include the formation of cross-cutting faults and shear zones, some of which have been re-activated at various times during the later Proterozoic and Phanerozoic, and also, at least in the northwest of the Inlier, gentle basin-and-dome folding which affected late Proterozoic sediments that unconformably overlie cover sequence 3, but not overlying Cambrian sediments.

NEW GEODYNAMIC CONCEPTS REGARDING THE CRUSTAL EVOLUTION OF N.E BRAZIL

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The existence of several branched and sinuous vertical shear zones is one of the most striking features of the Precambrian of N.E Brazil. The major ones are transcontinental lithospheric strike-slip faults which partly match with those of West Africa around Benin, Nigeria and Cameroons (1). Rb/Sr dating on syn to late orogenic granitoïds and apparent K/Ar and Rb/Sr mineral ages, which are both in the range of 600-500 Ma, testify that thermo-tectonic events (the Brazilian orogeny) affected the whole of N.E Brazil (2). On the basis of older age determinations, the concept of several successive orogeneses which would have affected this area before the Brazilian cycle has been recently put forward (3). Our petro-structural investigations favour only two stages of crustal evolution, similar to that we have proposed for the Pan-African belt of West Africa (4).

1. Reworked Archaean rocks (mostly grey gneisses of plutonic origin and granitoïds) cover much larger areas than shown on maps. Many plutonic rocks display the features of one single stage of synkinematic recrystallization. Their Rb/Sr W.R systems are in many cases unreset in spite of lower amphibolite facies conditions (i.e the 2.7 GA old Caico Complex) (5), but meaningless younger Rb/Sr W.R ages have also been obtained on migmatized rock assemblages.

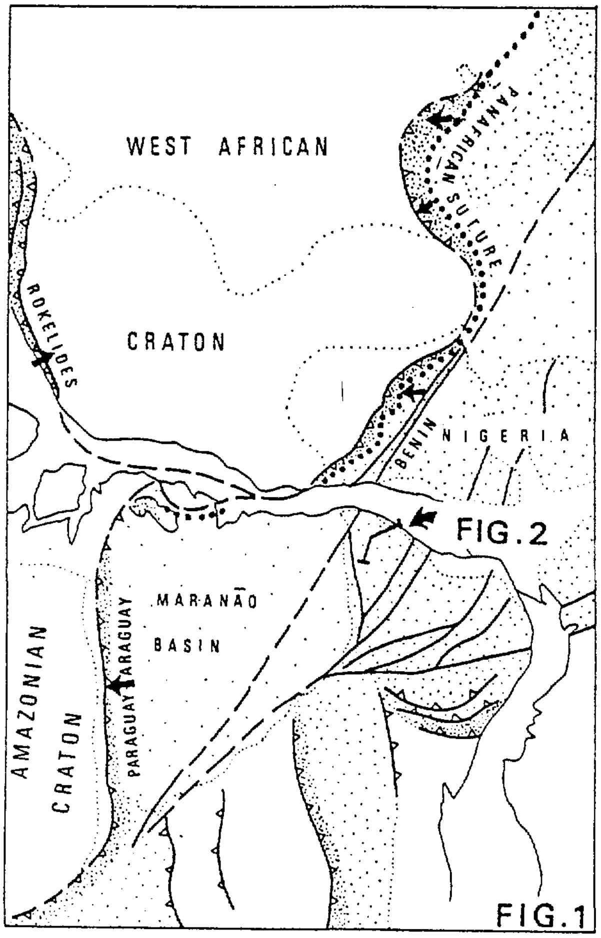

FIG.1

2. Proterozoic metasedimantary units (i.e Ceara, Serido, Cachoerinha, Espinhaço Groups, etc...) share the typical features of monocyclic terranes. They include an older quartzite-carbonate shelf-type unit and thick metapelites of assumed lower Proterozoic age, overlain by younger flysch-type units (3). Since no angular and/or structural unconformity has anywhere been reported in those terranes, and since they progressively grade from a shallow-crustal evolution (open folding asso-

ciated with greenschist facies metamorphism, sedimentary structures often preserved) into mesocrustal conditions (polyphase evolution with Barrovian-type metamorphism followed by higher temperature conditions), we can conclude that they suffered one single main thermotectonic evolution during the Brazilian orogeny. Rb/Sr W.R dates in the range of 2 Ga - 1 Ga obtained on metasediments are not metamorphic ages, whereas similar figures obtained on some interlayered orthogneisses are premetamorphic emplacement ages of pre-kinematic intrusions, often anorogenic in character.

3. Large scale geometry of structures and kinematic criteria are consistent with one single major post-Archean orogenic cycle in N.E Brazil : the Brasilian cycle. Two types of evolution can be recognised:

(a) emplacement of huge crystalline nappes (moving to the W and to the SW in Ceara) : both reworked Archaean thrust onto Proterozoic, and Proterozoic with a Himalayan-type reverse metamorphism thrust onto less reworked Archaean are observed (fig 2) ;

(b) open folding associated with wrench movements in ensialic palaeo-troughs filled up by the younger flysch-type units.

Several sinuous shear zones show a gradual passage from steep structures underlined by retrogressive ultramylonites with overall horizontal stretching lineations, into low angle and flat thrusts, without change in the direction of movement. Thus, the vertical shear zones partly represent lateral ramps of huge nappes in spite of late and post-orogenic vertical reactivations.

In conclusion, the Precambrian crust of N.E Brazil exhibits Himalayan-type features generated by extensive crustal thickening during stacking of both the Archean basement and a tectonic pile of Proterozoic terranes at once deformed and metamorphosed during the Brazilian orogeny. We regard the Paraguay-Araguay belt as the front of the Brazilian belt with large scale overthrusting westward onto the Amazonian Craton : this suggests that the Pan-African suture zone does not run through the Precambrian of N.E Brazil but is most probably hidden below the Maranão basin or north of it (6). The late Precambrian fit between N.E Brazil and Togo-Nigeria-Cameroons does not match accurately : we speculate a large virgation of the frontal zones of the Brazilian/Pan-African belt and its palaeo triple junction with the Rockelides (Fig 2).

FIG.2

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(4) CABY, R., in press. in Anatomy of mountain ranges, SCHAER and RODGERS ed. Princeton Univ. Press.

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STRUCTURE AND STRATIGRAPHY OF THE PROTEROZOIC OF THE OLARY BLOCK, SOUTH AUSTRALIA

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The Olary Block, South Australia, dominantly comprises a sequence of quaratzofeldspathic gneisses which have undergone an amphibolite facies metamorphism (musc-bi-garnet-sill migmatites in places). The gneisses are interlayeread with quartzites, pelites (andalusite ± sillimanite schists) and a conspicuous calc-silicate horizon which represents one of the few reliable marker horizons throughout the block. The rocks are interpreted to represent a Lower Proterozoic sequence which has been deformed and metamorphosed during the Olarian orogeny, occurring between 1850 and 1580 Ma. The gneissic sequence is intruded by later 2 mica and sodic granites and adamellites. Correlation of stratigraphy is made with the Willyama Supergroup of the Broken Hill Block, New South Wales.

The complex outcrop pattern is generated by the superposition of five deformation events (D1-D5) within the Lower Proterozoic sequence. D1 and D2 resulted in penetrative fabrics of amphibolite facies and D3, a retrogressive fabric of greenschist facies. D1 developed visibly recumbent, tight to isoclinal F1 folds with a near flat lying axial planar fabric (S1). The initially north-east to north trending F1 axes have been folded about north-east trending, open to tight F2 folds possessing a near vertical, north dipping axial fabric (S2). S2 is the dominant fabric throughout the area. It can be shown that both D1 and D2 indicate a southeasterly direction of transport on a regional scale. The D3 event includes dissection by retrograde shear zones and minor F3 structures interfering with F2 to produce dome and basin outcrop pattern. Events D4 and D5 produced weakly penetrative fabrics of upper greenschist facies in the unconformably overlying Upper Proterozoic sediments.

DEFORMATION SEQUENCE IN THE RAYNER COMPLEX, MACROBERTSON AND KEMP LAND, EAST ANTARCTICA

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Four structural episodes (D1-D4) are recognised in the gneisses comprising the Proterozoic Rayner Complex on the MacRobertson and Kemp Land coast, East Antarctica. Tectonic fabrics preserve three folding episodes (D1-D3) accompanying transitional granulite facies metamorphism and preceding dissection by amphibolite facies retrograde shear zones (D4). Analysed, the deformation events separate temporally the two prominant gneissic types in the west and east. The western metasedimentary sequence preserves all 4 events but the charnockitic gneisses in the east display effects of only the last 2.

Deformation events are characterised by (i) mesoscopic, recumbent isoclinal F1 folds with a mineral elongation lineation, L1, indicating a westward transport direction, (ii) upright to reclined, open to isoclinal F2 folds with a steep to moderately dipping, east striking axial surface, (iii) upright, open to isoclinal F3 folds with a north striking, steeply east dipping axial surface, S3, containing a steeply plunging mineral elongation lineation, L3, indicating continued westward transport, (iv) retrograde shear zones of upper amphibolite facies and pseudotachylite - ultramylonite zones indicating block movement of south over north.

ACCRETION OF WESTERN AND CENTRAL NORTH AMERICA DURING THE PROTEROZOIC

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Available geological and isotopic data indicate that western and central North America grew during the early and middle Proterozoic by a combination of microplate collisions and arc accretion. Reactivated continental crust is widely distributed as reflected by the distribution of K-Ar and Rb-Sr mineral and whole-rock dates. These dates record regional metamorphism (± deformation) at 1800-1850, 1600-1700, 1400-1500, and 1000-1200 Ma. With exception of the Wyoming shear zone, collisional sutures are not preserved or not exposed. Proterozoic arc systems exhibit dominantly northeastern strikes while the trends of cratonic rifts range from north (or northwest) prior to 1600 Ma, to dominantly northeast at 1350-1500 Ma. Late Proterozoic rifts (1000-1200 Ma) exhibit variable trends. Sm-Nd isotopic data reflect maximum growth of the North American continent in the late Archean. Most of southwestern and south-central North America appear to have been extracted from the mantle between 1700 and 2000 Ma.

The following is a summary of the major events in the accretional history of western and central North America between 2400 and 1000 Ma.

1) 2400-1900 Ma. Uplift and stabilization of the Archean continent led to deposition of thick successions cratonic sediments along the southern margin of the Superior-Wyoming craton. The Animikie Basin in Minnesota may reflect a proto-rift system.

2) 1900-1800 Ma. At about 1900 Ma, the Archean crust rifts apart along a zone extending from northern Manitoba to South Dakota producing a small ocean basin in central Canada. Cratonic sediments are deposited along the margins of the rift zone and the small ocean basin closes along two marginal subduction zones between 1860 and 1820 Ma. At 1900 Ma, a segment of Archean crust is rifted away from the Superior Province in northern Wisconsin. A southward-dipping subduction zone develops beneath the rifted crust and the crust closes against the Superior Province producing the Penokean orogeny (1860-1820 Ma). Alternately, a microcontinent may have collided with the Superior Province at this time.

3) 1800-1750 Ma. A foreign arc system with a south-dipping subduction zone along its northern margin collides with North America. The arc is added to North America along a boundary extending from southeastern South Dakota to eastern Nevada. Arc volcanic and plutonic rocks are exposed in southeastern Wyoming, northern Colorado, and western Arizona. Cratonic rifting in southern Wisconsin and adjacent areas at 1760 Ma is accompanied by widespread eruption of rhyolites.

4) 1750-1700 Ma. The subduction system is relocated along the newly formed continental margin extending from southern Arizona northeastward through central Colorado into Nebraska. Bimodal volcanic arcs are accreted to the continent as the convergent margin migrates southeastward to line extending from west Texas to eastern Illinois. Continental back-arc basin successions formed at this time are exposed in central Colorado.

5) 1700-1650 Ma. The northeast-trending subduction zone contracts, extending only from north Texas to eastern Illinois, and major arc-related granitic plutons are emplaced in Colorado (Boulder Creek type) and adjacent areas. Rifting occurs in southern Arizona (1700 Ma) and central New Mexico (1650 Ma) where bimodal volcanic-arkose-conglomerate successions are deposited.

6) 1650-1600 Ma. Widespread stabilization of the continental crust, extending from Wisconsin to Arizona, is recorded by deposition of cratonic, quartzite-dominated sediments. Facies changes in these sediments reflect a continental margin trending northeasternly from west Texas to Michigan. Diminishing arc activity is restricted to the continental margin in central Kansas. Collision of a microcontinent occurs along the southeastern continental margin at about 1630 Ma. This results in widespread deformation and metamorphism of the cratonic sediments as well as localized reversal of source areas.

7) 1600-1500 Ma. Renewed northwest-trending rifting in the central Dakotas propogates into Nebraska and Missouri, as reflected by geophysical anomalies today.

8) 1500-1350 Ma. Widespread anorogenic granitic plutonism and minor rhyolitic volcanism occur in a belt extending from southern California to Labrador (1500-1400 Ma). Northeast-trending rifting may have accompanied the anorogenic plutonism. Deposition of the Belt Series occurs in cratonic and rift basins in western Montana and Alberta. Terminal anorogenic plutonism (1350-1400 Ma) is largely confined to Oklahoma and parts of adjacent states.

9) 1350-1000 Ma. Widespread abortive rifting occurs in the Great Lakes area extending southward as far as Alabama (1000-1200 Ma). Basalts and arkosic sediments dominate in the rifts as exemplified by the Keweenawan rift succession exposed around western Lake Superior. Rifting also occurs in southeastern New Mexico, west Texas, northern and southern Arizona, eastern California, and other areas along the western margin of the continent (1000 Ma). These latter rifts are filled chiefly with sediments. An arc collides with the southern margins of the continent extending from northern Mexico to northern Louisiana and perhaps farther east (1100-1200 Ma). Volcanic and plutonic remnants of this arc are exposed in the Llano area of central Texas.

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Platform. Its tectonic evolutionary characteristics and stages are very similar to those of the abovementioned intracontinental basin. But a failed arm of a triple rift system was developed and filled with subalkaline and calc-alkaline volcanics during the first stage of middle Proterozoic. Another continental marginal basin elongated in E-W direction, occurring in the northern border of the platform, in which such a sequence of flysch association and carbonates as well as intercalated with volcanics in complicate composition was properly accumulated in the middle Proterozoic. Subsequently, only smaller basins were preserved at the late Proterozoic.

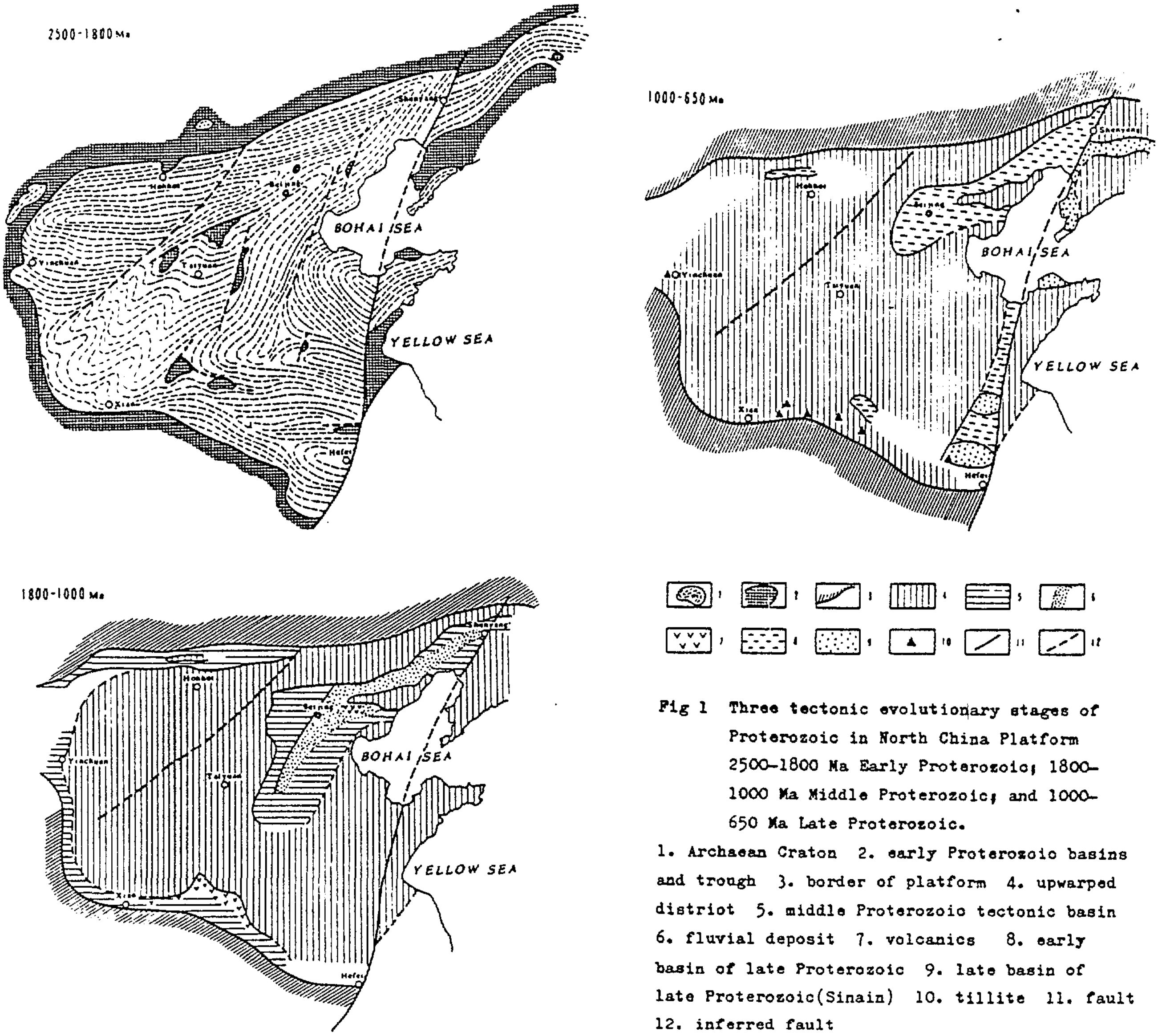

Fig 1 Three tectonic evolutionary stages of Proterozoic in North China Platform 2500–1800 Ma Early Proterozoic; 1800–1000 Ma Middle Proterozoic; and 1000–650 Ma Late Proterozoic.

1. Archaean Craton 2. early Proterozoic basins and trough 3. border of platform 4. upwarped district 5. middle Proterozoic tectonic basin 6. fluvial deposit 7. volcanics 8. early basin of late Proterozoic 9. late basin of late Proterozoic(Sinain) 10. tillite 11. fault 12. inferred fault

Tectonic stages	Tectogenesis	Lithology	Tectonic environment	Magmatism
Palaeozoic platform		shale, limestone	transgression sea	
Late Proterozoic platform (650–1000 Ma)	Jixianian (800 Ma?)	predominant carbonates	intracontinental taphregenic basins	anorthosite (750 Ma)
		littoral sandstone shale and neritic limestone		
Middle Proterozoic platform (1000–1800 Ma)	(Qinyu uplift) (1000 Ma)	epeiric carbonates predominant dolomite	intra-& inter continental tectonic basins	basic dyke swarm (1200 Ma)
	(Qinglong uplift) (1600 Ma)	littoral-neritic shale & dolostone potassic volcanics ortho-quartz sandstone fluvial deposits		
Early Proterozoic proto-platform (2500–1800 Ma)	Lüliangian (Zhongtiao-an) (1800 Ma)	dolomite, slate metaarkose and minor basic lava	(terminal cratonization) intracratonic sedimentary basins	granite (~ 1800 Ma)
	Wutai-an (2300 Ma)	phyllite and meta-silt (turbidite) chlorite schist, BIF, amphibolite, mica schist	ensialic volcano-sedimentary basins & troughs	granite & minor TTG (2200–2300 Ma)
Archaean craton (> 2500 Ma)	Fupingian (2500 Ma)	high grade metamorphic rocks	(primary cratonization)	granite & TTG (2500 Ma)

Fig 2 Major events of Proterozoic in North China platform

THE STRUCTURE OF THE BUSHVELD COMPLEX, SOUTH AFRICA AS DERIVED FROM GEOELECTRICAL SOUNDING DATA

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The structure of the Bushveld Complex (Fig. 1) was studied by means of deep Schlumberger soundings.

The Bushveld Complex consists of a large array of plutonic to volcanic igneous rocks of Proterozoic age ranging in composition from ultramafic to acid and it underlies an area of approximately 65 000 km^2 in the Central Transvaal, South Africa. It is not only the largest known intrusion of its kind, but also unique because of its diverse suite of economically important ores and the regularity and persistence of the layering in the basic and ultrabasic rocks. The layered nature of the complex and the generally low dip angles of the layers (10-25°) makes it an ideal target for investigation by deep Schlumberger soundings. Gravity data (Cousins, 1959) demonstrated that the Bushveld Complex is not a simple lopolith and the main complex is now regarded as consisting of four lobes, a western, a northern, an eastern and a southeastern compartment (Fig. 1). The complex is intruded into the Early Proterozoic Pretoria Group that occurs in a basin in the Archaean Kaapvaal Craton.

Up to the end of 1984 more than 120 electrical soundings with maximum current electrode spacings of up to 60 km were carried out on outcrops of the different lithological units of the Bushveld Complex and the Pretoria Group. From these soundings the resistivity distribution within the sedimentary strata and the different units of the layered complex could be established (Table 1). The Pretoria Group contains an excellent marker horizon in the form of a very conductive shale. A second geoelectrical marker horizon, namely a cyclic magnetite and gabbro assemblage near the top of the layered mafic complex has been identified in this otherwise resistive environment. With the aid of these marker horizons maximum thicknesses could be established for the different geological units. The interpretation of the geoelectrical results for the two main bodies of acid rocks in the complex shows that the granitic rocks have a maximum thickness of less than 2.7 km in the eastern lobe and less than 4 km in the western lobe. This agrees well with gravity models (e.g. Molyneux and Klinkert, 1979; Hattingh, 1980). The geophysical determined maximum thickness for the mafic sequence are markedly thinner than the geologically estimated average thickness for the eastern, western and northern sequences of 8000 ± 750 m (Vermaak and Lee, 1981).

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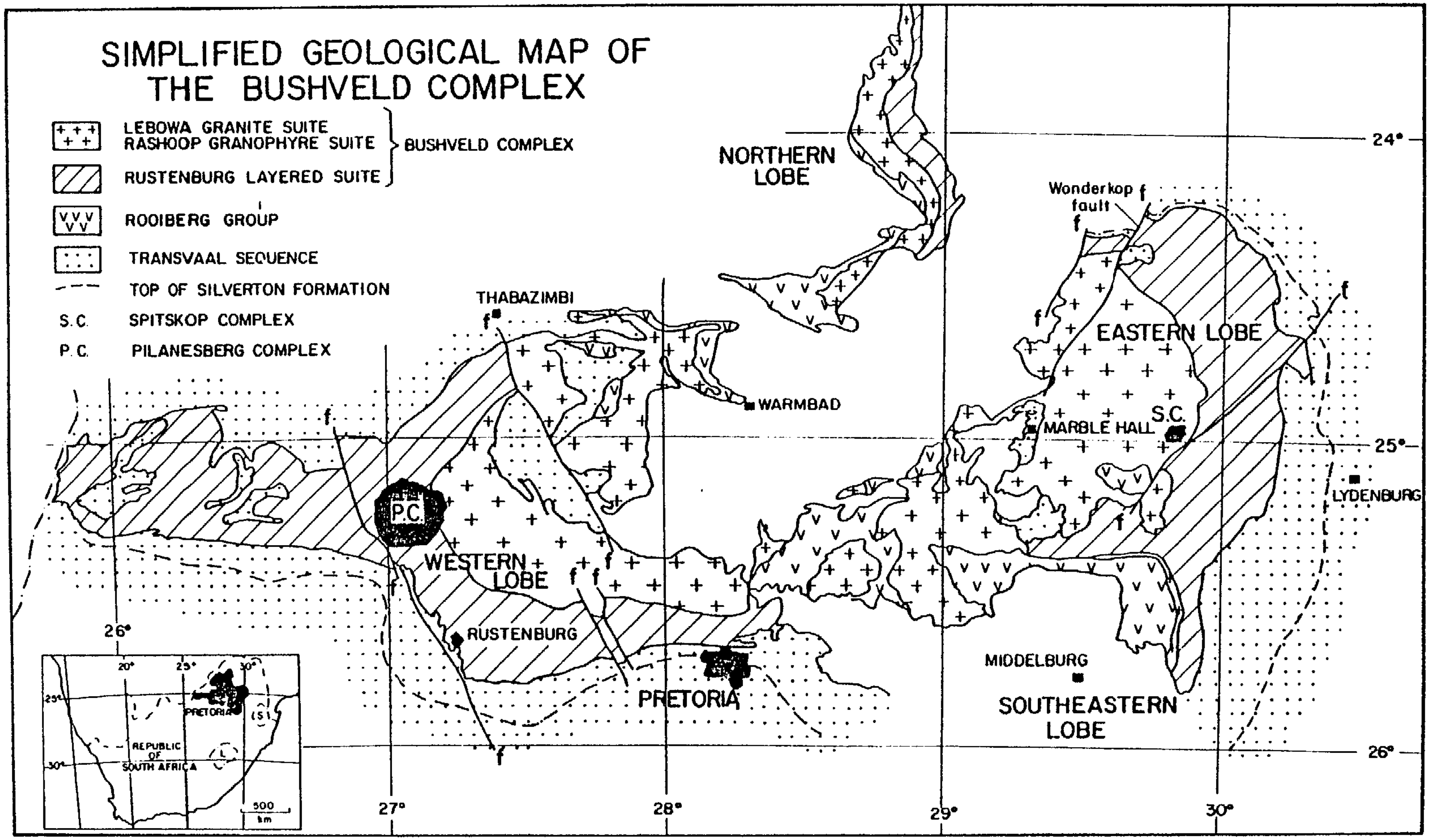

Fig. 1. Simplified geological map of the Bushveld Complex showing only the major geological subdivisions of the Complex.

TABLE 1. Simplified stratigraphic column for the Bushveld Complex with associated electrical resistivities

Geology		Resistivity (ohm.m)
Lebowa Granite Suite	Nebo granite (East)	6 000-40 000
	(West)	3 500-15 000
Rashoop Granophyre Suite		5 000-15 000
Rustenburg Layered Suite	Upper Zone	100-800
	Main Zone	>8 000
	Critical Zone	1 000-2 000
	Lower Zone	
	Marginal Zone	
Rooiberg Group		1 500-2 000
Pretoria Group	Dullstroom Basalt Formation (only Eastern Transvaal)	5 000-15 000
	Several formations comprising quartzites, shales and hornfels (in Central and Eastern Transvaal only)	
	Magaliesberg Quartzite Formation	∿10 000
	Silverton Shale Formation	200-3 000
	Graphitic Shale Member	<10

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STRATIFORM POLYMETALLIC ORE ENVIRONMENT - ASHBURTON BASIN, W.A.

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The Ashburton Basin is an intercratonic Lower to Mid-Proterozoic sedimentary basin which occupies the area between the Pilbara and Yilgarn Archaean cratons and probably extends also along the eastern margin of the former. Terrigenous clastic and carbonate facies outline the margins of the basin where these are not obscured by younger cover rocks. Monotonous sequences of turbiditic shales and greywackes occupy the central part of the basin, which is characterized also by the presence of a definite gravity ridge. Seismic data also suggest the presence of a dense "SIMATIC" crustal layer beneath the axial trough of the basin. It is likely that the rapid isostatic subsidence of this crustal inhomogeneity initiated this marine basin during deposition of the Fortescue Group.

The gentle curve of the southern margin of the Pilbara Craton is interrupted by the projection of an east-west trending basement ridge, (the Wyloo-Rocklea Anticline) into the north-western part of the Ashburton Basin. Repeated tectonic activation of this basement structure is attested by the history of sedimentation in the adjacent part of the basin. A significant major compressional folding episode (the Opthalmian Fold Period) occurred towards the end of Lower Proterozoic time, resulting in the formation of a series of fold structures whose axes parallel the Pilbara cratonic margin. This tectonic event was accompanied and outlived by a regionally extensive igneous event which has been designated the Boolaloo-June Hill igneous episode, dated at around 1720 Ma.

Tuffaceous and volcaniclastic sediments related to the June Hill volcanics appear to both underlie unconformably and interdigitate with the characteristic sediments of the Mt Stuart Formation. The latter include manganiferous chert, iron formation, dolomitic rocks, and sulphides in presumed sub-basins, whereas dolomite and clastic sediments, both of which may be manganiferous, occur where the basin shoals. Several stratiform polymetallic sulphide bodies have developed within the Mt Stuart Formation, but none yet known is of sufficient size or grade to constitute an orebody. Detailed evaluation of several of these prospects reveals that they possess geological attributes in common with many of the major sediment-hosted stratiform sulphide ore bodies in the world.

It is apparent therefore, that the tectono-sedimentary framework within the Ashburton Basin has provided the geological conditions in which stratiform polymetallic sulphide orebodies of significant dimensions could be expected to accumulate.

TECTONIC PROCESS IN THE EARLY TO MIDDLE PROTEROZOIC OF NORTHERN AUSTRALIA

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The exposed Early to Middle Proterozoic domains of northern Australia display an areally extensive, ensialic type of orogeny. As such, it differs significantly from the time-transgressive, lateral accretion models of modern orogeny, and may be specific to this period of the Earth's evolution. In this paper, we present a model of Proterozoic basin evolution, magmatism and orogeny that involves vertical accretion, both by underplating and overplating, during discrete, areally extensive events related to continent-wide or even global mantle processes. The similarity of process and timing between terranes is a key part of the model.

CHRONOTECTONIC FRAMEWORK

It is now well established that a major tectono-thermal episode occurred around 1800 Ma. There is a wide spread of isotopic "ages" which purport to date this episode in the north Australian terrane (1920-1730 Ma). However, the chronological framework for this time period has been substantially refined in the last 10 years, particularly by the application of the zircon U/Pb technique (Page, et al, 1984). A striking result of this refinement is that a widespread orogenic event is now constrained between about 1850 and 1880 Ma over much of northern Australia. This orogeny was marked, especially at its close, by a distinctive felsic igneous event of large magnitude and remarkably consistent chemistry, which has been recognized in the Halls Creek, Pine Creek, Arunta, Tennant Creek, Gawler and Mt Isa provinces. Thus, a major orogenic/magmatic event affected virtually all of the Early Proterozoic domains of Australia within a period of 30-60 Ma. This event separates two sedimentary cycles corresponding broadly to the Nullaginian and Carpentarian of Dunn et al (1966). The younger of these two cycles was variably deformed and metamorphosed between about 1650 and 1550 Ma.

TECTONOSTRATIGRAPHIC HISTORY

The first of the two sedimentary cycles is divided into three sequences of differing tectonostratigraphic character.

1.) A lower clastic sequence, quartz-rich and commonly demonstrably fluviatile, containing more or less extensive bimodal vulcanism. This sequence probably represents an initial phase of crustal extension.

2.) A middle, finer grained clastic sequence, commonly carbonaceous, and with abundant carbonates and some iron formations. This apparently represents post-extension thermal subsidence, and is of wide lateral extent.

3.) An upper turbidite or molasse facies, which may mark the beginning of the orogenic phase.

The second cycle is much more variable in character, thickness and extent, but it too commonly begins with a typical rift or extensional phase, followed by more uniform sequences typical of progressive, gradual subsidence

IGNEOUS HISTORY AND GEOCHEMISTRY

There are significant differences between the igneous rocks of the two cycles. In the older cycle, mafic compositions tend to dominate throughout the sequence, except near the base, where felsic volcanics are abundant locally. In the younger cycle mafic volcanic rocks are concentrated in the lower part while felsic rocks, most of which are anorogenic, occur throughout. Layered mafic complexes appear to be restricted to the older cycle. Throughout the Early to Middle Proterozoic, igneous compositions are bimodal, with SiO_2 contents between 56 and 63% rare. The igenous rocks associated with the orogenic event that separates the two cycles are dominantly felsic, and form a compositionally distinctive suite outcropping over 30,000 sq km. They are almost exclusively I-type, with high LIL and LREE concentrations and low MgO, CaO, Ni, and Cr relative to Phanerozoic and many Archean granitoids. They also have high Rb/Sr ratios and low initial $^{87}Sr/^{86}Sr$, implying a short pre-history, with a mantle source age of 2300 to 2000 Ma. These granitoids provide a mechanism for substantially enriching the upper crust in K, Th, U, Sn and possibly W.

The anorogenic felsic intrusives and extrusives of the younger cycle are also largely I-type, but can be distinguished from the orogenic rocks on the basis of higher K_2O, TiO_2, Th, U, Zr, Nb, Y, La and Ce contents. Some suites can be interpreted as A-types from the same source as the orogenic suite, but others were apparently derived from a younger underplated source.

DEFORMATIONAL STYLE

In northern Australia, the older cycle is everywhere at least moderately deformed, with a structural style and history that is consistent in all provinces. An early nappe-style event was followed by a regionally developed upright fold episode that dominates most of the published map patterns. Sub-vertical shear zones, commonly in several strike sets with steep movement directions, may be superimposed on the folded terranes. These zones may have a long history of reactivation. Where the younger sequence is deformed, a very similar style sequence is observed. However, in neither sequence do the nappe events produce widespread inversions of facing, and stratigraphic duplications are limited in thickness. Basement involvement in the thrusting is also rarely documented. Further, in spite of the shortening apparently associated with the upright folding, there is little evidence of substantial crustal thickening or of the consequential uplift and erosion in any of the terranes.

METAMORPHISM AND P-T-t PATHS

The high pressure metamorphism and paired metamorphic belts characteristic of modern orogenesis are absent in these Early to Middle Proterozoic terranes. Peak metamorphic grade commonly occurred during or prior to the main upright folding episode. Most importantly, this peak is commonly followed by a period of isobaric cooling, giving rise to a P-T-t path that is quite different from that typical of modern collisional orogens. It is incompatible with rapid crustal thickening and consequent isostatic uplift. The widespread andalusite and sillimanite-bearing assemblages suggest heating by addition of mantle-derived melts to the lower crust.

A MODEL

The main elements of a distinctive tectonic model for the Early to Middle Proterozoic based on northern Australian examples are:

- Two cycles of crustal (?lithospheric) stretching and consequent basin formation are separated by a major orogenic/magmatic event. The timing and character of these events are remarkably similar across northern Australia, and even in other continents. In some terranes, a very short time interval (20 Ma) was available for several episodes of deformation, synorogenic sedimentation, orogenic magmatism uplift, erosion, prior to the initiation of second cycle extension.

- The lithospheric stretching and the substantial mantle-derived magmatism throughout this period are attributed to small-scale mantle convection that began about 2300 to 2000 Ma. The pattern of Proterozoic mobile belts around Archean nuclei is considered to be related to the pattern of mantle convection.

- Initially, the bulk of the mantle melt was underplated at the base of the crust, only reaching the surface in limited quantities as first cycle extension began. Underplating would have been restricted to the regions above upwelling mantle that then evolved into Early Proterozoic rifts and basins. The mafic material underplated at about 2000 Ma formed the source for the extensive felsic magmatism from 1900 to 1750 Ma. In particular it formed a uniform source for the widespread and voluminous granitoids and volcanics of the distinctive and homogeneous 1880 to 1820 Ma event.

- There is no evidence that crust of modern oceanic character was formed during either extensional event. The style of sedimentation is consistent with basin formation by limited (50 to 100%) stretching of a pre-existing continental lithosphere, followed by thermal subsidence, analogous to that envisaged for a number of modern ensialic basins (e.g., North Sea, Aegean Sea, Bass Basin). Likewise, there is no evidence for subduction and island arc-style magmatism.

- The contemporaneous and widespread onset of orogenesis throughout the widely dispersed basins of the first cycle contrasts with the progressive lateral accretion of terrane typical of younger tectonism. The orogeny was characterized by high heat flow and absence of evidence for substantial crustal thickening.

- The second basin-forming cycle was initiated immediately after the orogeny by a further phase of stretching and rifting. The distribution of second cycle terranes is less regular, although they are apparently generally developed on a first-cycle basement, commonly where the basement is at higher metamorphic grade. Much of the middle Proterozoic platform cover of northern Australia was deposited in basins that apparently developed as a result of thermal subsidence following rifting.

- Broadly, this tectonic model involves vertical accretion of mantle-derived material to the crust, rather than the lateral accretion typical of modern orogeny. The crust beneath Early to Middle Proterozoic provinces comprises 1) an upper layer of Proterozoic rocks of one or both cycles, 2) a fairly thin upper to middle crustal layer of stretched Archean protolith, and 3) a substantially mafic lower crustal layer largely underplated between about 2000 Ma and 1800 Ma.

- The average crustal composition beneath the Proterozoic provinces therefore underwent substantial change between about 2000 Ma and 1800 Ma, as a result of massive underplating. Fractionation of this underplated material to the upper crust by partial melting during basin formation and orogenesis gave rise to an upper crust of quite different chemical character to its Archean basement and hinterland. In particular, there is little evidence for significant reworking by igneous processes of the Archean into the Early to Middle Proterozoic terranes, although such reworking has occurred through the processes of erosion and sedimentation.

TECTONIC INTERPRETATION OF THE MARGIN OF THE EARLY PROTEROZOIC SOUTHERN LITCHFIELD PROVINCE, NORTHERN TERRITORY OF AUSTRALIA

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The southern part of the Litchfield Province represents the northern extension of the Halls Creek Mobile Zone of Western Australia and the Northern Territory. This Early to Late Proterozoic mobile belt flanks the western part of the Pine Creek Geosyncline and is an important tectonic zone along which low to high-grade polymetamorphism, multiple deformation, and faulting occurred between 1920 and 700 Ma. Orientation of the faults and their locally-known slip-sense suggests strike-slip movement within the mobile zone.

Of critical importance to the interpretation of the southern Litchfield Province is the region of the dextrally-sigmoidal Wingate Bend in the Giants Reef Fault. Here are exposed both low-grade to amphibolite/granulite facies metasediments and metabasites (Hermit Creek Metamorphics), which form the basement, and a younger sub-greenschist to greenschist facies sequence (Finniss River Group) which in its western outcrops overlays the basement unconformably.

The Finniss River Group is a proximal submarine-fan sequence, consisting of greywacke sandstone and slate (Burrell Creek Formation), grading westward and upwards through upper/supra-fan fine sandstones, siltstones, and conglomerates, to fluvial to shallow marine white quartzite and quartzitic grits (Chilling Sandstone). The base of the group contains rhyolitic to dacitic extrusives. The westernmost unit is the fanglomeratic Henschke Breccia which rests unconformably on slates of the Hermit Creek Metamorphics. Both Henschke Breccia and the upper to supra-fan conglomerates contain considerable quantities of angular to sub-angular vein quartz clasts; other clasts include schistose greywacke sandstones and slates (?Hermit Creek Metamorphics), acid volcanics, cleaved white quartzites, and very rare cherts. Regional deformation and metamorphism of the Finniss River Group occurred during the Pine Creek Orogeny (1870-?1800 Ma). In the later stages of the orogeny, the Hermit Creek Metamorphics and deformed Finniss River Group were intruded by the Murra-Kamangee granodiorite batholith at 1850-40 Ma before their uplift and erosion. Deposition of the Middle Proterozoic Tolmer and Fitzmaurice Groups followed.

In the Wingate Bend, differing deformational styles distinguish two structural domains (eastern and western) in the Finniss River Group. In the eastern domain, folds trend north, are tight to isoclinal, upright to slightly overturned, and in slates and sandstones display an axial plane cleavage; the folded quartzite of the Chilling

Sandstone have shattered rather than producing an axial plane cleavage. Fold axes range in plunge from 60° northwards, through subhorizontal, to 60° southwards in a uniform steeply-dipping axial plane. These folds are flexed into a broad, sinistrally sigmoidal bend, and have been truncated by the last, dextral (6-10 km) movement on the Giants Reef Fault.

In the western domain, folds appear restricted to the region adjacent to the NE-SW trending section of the Giants Reef Fault. They plunge moderately to steeply, trend east to northeast, are overturned slightly to the northwest and are associated with north-east trending faults. South of the folded and faulted zone Chilling Sandstone dips southeast at 25-50° and youngs southeast below the Cretaceous cover.

The boundary between the two domains follows approximately the alignment of the northern arm of the Giants Reef Fault, and the eastward sedimentary facies change from shelf to deep-marine sedimentation in the Finniss River Group. It is proposed that this domain boundary follows more-or-less a fundamental crustal feature that controlled depostion and deformation of the Finniss River Group.

West of the boundary lay continental basement (Hermit Creek Metamorphics) which received the fanglomeratic Henschke Breccia and the supra-fan conglomerates; east of the boundary lay a marine basin which received principally the flyschoid Burrell Creek Formation. Chilling Sandstone represents the closing, transgressive phase of sedimentation, eventually overstepping the continental margin.

Two explanations are proposed for the changes in deformational style (Case 1 and Case 2, see Table below).

CASE ONE	CASE TWO
Compression normal to continental margin deforms the Finniss River Group producing tight, north-trending folds in the eastern domain (marine basin) and an open, north-east trending structure in the western domain (continental shelf)	Sinistral transpression along continental margin folds Finniss River Group (east and west domains) about NE-SW axes. Continued sinistral transpression against continental block rotates NE-trending folds (eastern domain) to northerly trend and fold axes to variable plunges. Folds on continental block (western domain) not so rotated. Fold belt in eastern domain locks: transpressive strain concentrated along continental margin leads to formation of Giants Reef Fault and reverse faulting in Wingate Bend.
Later dextral displacement along the Giants Reef Fault System produces north-east trending drag folds in the western domain, buckling in the eastern domain which rotates fold axes to variable north-south plunges, and, locally, north-east trending folds in the Tolmer Group.	Later dextral displacement along Giants Reef Fault.

THE BARRO ALTO COMPLEX OF CENTRAL BRAZIL

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The Barro Alto Complex comprises a highly deformed and metamorphosed association of early to Middle Proterozoic plutonic, volcanic, and sedimentary rocks and it is not identical or equivalent to the Bushweld complex of South Africa as it has been reported elsewhere. It display a 150 x 25 Km boomerang-like shape strip that forms the southernmost tip of an extensive yet discontinuous belt of granulite and amphibolite facies metamorphic rocks including the Niquelândia and CanaBrava Complexes. At its eastern and southern borders, the complex is thrusted over coarse-grained granodiorite to tonalite gneisses of the Archaean basement. At the western and northern borders, it is tectonically overlain by low-grade metasediments of the Middle to Late Proterozoic Araxá Group.

Recent detailed mapping (Fuck et al. 1981; Danni et al. 1984) has lead to the division of the complex in two rather distinct units: Granulite facies rocks form the eastern and southern portion whereas amphibolite to greenschist facies rocks overthrusting the former appear in the western and northern portion.

The granulite belt comprises several petrographic types. Mafic rocks (pyriclasites) composed of plagioclase, hypersthene, salitic clinopyroxene, minor hornblende, biotite and garnet, occasional quartz, and ilmenite, pyrrhotite, zircon, rutite, and apatite as accessory minerals, make up the better part of the belt. They locally contain small lenses of websterite, olivine pyroxenite, and peridotite. More differentiated rock types are represented by gneissic hypersthene bearing quartz diorite. The texture is granoblastic to cataclastic; pseudo tachyllites are locally developed. Foliation, composite layering, and mineral lineation are widspread. Large deformed orthopyroxe porphyroclasts rich in exsollution lamellae and complexly twinned plagioclase crystals represent igneous relics. Igneous textures may be locally well preserved. Textures and field relations provide evidence that these rocks are of plutonic origin. Chemically they display a tholeiitic trend of iron enrichment, and normatively they are quartz and olivine tholeiites. K_2O contents of the more mafic rocks are rather low, whereas Rb and Sr are high. The K/Rb ratio is unusually low.

Ultramafic rocks form a large band some 20 Km long and 2 Km wide representing a tectonic slice interthrusted between the mafic granulites and the overlying amphibolite and meta-anorthosite unit in the Barro Alto area. It comprises dominantly serpentinized harzburgite (olivine, enstatite, spinel), locally interlayred with minor dunite and orthopyroxenite, to which an important lateritic nickel deposit and a small chrysotile asbesto deposit are associated.

High-grade supracrustal rocks are widespread within the granulite belt, particularly in the western portion between Ceres and Goianésia. In the field there is a conformable intercalated sequence of fine-grained mafic granulite, hypersthene-quartz-feldspar granulite, garnet quartzite, sillimanite-garnet leptinite, sillimanite-cordierite gneis, minor calc-silicate rock and magnetite-rick iron formation. The mafic rocks are dominant within the sequence, but they are not easily distinguishable from the above described pyriclasites of plutonic origin, unless the mentioned intercalations are present. The fine-grained mafic granulites are presumed to have been basic volcanic rocks whilst at least part of the felsic rocks may represent acid volcanics. Therefore the supracrustal volcanic-sedimentary sequence includes a bimodal volcanic suite. In many places fragments of these supracrustal form abundant xenoliths within the granulites of plutonic origin, which therefore are intrusive into a roof of older supracrustal material. The mafic metavolcanics display a tholeiitic trend. Normatively they are olivine and quartz tholeiites. K_2O is usually low and the K/Rb ratio is also very low. Minor and trace elements relations bear similarities to those of oceanic basalts. The felsic granulites are acid rocks with more than 65% SiO_2 and a high K/Na ratio. The trace elements show considerable dispersion but Ba, Zr and Rb are consistently high. Sr is low in some samples. The K/Rb ratio is similar to that of the normal crust.

Retrogressive amphibolite facies are common near the contact with the overlying amphibolite units. Hornblende, biotite, garnet, epidote, and more sodic plagioclase are the main phases. Lower grade paragenesis are developed along shear zones; they comprise variable amounts of actinolite, chlorite, carbonate, clinozoisite, white mica and albite.

The upper unit of the complex comprises both layered mafic rocks and a volcanic-sedimentary sequence that are deformed and recrystallized under amphibolite to greenschist facies conditions. The layred rocks form dome-like structures with troctolite and anorthosite occupying the central parts whereas gabbros are exposed in the outer zones. The gabbros are nearly always deformed and recrystallized into coarse-grained banded amphibolites. They show a clear upward gradation to the fine-grained amphibolite through metadolerites with preserved diabasic texture. The finer-grained amphibolites form the basal part of the Juscelância metavolcanic-sedimentary sequence. These amphibolites are interbedded with garnetiferous metachert and display chemical affinities of ocean ridge tholeiite basalts (Danni & Kuyumjian, 1984). Towards the top the metabasalts are interlayred with muscovite-biotite gneiss, which gradually becomes the dominant rock. Some of these display textural features typical of felsic volcanics. Their trend is distinctly calc-alkaline, with over 65% SiO_2 and high contents of Ba, Zr, Rb and Sr. Chemically intermediate terms are lacking: The gneiss unit is followed upwards by a pile of micaschist, minor amphibolite, gneis, iron formation, calc-silicate rock, gondite, and quartzite. Rb-Sr age determinations of the gneisses yield isochrones around 1300 my, with R_o near 0.708.

Granite bodies of unknown age intrude the western tip of the granulite belt to the south of Rubiataba, and the Juscelândia sequence to the north of Goianésia.

The thrusted nature of the contacts of the Barro Alto Complex with the tonalite basement and the presence of thrust-faults separating the different units suggest that thin-skinned tectonics must have played a major role in its geometry.

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GEOCHEMICAL PATTERNS IN A LOWER PROTEROZOIC BASIC GRANULITE - ANATECTIC GNEISS SUITE, SOUTHWESTERN, ARUNTA INLIER, CENTRAL AUSTRALIA: EVIDENCE OF DEEP CRUSTAL PARTIAL MELTING

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Major uplifting of basic granulites and intermediate to felsic charnockites and biotite-hornblende-garnet gneisses along the Redbank-Mt Zeil thrust zone, southwestern part of the Arunta inlier (Fig. 1), allows detailed observations of deep levels of the lower Proterzoic (2.3-1.8 b.y.) crust. The major and trace element geochemistry of a suite of granulite facies tholeiitic basic rocks, including high-Mg basic granulites and swarms of quartz dioritic to adamellitic bands, provides evidence for the nature of infracrustal melting processes and the root zones of granites. The two pyroxene and garnet-two pyroxene plagioclase granulites are akin to continental tholeiitic composition including Fe-rich types (FeO_t~12-14%; Mg'~35-40) in the Mt Chapple massif. These rocks are characterized by high (Ce/Nd)N (~1.3-1.6) and (Nd/Y)N (~1.3-2.0) values, low (Sm/Nd)N values (0.8) and negative Nb and Sr anomalies (Fig. 2a). The high-Mg granulites (~8-15% MgO; Mg'=63-75) of the Mt Hay massif (DHMG) are strongly depleted in LIL (large ion lithophile) elements (K, Rb, Ba, Pb, U, Th) and HFS (high field strength) elements (REE, Ti, P, Zr, Nb, Y), and have high Al_2O_3 (~16-17%), CaO(~12-13%) and Sr (~280-300 ppm) (Fig. 2b). An interpretation of these rocks as residues of partial melting rather than meta-cumulates is favoured by scarcity of monomineralic bands and by textural criteria. Enclaves of high-Mg basic granulite (EHMG) within charnockite gneiss bodies (Mt Chapple and Redbank Hill massifs) have been re-enriched in LIL and HFS elements introduced from intrusive granitic magma, as shown by similar chondrite-normalized distribution patterns of elements in the EHMG enclaves and in enveloping gneisses (Fig. 2C). Comparisons between the DHMG, the EHMG and the gneisses indicates increasing mobility of elements in the order: Sr, Ti, Y, P, Zr, K, Ce, Ba, Th. The involvement of the HFS elements in the depletion/enrichment relations supports an interpretation of their distribution in terms of differential mobility. Mass balance calculation and partial melting models suggest that the Mt Hay gneiss units could form by about 20-27% partial melting of parental Mt Hay type continental tholeiitic basic rocks, but that some of the HFS elements (Ce, La, Zr, Nb, Y) have been removed from the system altogether (Fig. 3). Two types of anorthosites are recognized in the Mt Hay Massif: (1) LIL and HFS element-depleted bytownite anorthosites (Mg'~70) forming a contiguous laminated unit, and (2) anorthositic gabbroic bands (Mg'~40-45) of higher LIL and HFS element abundances. The charnockitic gneisses and biotite-garnet gneisses have low (Ce/Y)N<9.0) relative to average low-Ca and high-Ca granites and Mt Isa type granite (Ce/Y)N~10-11. This renders possible a view of the granulite-facies gneisses as primtive partial melts from which differentiated higher level granites developed by fractional crystallization. If so, the anatectic relations observed in the southwestern part of the Arunta inlier can be tested as a model for the origin of higher level lower Proterozoic granitoids in central Australia, and possibly other sectors of the North Australian Precambrian Shield, in terms of the following stages: I. deep crustal intrusion of and/or underplating by LIL-rich tholeiitic basic magmas and their crystallization under opx-plg to cpx-gnt granulite facies conditions (PT estimates for gnt-cpx-opx assemblages of the Mt Chapple massif yield values in the 680-770°C and 7.3-8.1 kb range); II. remelting of the basic granulites under lower PT conditions in the presence of water (~ 670°C, 5.9 kb), producing quartz dioritic to adamellitic liquids; III. segregation and fractional crystallization of intermediate to felsic magma fractions upon ascent, yielding the larger scale K-rich granitic gneiss stocks of the Mt Chapple, Redbank Hill and Mt Zeil massive. Isotopic data suggest Sm-Nd model ages of 2.19-2.35 b.y. (TNd/DM) or 2.03-2.08 (TNd/CHUR)(Black and McCulloch, 1984) for phase I, and Rb-Sr isochron ages of 1778+/-20 m.y. (Ri = 0.7085) and 1728+/-65 m.y. (Ri = 0.706) (Black et al., 1983) for phases II and III. It is possible, however, that geothermal rises associated with continuous or intermittent subcrustal basaltic accretion resulted in repeated crustal remelting, ensuing in a complex secular succession of anatectic events whose identification requires U-Pb isotopic measurements.

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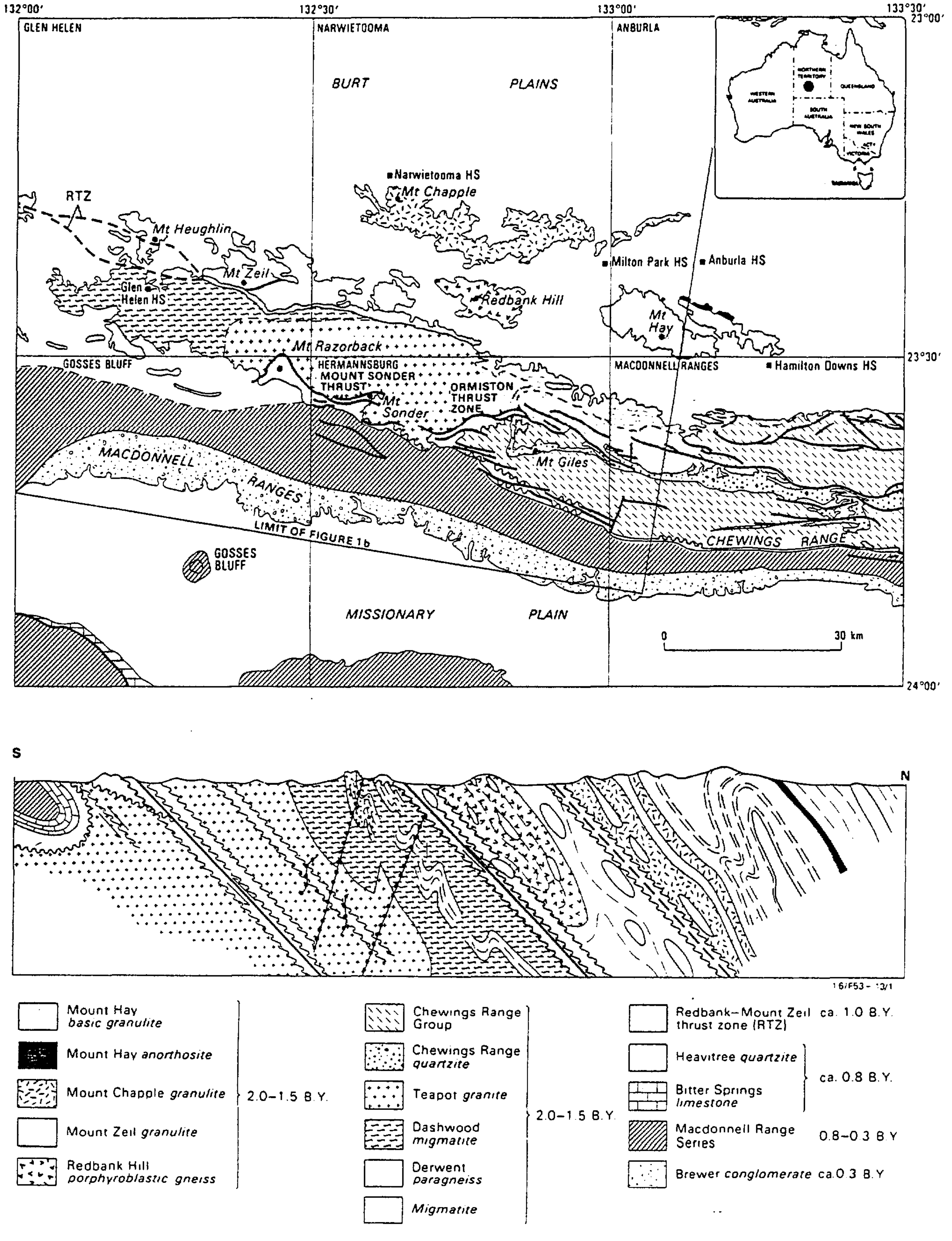
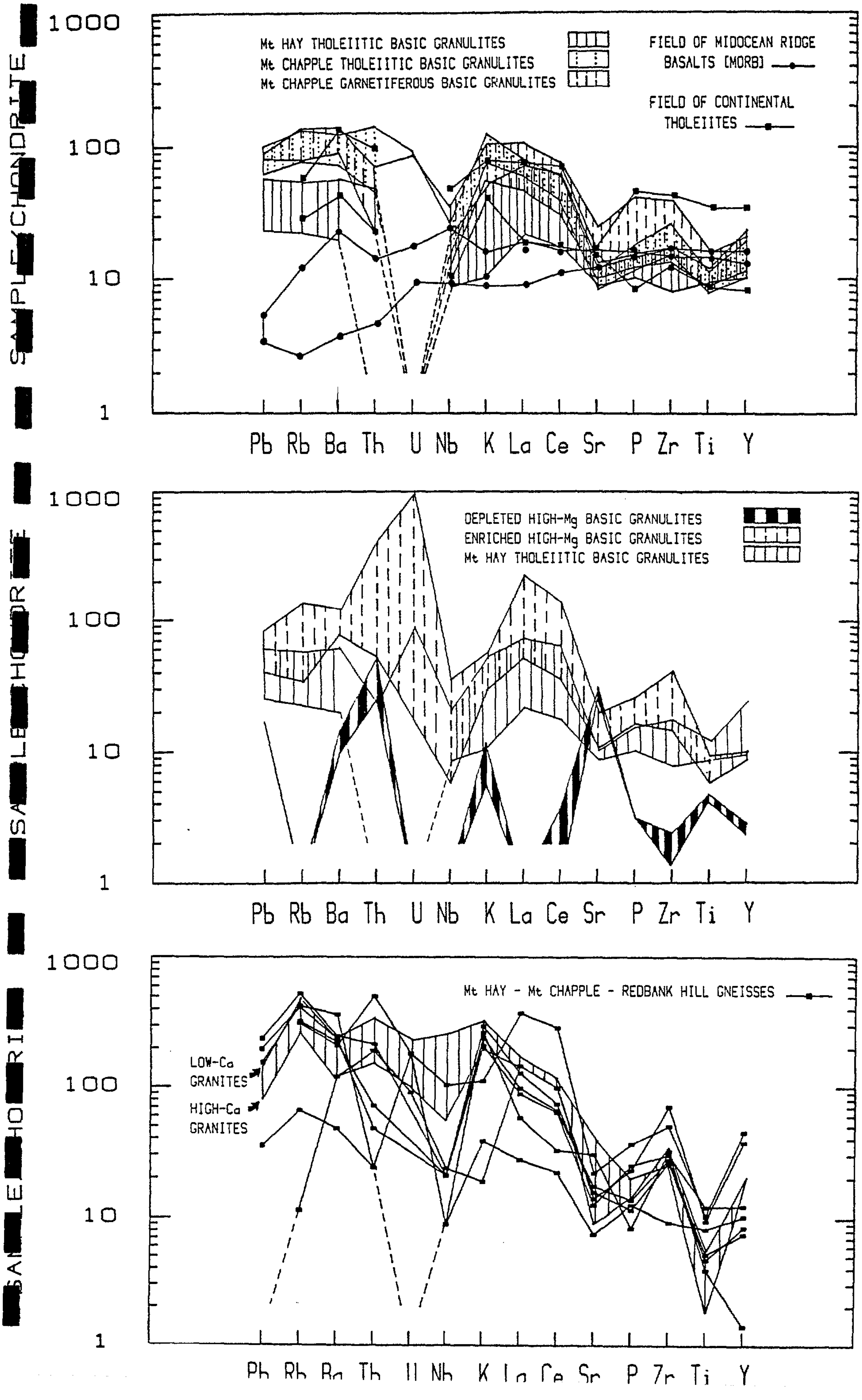
Fig. 1



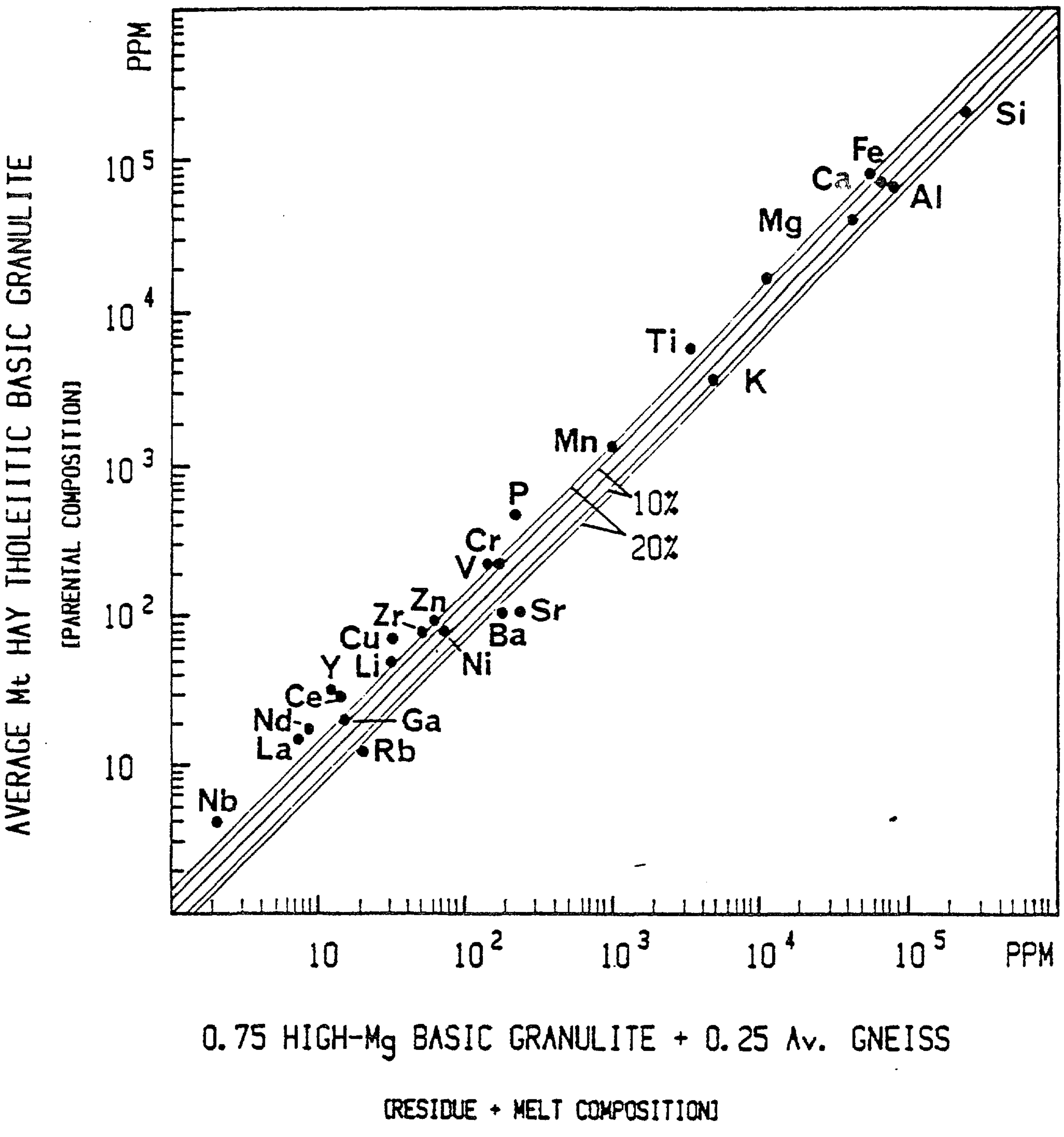
132°00'
132°30'
133°00'
133°30'
23°00'
23°30'
24°00'
GLEN HELEN
NARWIETOOMA
ANBURLA
BURT
PLAINS
Narwietooma HS
Mt Chapple
RTZ
Mt Heughlin
Mt Zeil
Glen Helen HS
Milton Park HS
Anburla HS
Redbank Hill
Mt Hay
Mt Razorback
GOSSES BLUFF
HERMANNSBURG
MOUNT SONDER THRUST
Mt Sonder
ORMISTON THRUST ZONE
MACDONNELL RANGES
Hamilton Downs HS
MACDONNELL RANGES
Mt Giles
CHEWINGS RANGE
LIMIT OF FIGURE 1b
GOSSES BLUFF
MISSIONARY
PLAIN
0
30 km
NORTHERN TERRITORY
WESTERN AUSTRALIA
QUEENSLAND
SOUTH AUSTRALIA
NEW SOUTH WALES
ACT
VICTORIA
TASMANIA
S
N
16/F53-13/1
Mount Hay basic granulite
Mount Hay anorthosite
Mount Chapple granulite
Mount Zeil granulite
Redbank Hill porphyroblastic gneiss
2.0–1.5 B.Y.
Chewings Range Group
Chewings Range quartzite
Teapot granite
Dashwood migmatite
Derwent paragneiss
Migmatite
2.0–1.5 B.Y.
Redbank–Mount Zeil thrust zone (RTZ)
ca. 1.0 B.Y.
Heavitree quartzite
Bitter Springs limestone
ca. 0.8 B.Y.
Macdonnell Range Series
0.8–0.3 B.Y.
Brewer conglomerate
ca. 0.3 B.Y.

Fig. 2


SAMPLE/CHONDRITE
1000
100
10
1
Mt HAY THOLEIITIC BASIC GRANULITES
Mt CHAPPLE THOLEIITIC BASIC GRANULITES
Mt CHAPPLE GARNETIFEROUS BASIC GRANULITES
FIELD OF MIDOCEAN RIDGE BASALTS [MORB]
FIELD OF CONTINENTAL THOLEIITES
Pb Rb Ba Th U Nb K La Ce Sr P Zr Ti Y
DEPLETED HIGH-Mg BASIC GRANULITES
ENRICHED HIGH-Mg BASIC GRANULITES
Mt HAY THOLEIITIC BASIC GRANULITES
Pb Rb Ba Th U Nb K La Ce Sr P Zr Ti Y
Mt HAY - Mt CHAPPLE - REDBANK HILL GNEISSES
LOW-Ca GRANITES
HIGH-Ca GRANITES
Pb Rb Ba Th U Nb K La Ce Sr P Zr Ti Y

Mt HAY GRANULITES - PARTIAL MELTING MODEL

Fig. 3



ON THE ORIGIN OF PROTEROZOIC CRATON-MOBILE BELT PATTERNS, WITH REFERENCE TO AUSTRALIAN LOWER-MIDDLE PROTEROZOIC TERRAINS

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Significant constraints on theories of the evolution of early to middle Proterozoic crustal domains of the Australian Precambrian Shield includes:

(1) Preservation of little deformed Archaean cratons (Yilgarn and Pilbara blocks), reworked late Archaen-early Proterozoic nuclei (within the Pine Creek, Gawler Block and possibly Tennant Creek and Georgetown inliers) and lower Proterozoic stable platforms (McArthur Basin, Kimberley Basin, Victoria River Basin) within a network of lower-middle Proterozoic supracrustal mobile belts and their infracrustal root zone (i.e. Gascoyne, Arunta, Tennant Creek, Granites-Tanami, Halls Creek, Pine Creek, Mt Isa, Georgetown and Broken Hill inliers).

(2) A predominantly intra-sialic nature of sediments within the mobile supracrustal belts, namely, prevalence of quartz arenites, siltstones and carbonates. Geosynclinal facies turbidites occur in some mobile belts (Halls Creek, Cloncurry, Gascoyne) and olistostromes are known in the latter.

(3) Scarcity of igneous products of two-stage mantle melting processes, such as andesites, Na-dacites and tonalites, and an absence of ophiolites (Glikson, 1983).

(4) Major geochemical and isotopic distinction between of lower-middle Proterozoic and Archaean igneous units (Fig. 1) suggesting more fractioned LIL (large ion lithophile) element enriched mantle sources and/or crustal contamination for the Proterozoic magmas. Isotopic studies suggest positive I/Nd and low I/Sr values for Proterozoic igneous units, and a major accretion of mantle-derived materials about 2.1-1.9 b.y. ago (Page et al., 1984 Black and McCullouch, 1984).

(5) Major intra-sialic basic igneous events, including dyking (Pilbara and Yilgarn), intracratonic volcanism (Fortescue Group), rift-related volcanism (Eastern Creek Volcanics, Strangways Volcanics) and plutonic activity (Lamboo Complex, Hart dolerite, Mt Hay basic granulites).

(6) Relatively fixed positions (±1000 km) of individual lower-middle Proterozoic domains is suggested by a contiguous apparent polar wander path (McElhinny and McWilliams, 1977).

The possible extension of the craton-mobile belt tectonic patterns which characterize the Yilgarn and Pilbara blocks into the North Australian Precambrian Shield (NAPS) (Etheridge et al., 1984), may be tested by a combination of palaeomagnetic and isotopic methods. Inherent in this model is the question of whether the platform-covered blocks (Kimberley Basin, Victoria River Basin, McArthur Basin, Lawn Hill platform) overlie Archaean blocks (Model A) or whether they overlie mobile lower Proterzoic domains similar to those listed above (Model B)? Depending on which the above alternatives apply, contrasted schemes of crustal structure and evolution as follow:

Model A - If stable platforms of the NAPS are underlain by Archaean crust, extensive contamination of lower Proterozoic igneous units juxtaposed with or above these blocks can be expected, which would result in predominance of low I/Nd and high I/Sr values. Furthermore, where strong uplift and thrusting occur, i.e. in high grade lower Proterozoic metamorphic terrains, progressive involvement of Archaean crust could be expected. However, these difficulties can be overcome if Proterozoic mobile belts represent originally rifted zones developed above simatic crust between older sialic blocks - implying considerable lateral divergence of the latter and thereby a plate tectonic regime. In this model, accretion of mantle derived igneous materials and their reworked derivates occur within rift zones developed between Archaean and/or early Proterozoic sialic microcontinents. Such rifts may be underlain by both simatic and older sialic crust. If the present day ratio of the exposed Proterozoic mobile domains to intervening cratonic blocks in the NAPS is any indication, significant lateral plate movements are implied and should be indicated by palaeomagnetic APWP data from the oldest components of the cratonic blocks.

Model B - If the stable platforms of the NAPS are underlain by mobile Proterozoic terrains, for example, if the Kimberley Basin is underlain by Halls Creek Group equivalents and the McArthur Basin by equivalents of the Leichhardt Metamorphics, it would follow that the bulk of the NAPS has been derived from mantle-type materials about 2.1-1.9 b.y. age (Page et al., 1984). In this case, instead of an early Proterozoic craton-mobile belt pattern, an originally contiguous simatic regime would be implied. Reworking of simatic crust through multistage remelting and metamorphism would result in the ensialic assemblages observed in the lower-middle Proterozoic mobile belts. In this model, the craton-mobile belt patterns became defined only upon relaxation of tectonothermal activity in relatively stable domains, parallel to ongoing tectonic and magmatic activity in mobile zones, i.e. before 1.9 b.y. in the Kimberleys, before 1.75 b.y. in the McArthur Basin area, and before 1.7 b.y. in the Birrindudu Basin area. The contiguity of palaeomagnetic APWP (McElhinny and McWilliams, 1977) places limits on lateral movements within the NAPS following stabilization. Allowing for small Archaean cratonic nuclei (in the Pine Creek, Gawler, Georgetown and Tennant Creek inliers), this model is consistent with the geochemical and isotopic data which indicate little involvement of Archaenan material in crustal petrogenesis. Whereas a significant role of lateral crustal movements associated with differential lower

Proterozoic cratonization is likely no Palaeomagnetic evidence for significant relative motions are as yet at hand. The alternative models remain to be discriminated. Regardless as to which model is preferred, a principal question inherent in the addition of mantle-derived materials to the crust is whether this process has taken place in plate tectonic-type environments (midocean ridge, Red Sea rift island arc-tench) or in temporally unique tectonic settings. The scarcity of relics of oceanic crust and of two stage mantle melting products in early-middle Proterozoic terrains is difficult to explain in terms of either model, and is contrasted to the occurrence of simatic relics in Archaean and in late Proterozoic systems. One possible process, consistent with both models, involves progressive accretion of basic magmas along the Moho interface in agreement with the model of Etheridge et al (1984). The high geotherms produced by this process would be expected to intersect the wet gabbro solidus, resulting in partial melting and production of dacitic liquids. Progressive basic intrusions/underplating would result in remelting of older basic materials and of incorporated older felsic anatectic units, producing increasingly evolved magmas. In the long term, ongoing or recurrent refusion events associated with basaltic accretion can give rise to the geochemically evolved high-level granitic and felsic volcanic units typical of the NAPS. Such a process is capable of explaining advanced geochemical fractionation of mantle-derived (by two-stage melting)felsic igneous rocks of short crustal residence (Wyborn and Page, 1983). An example of a lower Proterozoic infracrustal granulite-gneiss facies root zone in the southwestern Arunta inlier, where this type of anatectic processes took place, is given in an accompanying paper.

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PRECAMBRIAN DEVELOPMENT OF THE BALTIC SHIELD

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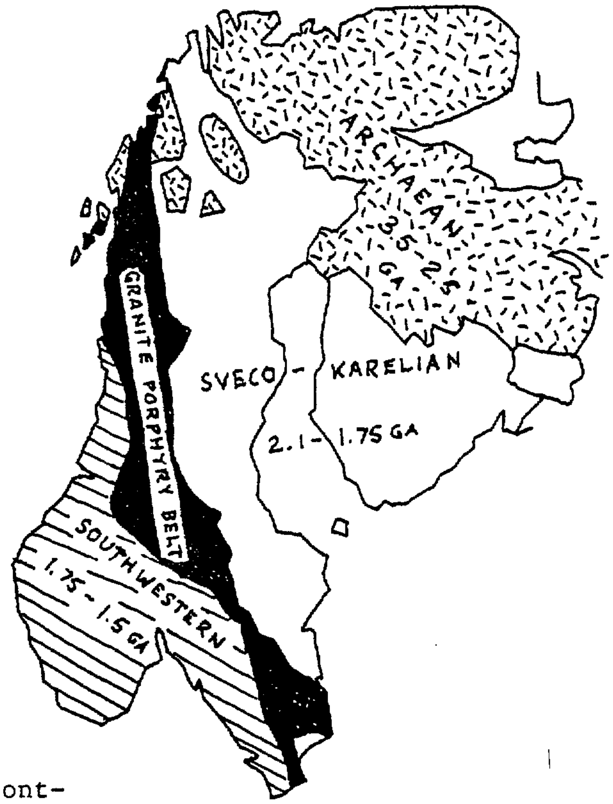
The Baltic Shield comprises Scandinavia and the area between the Baltic and the White Seas. Its Precambrian record documents the formation of continental lithosphere during a period extending from about 3500 to 800 Ma ago. In the Archaean, contrasting granite-greenstone belt and high-grade gneiss terrains can be distinguished on a scale suggesting the existence of large continental blocks and mobile-belt environments at least 3000 Ma ago. Komatiitic volcanism characteristic of the greenstone belts does not cease at the Archaean - Proterozoic boundary. However, the greenstone environments appear to evolve from orthodox greenstone belts to komatiite-bearing greenstone rifts, which are a cratonic facies in the hinterland of the middle Proterozoic Svecokarelian mobile belt. The 2100 - 1750 Ma old Svecokarelian orogenic environments comprise belts of bimodal volcanics and an intervening (back-arc ?) basin. There are analogies with recent plate-tectonic patterns, but high-P environments and andesites are scarce or absent. This may suggest deviation from strictly actualistic conditions. Geochemistry and isotope geology provide a basis to discuss the formation of Svecokarelian crust by derivation from the mantle and reworking of Archaean crust. During later Proterozoic orogenies, 1750 - 1500 Ma old continental crust was developed in western Scandinavia. This crust was reworked repeatedly. Reworking culminated during the Grenvillian-Sveconorwegian orogeny 1200 - 900 Ma ago. In the Baltic Shield, the Grenvillian events were essentially ensialic, adding very little new continental crust to the craton. Sutures and rifting belts occur particularly in the northernmost and southwestern parts of the shield. In the north, sutures vary in type from ensialic to collisional. In the west, a 1000-mile long belt of granites and porphyries associates with later mafic dyke swarms developed along an apparently encratonic tectonic belt trending parallel to an inferred destrucive plate margin to the present west of the Baltic Shield.



PARTIAL MELTING DURING GRANULITE METAMORPHISM- A MECHANISM FOR CONTROL OF FLUID COMPOSITION?:

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Anhydrous pyroxene-K feldspar bearing granulites in the Arunta Inlier, central Australia, have been pervasively but partially retrogressed during early cooling with the formation of biotite. That this retrogression was not accompanied by regional deformation is shown by the essentially random fabric of the late biotite. Later complete hydration, at lower temperature, only occurs in shear zones that transect the granulite terrane. The fact that complete hydration is restricted to highly deformed zones is taken to be an indication of relatively low permeability in the granulites. There is no evidence for any deformation to permit the introduction of H_2O from an external source during the early partial hydration, and its pervasive nature requires a widely distributed source of H_2O.

We suggest that granulite metamorphism was accomplished by dehydration melting and that the subsequent crystallisation of the melt fraction during cooling involved reaction with the anhydrous residuum thus producing the observed partial rehydration. Our model assumes that the granulite protolith had been essentially dewatered, but for the persistence of biotite and/or amphibole, prior to the onset of partial melting. A small amount of melt segregation into patches and veins may explain the apparent overall loss of water from the rocks during the heating and cooling event straddling the upper amphibolite-granulite facies boundary.

Evidence for partial melting in the granulite terrane is provided by the widespread distribution of migmatites in felsic rocks. In some granulites a crystal-liquid environment is indicated by the occurrence of euhedra of sapphirine, orthopyroxene, kornerupine and garnet in small pegmatite-like patches rich in K feldspar and/or plagioclase. On the whole, little or no melt segregation seems to have taken place in rocks where the melt fraction was small (<30 percent,cf. von de Molen & Patterson, 1979; McLellan, 1983).

Calc-silicate rocks equilibrated in the same granulite terrane contain the asemblage meionite-calcite-wollastonite- garnet; this requires high H_2O activity, presumably buffered by the mineral assemblage. The juxtaposition of calc-silicate rocks containing assemblages requiring high water activity and rocks with assemblages stable at low H_2O activity has been previously described from the Adirondacks by Valley and others (1983), who interpreted it as evidence against pervasive CO_2 flushing in that terrane.

The low K/Rb ratios (150-210), high K_2O (3.26-6.08) and Rb (140-290) contents of felsic rocks within the Arunta granulite terrane are inconsistent with partial melt extraction on a significant scale, and support a model in which melt is retained. Allen (1979) reported depletion of K and Rb in the southern Strangways Range, but his observations are not typical of Arunta granulites overall.

Partial melting as the dehydration mechanism for the formation of granulite terranes has been suggested by a number of investigators (e.g. Fyfe and others, 1978; Nesbitt, 1980; Barnicoat, 1983; Wall and others, 1983; Valley and others, 1983; Powell, 1983). Partial or complete retention of a small melt fraction, particularly in rocks that did not undergo contemporaneous deformation, would imply H_2O retention. On cooling, the liquid portion of the rocks would react with the anhydrous residium, thus producing the pervasive retrograde hydration observed in many granulite terranes.

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ARCHEAN BASEMENT INLIERS IN TWO EARLY PROTEROZOIC OROGENS IN CANADA: THEIR STRUCTURAL POSITION AND GEOTECTONIC SIGNIFICANCE

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ABSTRACT

Occurrences of Archean basement inliers in Proterozoic orogenic belts have often been cited as evidence for the intracontinental origin of the belts in question. Such a conclusion can only be justified for rocks that can be structurally "pinned" to the basement. Basement inliers in eastern Wopmay Orogen (District of Mackenzie) and the Cape Smith Belt (northern Quebec) are being studied to ascertain their structural position and geotectonic significance.

In Wopmay Orogen, there are two classes of inliers — autochthonous and allochthonous. The largest inliers are autochthonous structural culminations resulting from constructive interference of intersecting thick-skinned folds. The autochthonous inliers are sheathed by 200-300 m of autochthonous sedimentary cover, above which is a regional isostratigraphic decollement separating the autochthon from an overlying allochthon. The decollement grades from a relatively brittle thrust surface in the foreland to a wide zone of ductile thrust shear in the hinterland. The allochthon experienced a minimum of 40% horizontal shortening by means of imbricate thrusting and detached folding, from which it can be inferred that the allochthonous hinterland has been translated in excess of 50 km toward the craton. The shortening estimates are based on well-constrained structural cross-sections of the fold-and-thrust belt, constructed by means of axial projections on the flanks of late high-amplitude crossfolds. From the geometry of metamorphic isograds in the allochthon and autochthonous cover, it can be demonstrated that the main metamorphic-plutonic culmination in the hinterland is rootless, and was translated while still hot over a relatively cold autochthon. The autchthonous basement inliers provide no information regarding the original basement of the allochthon in the hinterland. However, the former existence of stretched continental basement beneath rift-facies allochthons can be inferred from the occurrence of relatively small, apparently allochthonous, basement inliers in the Wopmay hinterland.

Archean basement north of the Cape Smith Belt, which consists dominantly of mafic and ultramafic lavas and related sills, is separated from the structurally overlying volcanics by a ductile shear zone, which contains structures indicating south-directed overthrusting. The volcanics above the ductile decollement are involved in south-directed imbricate thrusting. To varying degrees, structures related to south-directed thin-skinned thrust translation are overprinted by consistent top-side-down shearing on the flanks of late thick-skinned folds. The late shearing is indicative of gravitational amplification of the thick-skinned folds, driven by the strong density inversion resulting from the earlier thin-skinned thrusting of mafic-ultramafic volcanics onto sialic basement. Allochthonous basement inliers are unknown and therefore an oceanic ancestry for the volcanic allochthons cannot be ruled out. Furthermore, because the volcanic belt is apparently a klippe, the existence of Archean basement everywhere beneath it does not constitute evidence that the belt is intracontinental in origin.

DISPLACEMENT AND STRAIN WITHIN THE NAPPE SEQUENCES OF THE HARTS RANGE AREA, CENTRAL AUSTRALIA

P. R. James, P. Ding, L. Rankin & G. Scales

In a recent review of the structure and tectonic history of the Harts Range area, Ding and James (1985) described this area of the eastern Arunta Inlier as comprising, a basement infrastructure and a cover sequence suprastructure, both of which suffered separate complex tectonothermal evolutions before being juxtaposed by major subhorizontal shearing and subsequently redeformed in a further complex orogenic episode (the Harts Range event). During their early histories, but also more importantly during the Harts Range event, the two structural sequences were repeatedly inhomogeneously strained, with strain partitioning on all scales. The sequences were also subject to both large- and small-scale continuous-discontinuous strain histories with the characteristic development of major mylonite zones.

Basement gneisses which include the Oonagalabi Tongue, the Entia Dome and the whole southern margin of the study area display repeatedly superposed isoclinal folds developed under high amphibolite to granulite facies conditions. Intense S>L fabrics with mineral/stretching lineations subparallel to the fold hinges attest to the overall intensity of the strains, and suggest prolonged subhorizontal ductile flattening strain with a predominant NE-SW principal elongation direction. The actual sense of shear, or any indication of the amount, of strain cannot be estimated from the basement lithologies, although some individual mafic layers show a significant ductile thinning from hundreds of metres down to less than one metre. The bulk strain however was much less than this, as , while folding due to lateral (layer-parallel) compression thickened the sequence, flattening due to vertical (layer-normal) compression concomittantly attenuated the same sequence.

The basement strain geometry appears to have been produced largely by subhorizontal flattening probably caused by the great weight of rocks overlying the sequence. Intermittant subhorizontal SE-NW trending compressional stresses may be related to transcurrent E-W shearing, with the constant NE-SW principal elongation/minimum compression a product of the early initiation of basement extension in this direction.

The cover sequence of the Irindina supracrustal assemblage suffered only moderate early deformation. The first phase isoclinal folds are minor and infrequent with an intense axial S fabric in pelitic gneiss and a weak northerly trending mineral lineation. The second phase isoclinal folds are of major scale and upright, close to tight structures. They trend E-W, with shallow plunges and a parallel weak axial mineral lineation. The bulk strain appears to be similar to that displayed in the basement, while strain shown by individual layers may be much less than that shown by such layers in the basement.

Early planar fabrics and folds in the cover indicate largely subhorizontal flattening deformation. This developed as a thin-skinned style tectonic response probably to initial contraction on a large-scale near flat-lying detachment structure associated with a major (master) northerly inclined basement shear zone.

Crustal extension associated with the shear and detachment zones then began. Non-coaxial strain associated with incipient retrogression of the granulite facies gneisses in the Oonagalabi tongue led to the eventual juxtaposition of basement and cover along the HRT1 (Oonagalabi Shear Zone) which now bounds the Oonagalabi Tongue. This zone and its thick mylonite development attest to the intensity of predominantly simple shear strain produced during northerly extension probably close to the transverse (E-W) cratonic margin. Granitic magma intruded along the detachment shear zone and formed small sills and stock-like apophyses within both the cover and basement.

An important change in the displacement history is indicated by a reversal to thrust sense contraction along the Oonagalabi Shear Zone (HRT1) to produce HRF1 folds, which folded both the cover (the third overall phase) and basement, as well as the shear zone itself, about tight upright folds. However the most dramatic change in displacement history is indicated by the near isoclinal major refolding of the Oonagalabi Shear Zone to form the major reclined fold of the Oonagalabi tongue which together with other major folds to the south also refolded the cover and the basement as well as their internal foliations and lineations. The easterly vergence of these structures, plus their style and the probable intensification of the shallow northerly inclined finite strain fabrics, suggests E-W subhorizontal shearing of the hanging wall gneisses most likely caused by dextral transcurrent shear again concentrated on the major northerly inclined shear/detachment zone.

A further fundamental change in strain and displacement history occured with the development of another major shear zone HRT2 (the Florence Creek Shear Zone) which developed by reverse reactivation of the strain softened original basement detachment zone which it subsequently truncated. This zone is the largest, longest lived and most intense found in the Harts Range area. The Florence Creek Shear Zone forms a major intense mylonitic and LS tectonite developing zone, occuring as a major NW-SE trending lineament from southeast of Leaky Bore in the SE to Bullocky Bore in the NW, where it is truncated and overridden by a later thrust zone. In this lineament the Zone reaches up to 1 km in true thickness and dips moderately to the NE with a regular N-NE trending near down-dip intense and pervasive stretching lineation. The Zone was intiated at high metamorphic grades(granulite facies) and brought further granulite facies basement gneisses up and into contact with both lower grade basement (Entia) and the supracrustal cover. Retrograde metamorphism also occured during the continuous development of the shear zone. To the northeast, the Florence Creek Shear Zone reappears around the margins of the Entia Dome, however it is mostly hidden by the effects of the intrusive Bruna granitic gneiss which intruded along this zone during its development. The strain history of this zone indicates a prolonged simple shear episode with intensly elongate transverse principal extension and flattened foliation, and with little strain in the tectonic Y direction.

The precursor to the Bruna gneiss, a coarsely porphyritic and potassic granite preferentially intruded along the still active Leaky Bore Shear Zone. Bruna gneiss is thinnest in the west of the zone and thickens rapidly eastwards and southeastwards until it almost excludes mylonites of the zone. Such mylonites and other shear zone products remain as large xenolithic fragments within the Bruna gneiss. HRT2 shearing continued after solidification of the Bruna granite which was thus deformed and mylonitised with the strain preferentially partitioned into shear zones at the margins and occasionally within the Bruna gneiss. Strains within the Bruna gneiss as estimated from flattened and elongated feldspar megacrysts indicate both oblate and plane strains, while rotational criteria suggest movements both to the north and south of succeeding shear zones. This zone was locally folded by reclined HRF3 folds.

The southern margin of the Harts Range area is marked by a narrow mylonite/schist zone (HRT3 - the Muller Bore Shear Zone). This zone trends ENE-WSW across the whole area and varies from 10's up to hundreds of metres across and dips from 45-54 degrees north with a regular strong down-dip lineation. Internally muscovite and biotite develop in typical retrograde assemblages associated with epidotisation. Relict high grade mylonites suggest that this relatively narrow zone, which also transects all earlier structures, became the locus of displacement as the whole area moved through the ductile/brittle transition.

THE MOZAMBIQUE OROGENIC BELT IN NORTHERN KENYA

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A northerly section of the Late Precambrian-Early Phanerozoic Mozambique Orogenic Belt is well exposed in northern Kenya. An Upper Amphibolite/Granulite facies tectonothermal event (Samburuan) produced a coarse gneissic fabric in supracrustal rocks (locally founded on migmatites) which, by obliterating pre-existing structures, effectively destroyed evidence of the earlier history of the orogen. Predominant lithologies (apart from altered mafic volcanic complexes tectonically emplaced from the NW) are altered clastic sediments, including small crustal-melt granites. At present (deep) exposure levels, linear elements of the Samburuan horizontal fabrics are orientated essentially E-W. Subsequent events produced (at high levels) upright structures (including vertical shear belts) trending in the arc NNW to NE. Crustal uplift and/or erosion during the waning orogenic period preceded the Tertiary doming and subsequent rifting (of the East African System).

The preserved history of the orogen in N. Kenya suggests initial continental rifting with minimal development of new oceanic crust. This agrees with evidence presented from more southerly areas but contrasts with the simatic northern extremities (ophiolites of Ethiopia). This fundamental change could be due to differential opening (N to S) along a wedge-shaped rift; new oceanic crust being confined to the wide northern parts. Further south, mantle-derived material formed intrusive pods along deep seated fractures. Preliminary isotopic data indicate that the thermal peak during the Samburuan occurred at c820 Ma. Final uplift and cooling below the blocking temperature of biotite took place between c530 and c510 Ma.

Different crustal thicknesses along the Mozambiquian Rift had a profound effect on the development of the Cainozoic East African Rift System.

PAN-AFRICAN CRUSTAL EVOLUTION IN THE NUBIAN SEGMENT OF NORTHEAST AFRICA

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Similarities in rock assemblages and broad tectonic features between the late Precambrian to early Palaeozoic basement of Arabia, the Eastern Desert of Egypt and the Red Sea Hills of the Sudan have led to evolutionary models that envisage broadly contemporaneous processes of island arc formation and modern-type obduction-accretion tectonics for both the Arabian and Nubian segments of this large Pan-African shield. For Arabia such models are based on a wealth of geochemical and isotope data as well as on systematic regional mapping, while the information on northeast Africa is still fragmentary for many regions, and there are much fewer constraints on ages and tectonic settings.

All present models tacitly assume that the juvenile Arabian arc and ophiolite assemblages were accreted onto the African craton between ca. 900 Ma and about 600 Ma ago, but the precise location of the cratonic margin is still unknown. It is therefore of interest to find out whether the Eastern Desert and the Red Sea Hills are still part of the accreted juvenile domain or whether they define an Andean- or Cordilleran-type continental margin.

Our work in the southern Eastern Desert has revealed the local occurrence of shallow-water clastic and partly aluminous metasediments at Hafafit that we interpret as passive continental margin deposits and that were later incorporated in extensive thrust and nappe tectonics. The recognition of low-angle thrusts that form duplexes and ramps suggest similarities with modern foreland thrust and fold belts. The uppermost nappe units consist of an ophiolite mélange and well preserved remnants of layered ancient oceanic crust as well as mafic to felsic metavolcanics whose geochemistry suggests formation in marginal and/or intra-arc basins. Voluminous calc-alkaline plutonism occurred between ca. 650 Ma and 720 Ma ago, i.e. before and during the above period of thrust tectonics.

We tentatively propose that westward-subduction, some 700-750 Ma ago, transformed the attenuated passive margin of the African craton into an active belt whereby marginal basin closure, ophiolite obduction and arc accretion from the east (Arabia) facilitated thrust stacks of juvenile assemblages to override the ancient cratonic edge that may now be buried beneath the western part of the southeastern Desert.

In the Red Sea Hills of the Sudan farther south rocks of undisputed continental derivation have not been recognized to date, but the extensive exposures of carbonate metasediments along and east of the River Nile suggest a stable depositional environment that is not found in the volcanic arc terrane farther east. There, several distinct high-strain belts contain tectonically dismembered ophiolite fragments that range in size from almost complete segments of marginal basin-type oceanic crust to thin lenses of talc-carbonate schist. The ophiolite belts may define sutures between accreted arc terranes, and available age data suggest that arc magmatism occurred from at least 830 Ma to about 650 Ma ago. Nd isotopic systematics in the Gebeit metavolcanics of the northern Red Sea Hills demonstrate an intraoceanic environment of formation and derivation of the arc volcanics from a significantly depleted mantle as has previously also been shown for the arc and ophiolite assemblages in Saudi Arabia. Furthermore, our Sr isotopic data confirm the primitive nature of the Red Sea Hills crust, and we see no involvement of significantly older continental material in the generation of both the volcanic and granitoid rocks.

Rocks previously considered as older basement on account of their higher metamorphic grade are part of the Pan-African assemblage, and it can be shown at many localities that the increase in metamorphism is due to the thermal effects of the extensively developed granitoid batholiths. Migmatitic orthogneisses occur locally and may represent deeper crustal levels of the arc complexes as in Saudi Arabia. Even the granulites at Sabaloka, north of Khartoum, that were previously seen as part of the ancient, stable African craton are of Pan-African age and reflect a deep crustal thermal history that we consider to be genetically linked to the arc magmatism farther east.

Although we can delineate several distinct crustal blocks in the Red Sea Hills that are separated by ophiolite belts or shear zones our isotopic data do not support simple arc accretion models that would imply a general decrease in ages from west to east. However, we are able to demonstrate that many of the conventional large-scale lithostratigraphic correlations are erroneous and that there is no general trend from early, primitive arc magmatism to mature, andesite-dominated activity as has been postulated for the Arabian shield. It is therefore difficult at this stage to incorporate the Red Sea Hills into the evolutionary models that were proposed for Arabia, although at least two of the Nubian ophiolite belts clearly continue into the Arabian shield. It is possible that displaced terranes were involved in the crustal growth process of the Nubian shield, as has been suggested for Arabia, but direct evidence has not been found.

The Pan-African structural domain with low-angle thrusts and ophiolite mélanges extends at least as far west as the River Nile, and the ancient margin of the African craton may be found nearby. However, the domain farther east is characterized by newly accreted magmatic associations that may have evolved in settings similar to those presently observed in the Indonesian archipelago.

THE MARY KATHLEEN U-REE DEPOSIT, QUEENSLAND: AGE AND ORIGIN OF MINERALIZATION FROM SM-ND SYSTEMATICS

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The Mary Kathleen U-REE deposit is hosted by andradite-pyroxene exoskarn related to the intrusion of the 1730 Ma Burstall Granite. U-REE mineralization consisting of uraninite enclosed by a REE-rich allanite-apatite-amphibole assemblage occurs in zones of retrograde breakdown of the calcic skarn and appears to be structurally controlled by its position in the hinge of the Mary Kathleen Syncline and by the adjacent Mary Kathleen Shear. Early models favour a pyrometasomatic, single-stage origin for the mineralization, largely based on the apparent contemporaneity of granite intrusion and host skarn evolution. In these models, U and REE are released in hydrothermal solutions from the cooling Burstall granitic magma and are channeled to their present site, where they replaced earlier formed skarn.

Recent U-Pb isotopic (PAGE,1983) and field studies (OLIVER et al.1985) recognized, that granite intrusion and uraninite mineralization are separated by a ≈ 200 Ma interval and at least one phase of deformation. Models based on these observations suggest metamorphic remobilization of (originally granite derived) U (and REE) from an intermediate protore at around 1550 Ma, the age of uraninite crystallization at Mary Kathleen (PAGE,1983).

The 1550 Ma U-Pb ages for uraninite mineralization are confirmed by a Sm-Nd whole rock-mineral isochron, which gives an age of around 1500 Ma. The good fit of the data to the isochrons and the consistency of U-Pb and Sm-Nd data suggest that these ages do in fact represent the time of ore formation and not the time of isotopic resetting during metamorphism.

All U mineralization at Mary Kathleen is associated with calcic, garnet-rich skarn. Field relations suggest that original granite-related, high temperature skarn was metamorphically remobilized and hydrothermally altered during D_2/D_3, which finally led to U-REE mineralization. This is substantiated by Sm-Nd data for skarn, which give an age of 1700 ± 60 Ma for banded calcsilicate skarn and 1580 ± 50 for massive garnet-pyroxene-feldspar skarn. These results indicate that skarn evolution was a multistage process with at least two thermal peaks, corresponding to Burstall Granite intrusion at 1730 Ma and later amphibolite grade regional metamorphism. The Sm-Nd ages are thus fully consistent with the model proposed by OLIVER et al.(1985) who suggest a metamorphic origin of mineralization.

Models for the origin of REE (and by inference, U) can be constrained by the Nd isotopic data. Fig.1 shows the isotopic variation in ore, granite and skarn with time. At ~1500 Ma, the time of ore formation, ore had significantly less radiogenic Nd ($\varepsilon_{Nd} \approx -9$)

than contemporaneous granite or skarn (ε_{Nd}=-5 to -7.8). This indicates a pronounced, long-term LREE enrichment in the source for ore (i.e. very low ^{147}Sm/^{144}Nd$\leq$0.03), similar to that found in the ore today (LREE/HREE$_{CN}\geq10^3$), i.e. a strong LREE fractionation occurred considerably before the time of ore formation. At ~1730 Ma, the time of granite intrusion, granite and skarn had $\varepsilon_{Nd}\approx$-3 and the Nd isotopic composition of ore projects back into this field. It is therefore possible that REE fractionation occurred in the Burstall Granite or in skarn at 1730 Ma and was preserved until ~1500 Ma, when metamorphic hydrothermal solutions leached REE from their source. This >200 Ma time interval is sufficient to produce the difference in ε_{Nd} observed at the time of ore formation.

The most probable sources for both REE and U are LREE-enriched accessory minerals such as allanite, sphene and monazite which are common in both skarn and the Burstall Granite. Leaching of REE+U from such minerals during ~1500 Ma hydrothermal activity would be facilitated by internal radiation damage and could account for the geochemical and isotopic features of the ore.

The consistent but unusual association of calcic skarn and REE-U mineralization can be explained by the role of the skarn bodies as structural and chemical heterogeneities which promoted fluid channelling during metamorphic hydrothermal activity and provided a geochemical environment suitable for allanite formation. The preconcentration of REE and U in abundant accessory phases may be a result of the unusual A-type characteristics of the Burstall Granite and REE release during skarn-related garnetization.

Fig.1 ε_{Nd} versus time diagram for Burstall Granite, skarn and U-REE ore at Mary Kathleen. Initial Nd isotopic compositions shown in solid symbols. ε_{Nd} in ore at 1500 Ma is significantly lower than country rock (fields labelled 'granite' and 'skarn') indicating REE fractionation at ~1730 Ma. REE and U in ore are derived from 1730 Ma old accessory minerals in granite and/or skarn by hydrothermal leaching at ~1500 Ma during regional metamorphism. Numbers in brackets show average ^{147}Sm/^{144}Nd-ratios; dashed line, ore projected back in time.

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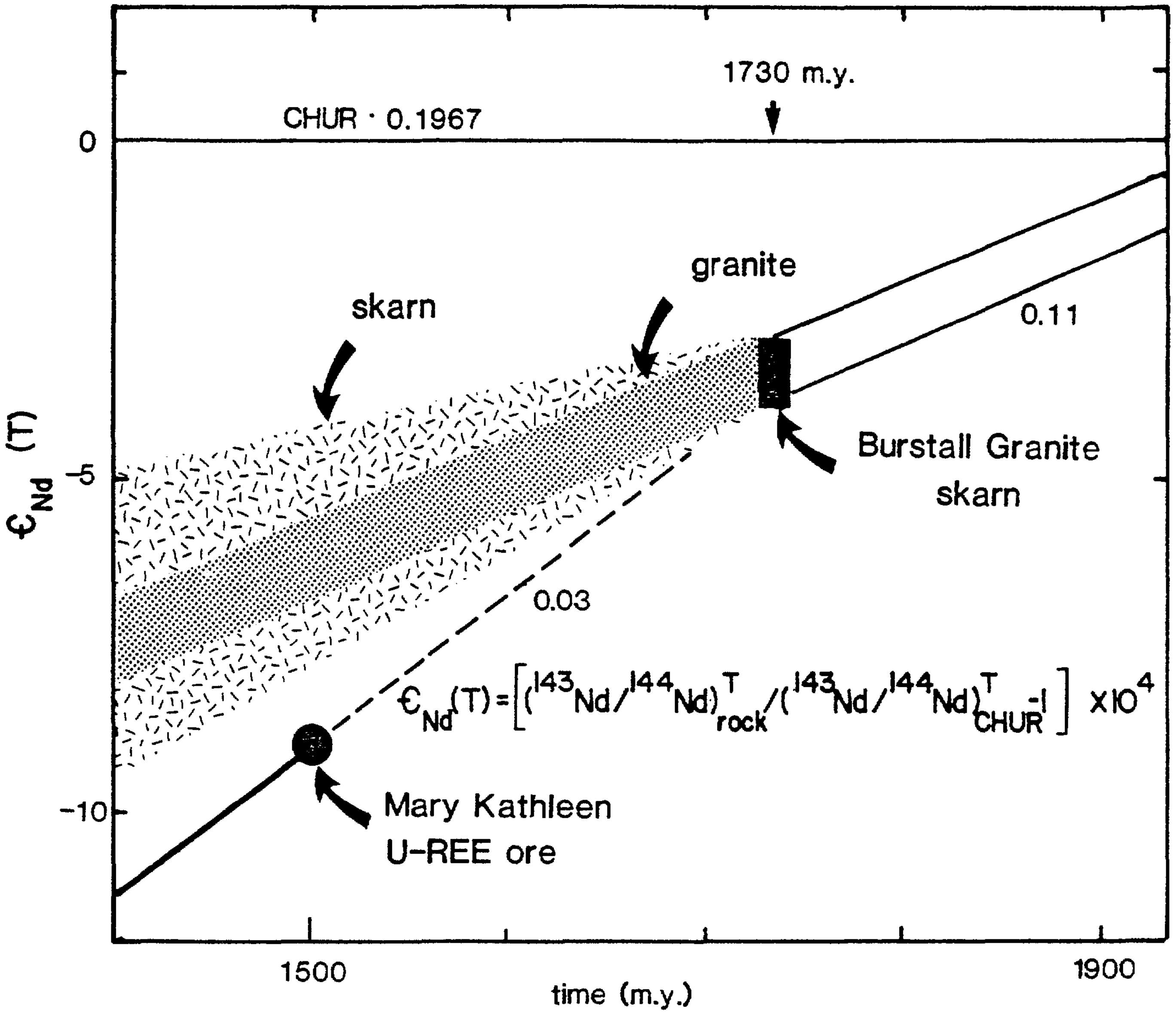
1730 m.y.
CHUR · 0.1967
0
granite
skarn
0.11
Burstall Granite
skarn
ϵ_{Nd} (T)
−5
0.03
$\epsilon_{Nd}(T) = \left[({}^{143}Nd/{}^{144}Nd)^{T}_{rock} / ({}^{143}Nd/{}^{144}Nd)^{T}_{CHUR} - 1 \right] \times 10^4$
Mary Kathleen
U-REE ore
−10
1500
1900
time (m.y.)

Fig. 1

MOUNT ISA COPPER AND LEAD-ZINC-SILVER ORES: COINCIDENCE OR CO-GENESIS?

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Although it is generally accepted that the Mount Isa Pb- Zn-Ag ores formed more or less contemporaneously with their enclosing sediments (the Urquhart Shales), no consensus exists regarding the origin of the closely associated Cu orebodies. Many workers have argued that both the Cu and the Pb-Zn-Ag ores formed from the same mineralizing system(s) (e.g., Finlow-Bates and Stumpfl, 1979), while others suggested that the Cu mineralization was epigenetic and had no direct link to the Pb- Zn-Ag ores (e.g., Smith and Walker, 1971).

Recent structural analysis (Perkins, 1984; Swager, 1985) of the "silica dolomite" (a general term for several related rock-types that are the hosts to the Cu mineralization) indicates that it was produced by hydrothermal alteration (silicification and dolomitization) of steeply dipping Urquhart Shales. The hydrothermal solutions were channelled along a major, basement-tapping fault system and locally directed out into the Urquhart Shales above sub-horizontal parts of the generally steeply dipping fault (Perkins, 1984). This hydrothermal activity was post D_2, and probably syn-early D_3. Chalcopyrite, the only important Cu-bearing phase in the Cu ores, is always observed to be late in the paragenetic sequence of silica dolomite rock types, and because of this Perkins and Swager both argued that all the Cu (and the sulphur) in the Cu ores was introduced during D_3 **by the same hydrothermal solutions** that formed the silica dolomite. Geochronological studies (Page, 1981) suggest that up to 180 million years may have elapsed between deposition of the Urquhart Shales and the D_3 deformation; if this is the case and the Perkins-Swager Model is correct, then the Cu ores cannot be related to the Pb-Zn-Ag ores, and the intimate spatial association of two of the world's largest base metal accumulations is sheer coincidence.

In the following discussion we present a **new co-genetic model** for the formation of the Mount Isa base metal deposits. Our evidence suggests that the silica dolomite hydrothermal event has **not** introduced significant Cu into the Urquhart Shales, but rather has extensively redistributed an earlier stratiform Cu mineralization that had formed contemporaneously with, and from the same solutions as the Pb-Zn-Ag ores. We interpret the textural evidence for late chalcopyrite paragenesis to simply reflect the relative annealing properties of sulfides, carbonates and silicates in the silica dolomite.

The distribution of a number of volatile metals in the Mount Isa ores places important constraints on i) the nature of the mineralizing solution(s) (e.g., redox state and temperature), and ii) the source of the sulfur in the deposit. Gold, Se and S isotope data for Mount Isa samples indicate that the Cu and Pb-Zn-Ag ores formed from similar solutions (cool and oxidized) and derived their S directly or indirectly from "seawater" sulphate. This insight into the character of the ore-forming fluids has important implications for the nature of the mineralizing process, and greatly limits the possible direct source(s) of the metals.

The Au contents of both the Pb-Zn-Ag ores and the Cu ores are remarkably low and form a continuum of values. The simplest explanation for low Au in the ores is that the mineralizing solutions did not contain Au. The only geologically reasonable solutions that could transport base metals and yet not carry Au would be cool (<200°C) and relatively oxidized ($SO_4^{2-} >> H_2S$). The Ba and Mn distributions associated with the Pb-Zn-Ag mineralization also support cool, oxidized solutions.

The S/Se ratios in both ore types are very large and provide strong evidence that magmatic S was not a component of the ores. Igneous or meta-igneous rocks could not have supplied S, which implies that models invoking deep leaching of the underlying (mixed) succession (e.g., Russell et al., 1981) are inappropriate for the Mount Isa ores. Large S/Se ratios are typical of "sedimentary" values where S is derived from co- eval (saline) waters, containing only minute amounts of Se and having very large S/Se ratios. Hence the Mount Isa S/Se ratios are compatible with a co-eval water (or evaporite sulphate) source for S in both types of ore.

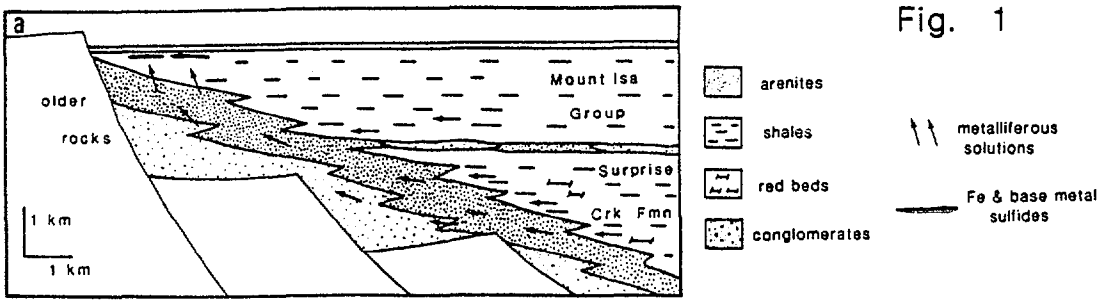
Published S isotope data for the ores (Smith et al., 1978; Solomon and Jensen, 1965; Stanton and Rafter, 1966) provide further support for a "seawater"- or evaporite-sulphate source for the sulfide contained in both types of ore. The isotopic data alone do not preclude a high temperature sulphate reduction mechanism. However, constraints imposed by textures in the ores (Love and Zimmerman, 1961; McGoldrick, 1985) and the depositional setting of the upper Mount Isa Group sediments (Neudert and Russell, 1981) suggests that sulphide production in the Urquhart Shales occurred at low temperatures in a system(s) closed to sulphate, but open to H_2S (i.e., actively precipitating metal sulphides). The processes may have been biologicaly moderated (i.e., bacterial sulphate reduction), or abiological (but utilizing organic compounds buried in the sediments), or both.

Similarities between the two ore types are extended still further when a number of chalcophile trace metals are considered. Cadmium, Ag, Sb and Co, although present in widely different amounts in the different ores, display a continuum of values directly related to the base metal content of the ores, a feature supporting a co-genetic origin for the ores.

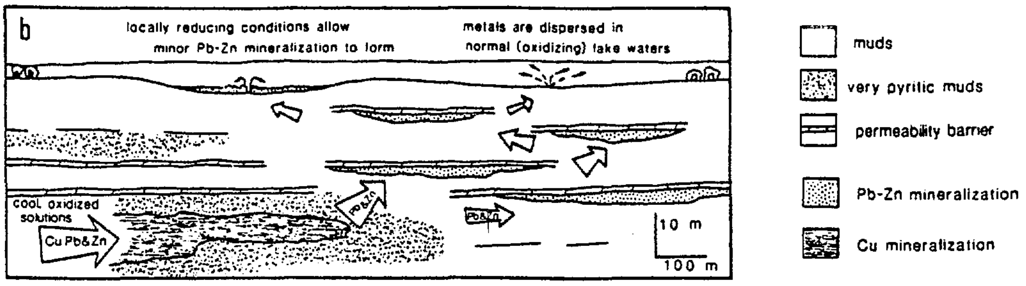
While all these features extend the coincidence if the Cu and Pb-Zn-Ag ores are unrelated, it is still only permissive evidence for a genetic link between the two types of mineralization. However, more direct evidence for an earlier Cu mineralization (presumably co-genetic with the Pb-Zn-Ag ores) is provided by the distribution of several chalcophile elements in 1100 orebody (by far the largest Cu orebody). The 1100 orebody occurs immediately above the basement fault contact, and contains examples of all the silica dolomite rock types, but the highest Cu grades are observed in siliceous lithologies overlying the fault. Coarse dolomitic rock types, containing less Cu, occur up dip from the siliceous lithologies. Unmineralized lateral equivalents of the 1100 orebody at higher levels in the mine are highly pyritic Urquhart Shales (the "Pyrite Rib"). Within 1100 orebody Cu grades are zoned about the basement contact, and the extent of silicification and the amount of Cu are correlated. In contrast several metals (Co, Bi, As and (possibly) Au) have distributions different to Cu and independent of the silica dolomite rock types, but which preserve a stratiform pattern extending down-dip from the Pyrite Rib. This pattern is readily explained if the silica dolomite hydrothermal event has affected pyritic Urquhart Shales that already contained stratiform Cu/Co mineralization.

With these constraints and observations in mind it is possible to construct a simple, geologically reasonable co- genetic model for the Mount Isa Cu and Pb-Zn-Ag mineralization; this model is depicted in Figure 1. Our model is consistent with the observed association of Cu with Pb and Zn in many sediment-hosted base metal deposits, and, although the separation of Cu from Pb and Zn at Mount Isa is extreme, zonation of the metals is a common feature of these deposits. Coincidence must still be invoked to account for the redistribution of the primary Mount Isa Cu mineralization by a later, unrelated, hydrothermal event. However, such a process (i.e., extensive silicification associated with a major, long- lived fault) is a far more common geological occurrence than the independent formation of interdigitating giant base metal deposits.

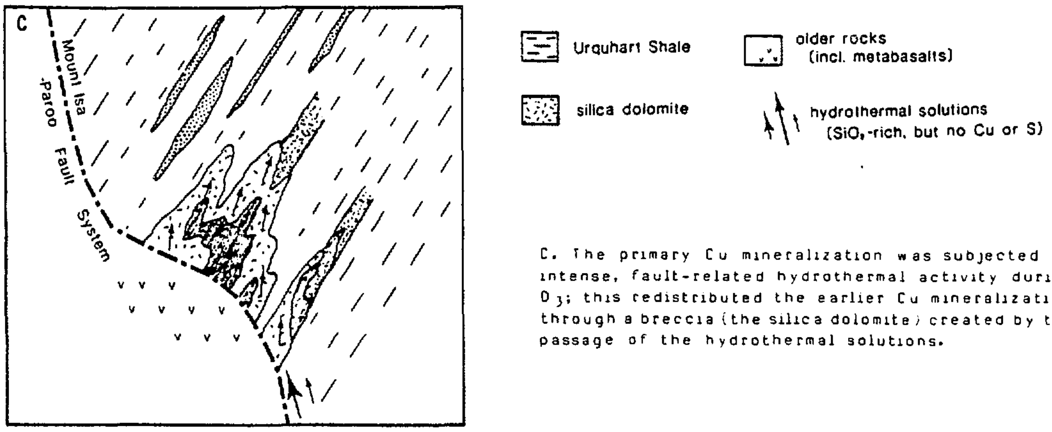
Fig. 1



A. Half cross-section of the Leichhardt River Fault Trough during Urquhart Shale times. Expulsion of oxidized, chloride brines from underlying sediments carries Cu, Pb, Zn and other metals into the unconsolidated Urquhart Shales.



B. Detail from A. The Urquhart Shales are a zone of intense sulphate reduction where base metals are fixed as sulphides; Cu and Co are efficiently separated from Pb and Zn by early precipitation of Cu/Co sulphides in pyritic muds.



C. The primary Cu mineralization was subjected to intense, fault-related hydrothermal activity during D_3; this redistributed the earlier Cu mineralization through a breccia (the silica dolomite) created by the passage of the hydrothermal solutions.

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U-PB AND RB-SR GEOCHRONOLOGY OF PROTEROZOIC SUPRACRUSTALS IN THE VICINITY OF THE HARTS RANGE RUBY MINE, ARUNTA INLIER, CENTRAL AUSTRALIA.

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ABSTRACT

Zircon U-Pb and Rb-Sr TR and mineral data from key rock units adjacent to the Harts Range ruby mine, approximately 100-150 km north-east of Alice Springs, throw light on the complex evolution of this portion of the Proterozoic Arunta Inlier. Detailed structural and metamorphic studies in the Harts Range area (Ding & James, 1985) have revealed a local basement gneiss complex, locally of granulite facies, structurally overlain by a supracrustal, amphibolite facies cover sequence. The basement and cover were brought into contact and tectonically reworked together during the Harts Range Event. A widely recognised granite gneiss, the Bruna granite, intruded along the basement-cover tectonic early in the Harts Range Event and locally cuts the basement and cover. Subsequent tectonic reworking has occurred during the Palaeozoic Alice Springs Orogeny.

The ruby mine occurs within the Harts Range metaigneous complex of the Proterozoic cover sequence. The metaigneous complex consists of interlayered mafic amphibolites and metagabbroic to meta-anorthositic gneisses with subordinate ultramafic boudins and is intercalated with metapelitic and calcsilicate gneisses of the Irindina supracrustal assemblage. Early amphibolite facies cover metamorphism and ductile deformation followed by thrust stacking during the Harts Range Event has obscured original stratigraphic relations. Ding & James proposed that the cover supracrustals represent the fill of an east-west trending Proterozoic aulacogen or proto-ocean.

Three groups of pegmatitic rocks have been recognised. Structurally concordant pegmatite-I sheets in the cover sequence were emplaced early in the tectonothermal history of the cover. Discordant pegmatite-II dykes have been folded late in the cover deformation. Discordant undeformed pegmatite-III dykes are steeply dipping, coarsely crystalline, and muscovite-rich, and are parallel to the axial plane of the last recognisable cover fold generation (Lawrence, pers. comm.).

Concordant Rb-Sr TR and mica data from the undeformed pegamtite-III dykes suggest that they were emplaced and rapidly cooled about 325 ± 2Ma with a wide range of initial $^{87}Sr/^{86}Sr$ ratios (IR 0.7123-0.7488). Rb-Sr TR data from a pegmatite-11 produce a curved array on the isochron diagram and suggest an age of emplacement probably near the older end of a possible 520 Ma to 300 Ma range. Muscovite and biotite Rb-Sr ages for this pegmatite-11 are concordant at 307 ± 2 Ma, but biotite from its strongly deformed aplitic apophysis is slightly younger at 298 ± 2 Ma. Zircons separated from the aplitic apophysis define an approximate discordia with a lower intercept on concordia close to the biotite Rb-Sr age. If the zircon data are constrained to pass through this lower

intercept age the upper intercept age is 520^{+5}_{-4} Ma. A structurally early pegmatite-1 south of the ruby mine area has a muscovite age of 342 ± 3 Ma and a biotite age of 329 ± 2 Ma. These data do not constrain the emplacement age of this pegmatite-1 but suggest that the micas have responded to the Carboniferous Alice Springs Orogeny.

Two individual zircon U-Pb studies have been made on the Bruna granite gneiss and is associated, cross-cutting aplitic phase adjacent to the ruby mine. The granite has preserved much relict igneous character whereas the aplitic gneiss sample comes from a highly strained sheet which is completely recrystallised. Zircons from the granite are a minimally discordant homogeneous population which define a perfect fit discordia with an upper intercept age of 1748^{+5}_{-4} Ma. The lower intercept age is less precisely defined at 103^{+82}_{-82} Ma. Well-correlated, simple systematics among U content and various isotope ratios suggest a simple emplacement and episodoc Pb-loss history to account for the zircon discordia. The aplitic gneiss zircons are a hetrogeneous population with more complex systematics. A more scattered discordia has intercepts of 1752^{+15}_{-13} Ma and 345^{+82}_{-82} Ma. The completely recrystallised nature of the aplitic gneiss is thought to account for one component of the excess scatter, which perhaps occurred at about the time of the lower intercept age. However the originally mixed population of zircons appears also to account for some of the dispersion. The indistinguishable upper intercept ages of the two Bruna gneisses constrain the minimum age of both the basement and cover sequence in the Harts Range and furthermore suggest the Harts Range Event juxtaposed the two complexes prior to about 1750 Ma.

Direct dating of the supracrustals and metaigneous complex rocks of the cover has proved difficult. Rb-Sr data from the amphibolites and meta-anorthositic rocks do not define an isochron of geochronological significance but scatter widely. Model interpretation of the data suggests that some extraneous Sr has entered the gneisses, perhaps in the Palaeozoic, and distorted the array. A small number of heterogeneous zircons have been extracted from an ultramafic boudin in the ruby mine. All four analysed fractions have extremely low U contents resulting in relatively imprecise data. Nonetheless an approximate linear alignment on the concordia diagram produces age intercepts of high uncertainty at 1802^{+648}_{-446} Ma and 465^{+75}_{-137} Ma. If this approximate concordia is interpreted as a Pb-loss chord the zircons have lost in excess of 85% of their Pb in the lower Palaeozoic. However correlations among U content and isotope ratios suggest rather that the discordia is a mixing line between primary zircons roughly 1800 Ma old and new-grown zircons of lower Palaeozoic age. In accord with this interpretation is the irregular shape of the presumed secondary grains similar to zircons in coronite metagabbros from the French Massif Central (Pin & Lancelot, 1982).

The precise U-Pb age for the Bruna granite (1748^{+5}_{-4} Ma) is a benchmark in the tectonic evolution of the Harts Range area. Black et al. (1983) and Windrim & McCulloch (1983) favour separation of granulite facies basement rocks in the adjacent Strangways Range from the mantle about 2000 Ma and metamorphism about 1800 Ma. If the Harts Range basement correlates with that in the Strangways Range apparently only 50 Ma, or less, is allowed for this deposition of the cover supracrustals and their subsequent tectonic evolution prior to emplacement of the Bruna granite. We rather favour the interpretation that the basement and cover sequences evolved prior to the Harts Range Event (and emplacement of the Bruna granite) independently, but essentially coevally, in different tectonic facies of a rifting continental block.

The Palaeozoic tectonic evolution of the Harts Range area is well constrained by our data. Emplacement of the pegamtites-11 at about 520 Ma was apparently succeeded by significant flattening deformation. Thus tectonothermal activity during the early stages of the Alice Springs Orogeny involved more pervasive activity than simple remobilisation along narrow shear/thrust zones as suggested by Plumb et al. (1981). Some new zircon growth apparently accompanied this activity. Post-tectonic pegmatite-111 dyke mica data suggest that major tectonism, uplift and cooling had ceased by about 325 Ma. Younger mica ages in a deformed pegmatite-11 apophysis (condordant with its zircon lower intercept) suggest localised younger reactivation in narrow zones at about 300 Ma. The lower intercept age of the Bruna granite (103^{+82}_{-82} Ma) may date near-surface uplift and dilational Pb- loss.

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TECTONIC EVOLUTION OF THE PINE CREEK GEOSYNCLINE AND CONTIGUOUS TERRANES, NORTHERN TERRITORY

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The Pine Creek Geosyncline is an inlier (c. 66 000km^2) of Early Proterozoic sediments and volcanics deposited about 1900Ma ago on granitic basement which crystallised around 2500 Ma (Page et al 1980, Needham et al 1980). About 10km of supracrustals accumulated in shallow to continental environments prior to an orogenic period 90 Ma long (1870 - 1780Ma, the "Top End Orogeny"). Felsic and mafic intrusives were emplaced before and after the main deformation, which ranged in style from open to tight upright folds in low-grade areas to reclined multiple isoclinal folds in areas of medium to high-grade metamorphism. Late in the orogenic period rift-related felsic extrusives and continental sediments developed upon the metamorphosed sequence (Needham and Stuart-Smith, in press). The earlier part of this sequence was itself deformed by the last significant perturbation of the Top End Orogeny.

The hiatus between these Early Proterozoic events and the beginning of Middle Proterozoic deposition is marked by a saprolitic weathered profile on the older rocks, indicating a stable subaerial period perhaps as long as 150Ma. The cover rocks are the basal part of the McArthur Basin sequence, which extends eastward into Queensland. In the Pine Creek region they are plateau-forming sandstone generally about 600m thick, which thickens up to 2000m in basins near Katherine developed by further movement of the late Early Proterozoic rift systems.

Basin development

An intracontinental basin developed in late Archaean granitic basement probably about 2000Ma ago. Maturity of much of the sedimentary infill and the shallow to continental environment of deposition indicate a mature hinterland and gradual basin development, probably by crustal extension. The shorelines of the basin are today concealed by cover units or ocean, but the character of the basement is known from small inliers in the west and east. Palaeofacies reconstructions suggest that the presently exposed part of the basin is the NW portion of a much larger structure.

Geosynclinal sequence

Syndepositional subsidence in half-graben bounded by N - NW trending normal faults allowed the continued accumulation of shallow to continental sediments (fig 1); these faults locally influenced facies patterns (e.g. ribbon carbonate along fault lines), and were also the loci of felsic and mafic extrusions (Needham and Stuart-Smith 1984). The main rock types are subtidal siltstone (distal deltaic), carbonaceous shale (euxinic), carbonate (marine shelf), continental to intertidal sandstone (proximal deltaic), and supratidal to intertidal evaporitic carbonate (sabkha). Flysch-like interbedded greywacke and siltstone which forms the uppermost part of the pre-orogenic sequence may reflect sudden deepening of the basin related to tectonic instability heralding the onset of the orogenic period. Volcanism during sedimentation was mainly agglomeratic basalt

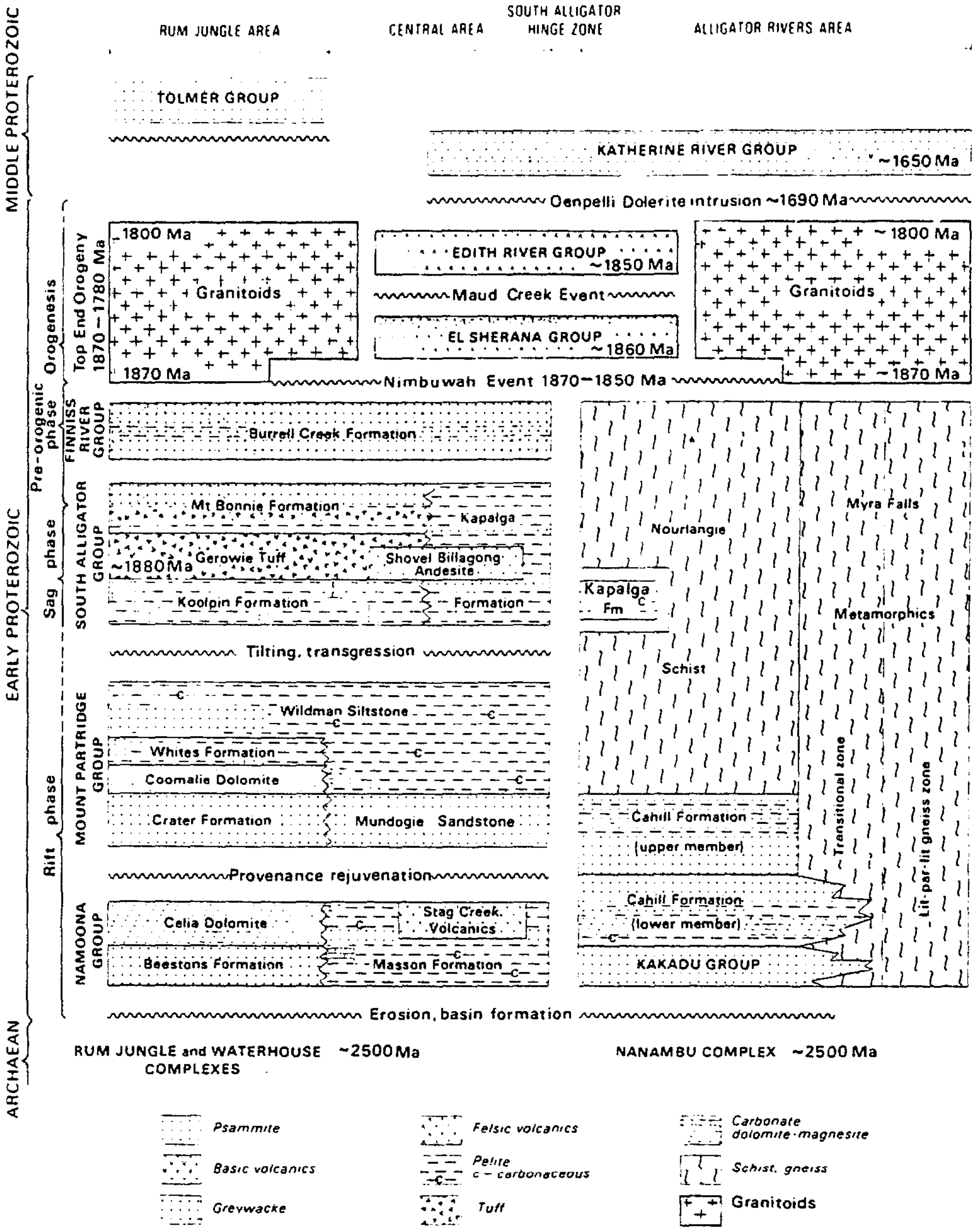

Figure 1. Diagrammatic stratigraphy of the Pine Creek Geosyncline showing tectonic stages and events, and age determinations

near the base of the sequence, extruded along a growth fault within the presently exposed part of the basin, and ashfall tuff, derived from vents east of its present area of exposure. Slight angularity, bevelling by erosion, and silicification and reworking at some contacts are related to periodic movement of growth faults or volcanic activity.

Top End Orogeny

The earliest dated orogenic event was intrusion of pre-deformation granodiorite and tonalite in the NE at 1870Ma. Isoclinal folding ("Nimbuwah Event") which accompanied the intrusion was widespread across this part of the basin, and deformed mafic sills thought to have intruded along a major growth fault near the end of sedimentation. This event, the most intense of several in the 1870 -1780Ma episode, decreased in intensity westward, and over most of the Pine Creek Geosyncline upright folds predominate. In all, five deformations have been recognised (Johnston 1984: D_1 bedding-parallel foliation, D_2 recumbent W-verging folds, D_3 upright N-NW folds, D_4 easterly tight folds, D_5 kink foliation) which are consistent with outward overfolding and overthrusting from an orogen in the NE.

Reactivation of faults in the SE after the Nimbuwah Event between about 1860 and 1850Ma formed rifts in and around which up to 3km of felsic volcanics and related sediments accumulated. Dominant rock types are rhyolite and conglomerate within the main rifts and ignimbrite, greywacke and siltstone elsewhere. One ignimbrite forms a sheet of at least $6000km^2$ associated with a subvolcanic granite at the intersection of two rifts. This sequence is divided into two groups by an angular unconformity related to upright folds of the "Maud Creek Event", restricted to the south of the region.

Intrusion of granite spanned the 90Ma orogenic episode. As well as the 1870Ma intrusion in the NE, granites were emplaced between 1840 and 1780Ma. Probably the youngest event was the "Shoobridge Event", in which hornfels related to 1840-1780 granite was deformed. This event is reflected by 1770 - 1780 Rb-Sr ages in the granites and may be the same event as the c.1800Ma metamorphic event in the northeast.

The last igneous event of the Early Proterozoic was intrusion of dolerite lopoliths at 1690Ma. The surface was peneplaned, involving removal of 1-2km of rock and deep weathering before development of the Middle Proterozoic sea east of the region at about 1650Ma.

Cover rocks

Continental sands, developed as braided alluvial fans NW of the Middle Proterozoic sea, cover the geosynclinal and orogenic sequences generally with marked angularity. Similar to the development of the Pine Creek Geosyncline, the McArthur Basin probably formed by crustal extension. Evidence of this later tectonism is in this region limited to rejuvenation of the late to post-orogenic rift systems near Katherine. Local basins formed in which up to 3 times the normal thickness of fluvial sand accumulated. Mafic lavas interbedded with the sandstone appear to have been emplaced along major faults which may represent incipient crustal extension structures outside the main boundary fault zones of the McArthur Basin further east.

The region has remained stable since Proterozoic time. Activity in this period has been restricted to minor reactivation of rift structures to allow accumulation of locally thicker Mesozoic and Eocene sequences, intrusion of minor mafic to intermediate dykes in the Late Proterozoic and Palaeozoic, and eustatic changes causing the incursion of shallow Palaeozoic and Mesozoic seas.

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ANCIENT "MASSIFS" IN THE PROTEROZOIC MOBILE BELTS OF BRAZIL

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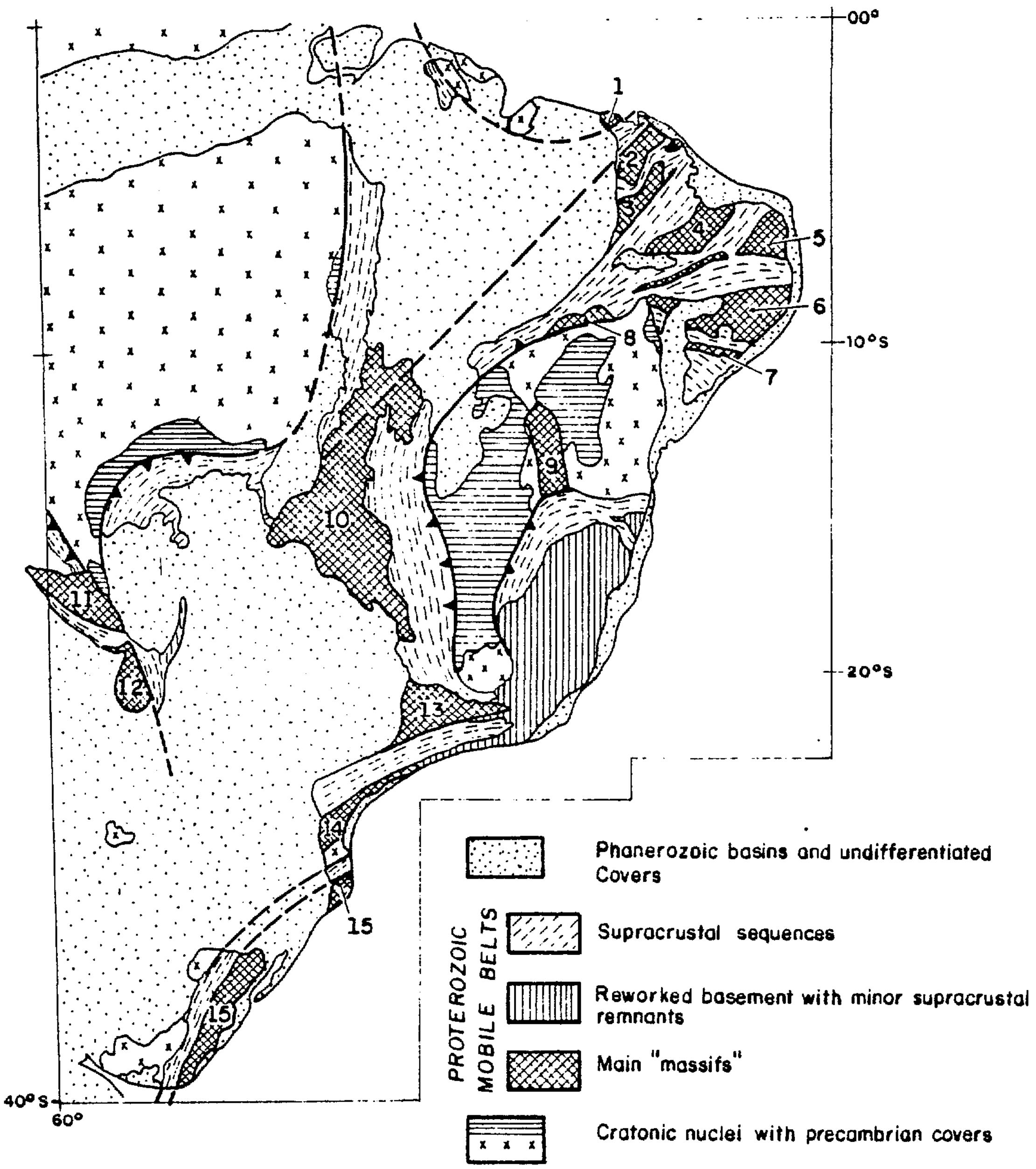
1. INTRODUCTION. Many references have been presented (Al - meida et alii, 1981) about occurrences of "median and marginal massifs" and similar structures in the Brazilian Proterozoic mobile belts. Generally, these basement inliers were dealt according to fixist concepts with modelling following simplistic points of view. All different types of basement inliers have been classified under fixist nomenclature, which presents only two or three general possibilities of choice.

Archean sialic masses have been identified as important participants of mobile belts of Early and Middle Proterozoic ages (CORDANI and BRITO NEVES, 1982), as well as Archean and Early Proterozoic blocks are continuously being identified as parts of the mosaic-like structural composition of the Late Proterozoic regions, branching them out into different fold belts. Obviously, the geodynamic roles played by all those types of "massifs" vary widely, and demand many different observations in order to be adequately classified.

Only during the last years, with a better support on structural analyses, new geophysical surveys and geochronological data, it has been possible to infer some modern insights on the roles played by such massifs according to concepts of plate tectonics.

2. Early Proterozoic. In the interior of the long vestigial belts of Early Proterozoic ages, some Archean sialic masses have been distinguished, with their ancient structural framework still preserved as well as their isotopic systems (Rb/Sr and U/Pb) not yet disturbed. The geodynamic roles of these Archean blocks (so-called "nuclei", "protocratons", "cratonic remnants", etc) is not well understood as a whole, remaining as a matter of dispute due to the lack of sufficient geological and geophysical data. Assumptions such as ancient plates (Jequie, Cobra, Cupixi, Croata areas) or fragments of plates have usually been adopted on speculative grounds.

3. Middle Proterozoic. The identification of ancient massifs in the interior of Mid-Proterozoic belts has been done with some restrictions. Good examples are the particular cases of the southern part of the Rondonian block or Jauru massive (southwest of the Amazonian Craton) and the Paramirim massif (interior of the Sao Francisco Craton) which worked out as microcontinents for Mid-Proterozoic belts. Quite often such discrimination is not possible to be done because most of the Mid-Proterozoic regions was retaken by the evolution of the Proterozoic mobile belts.



1·GRANJA, 2·SANTA QUITÉRIA, 3·TRÓIA, 4·RIO PIRANHAS, 5·CALDAS BRANDÃO, 6·PERNAMBUCO / ALAGOAS, 7·PROPRIÁ, 8·SOBRADINHO, 9·PARAMIRIM, 10·GOIÁS, 11·JAURU ("Rondoniano"), 12·RIO APA, 13·GUAXUPÉ, 14·CURITIBA, 15·PELOTAS

FIG. 1 - THE MAJOR GEOTECTONIC FEATURES OF BRAZIL, WITH EMPHASIS TO THE SO-CALLED MASSIFS

4. Late Proterozoic. Massifs in the interior of the Late Proterozoic regions, during the Brasiliano Cycle are the most common and varied cases. There already exists a fair amount of data about them which can provide first attempts of classification following plate tectonics concepts.

a) Some massifs - like Goias, Pernambuco-Alagoas and Santa Quiteria - are today recognized as remnants of small plates (250,000 km^2) that by collisional events against the major plates - the syn Brasiliano cratons - have built marginal fold belts of miogeosynclinal character, like in the Brasilia, Paraguay - Araguaia, Sergipano, Medio Coreau, etc. Indeed, there is the possibility that Gois massif be assembling two microplates separated by the Transbrasiliano lineament.

b) Other massifs seem to be the result of fragmentation of previous major plates, and so they worked out as microcontinents between ensialic troughs that evolved into ensialic fold belts through delamination processes and intracontinental subduction (Martin and Porada, 1977; Kroner, 1981). Massifs like Troia, Rio Piranhas, Caldas Brandao, Guaxupe, etc. can be envisaged this way. In fact, even position for points of triple parting would be possible to assume, like in the cases of Guaxupe, Caldas Brandao, Pernambuco-Alagoas and Jauru massifs/microcontinents (as shown in fig. 1).

c). Some elongated massifs (and/or "geanticlinal zones") are intensively pierced by calc-alkaline intrusions of Late Proterozoic times. These zones occur separating fold belts of different characteristics, and they are now being interpreted as associations of magmatic arcs ("mobile cores") between previous forearc and back-arc, environments. Examples for such cases are the Propria zone and the so-called Pelotas massifs among others.

d) The marginal massifs are localized at the peripheries of the cratonic nuclei-like Granja and Sobradinho - and characterized by intensive crustal reworking and as sites of negative gravimetric anomalies. Several different models of plate collisons can be invoked to explain the evolution of these reworked zones positioned between the craton/plate and the neighboring fold belt.

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ASPECTS OF METAMORPHISM IN THE HARTS RANGE BLOCK OF THE ARUNTA INLIER, NORTHERN TERRITORY

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In part of the Oonagalabi and of the Claraville areas, both studied in detail, evidence of hornblende granulite facies metamorphism of basement terrain (Bungatina and Cadney Formations of Division 1 of Shaw, et al, 1984 and Stewart, et al, 1984) during the presumed 1800-1750 Ma Strangways Event (Shaw et al. 1984) is provided by the presence of orthopyroxene, plagioclase and yellow brown edinitic to ferroan pargasitic amphibole in mafic gneisses. In the Oonagalabi area, granulite amphibolite facies recrystallisation appears to have taken place during BD_1, with development of a linear fabric. Evidence for a pre-BD_1 deformation event associated with the granulite facies metamorphism is obscure. In the Claraville area, a granulite facies - amphibolite facies isograd has been mapped (corresponding relatively closely with that depicted on the BMR 1:100 000 Riddock Sheet) separating an area with orthopyroxene bearing mafics from one without. Granulite facies - amphibolite facies metamorphism is interpreted as occurring during D_2. Evidence for D_1 is limited so that in both the Claraville and Oonagalabi areas, metamorphism appears to have occurred early in the deformation history, contrary to the belief of Shaw et al. (1984, p. 466) that "the Strangways event involved widespread deformation followed by regional metamorphism".

Early crystallisation temperatures in the Claraville area and other basement localities, indicated by the two pyroxene geothermometer, average 827°C. Temperatures derived from other mineral geothermometers (garnet-clinopyroxene, garnet-biotite, garnet-cordierite, and two feldspars) are somewhat lower. Pressures suggested by the garnet-cordierite and garnet-plagioclase-sillimanite geobarometers average 7 Kb at 700°C. A pressure of 9 Kb is suggested by the garnet-orthopyroxene geobarometer. Pressures and temperatures are thus similar to those characterising the Strangways Event in the Strangways Range, viz. 700 to 850° and 7-9 Kb (Shaw, et al. 1984). The mafic granolite at Claraville shows typical granulite facies lithophile element depletion. Calculations based on coexisting cordierite, garnet and biotite in rocks of pelitic composition indicate that during the high grade metamorphism in the Claraville area, water activity was of the order of 4-6. This may be related to the estimated 4.5 Kb P_{CO2} during metamorphism based on the biaxial positive 2V and relatively high birefringence of cordierite. Such P_{CO2} suggests that metamorphic fluids at the time of high grade metamorphism of the Claraville terrain consisted of possible 50%CO_2.

Retrograde metamorphism associated with D_4 in the Claraville area is evidenced by crystallisation of secondary green hornblende after pyroxene in mafic rocks and, in calc-silicate rocks, the development of abundant epidote. Retrograde epidote crystallisation which occurs also in calc silicate lithologies in the Entia gneiss dome area (see report by J.F.) maybe synchronous.

Throughout the project area, cover rocks (Division II of Shaw, et al., 1984 and Stewart et al., 1984) show amphibolite facies mineralogy such as hornblende-plagioclase, with subsidiary clinopyroxene and garnet, in the extensively outcropping amphibolites, and sillimanite-garnet-plagioclase in more pelitic compositions. Metamorphism to amphibolite facies is considered to have been associated with CD_1, the first recognisable deformation of the cover (Ding and James 1985) and to have formed an intense CS_1 foliation and a weak CL_1 mineral lineation. Amphibolite facies mineralogy has been retained throughout subsequent deformations.

Application of garnet-clinopyroxene, garnet-biotite and garnet hornblende geothermometry to the amphibolites of the Harts Range Igneous Complex suggests crystallisation temperatures averaging ca 700°C and pressures of 7 Kb. This tends to correspond with temperatures and pressures indicated by hornblende compositions based on Spear's hornblende equilibrium studies.

In what is known as the Ruby Mine area, pink corundum is found in an anorthosite layer in close association with ultramafic boudins within the anorthosite. The anorthosite is thought to be of igneous origin. As the result of amphibolite facies metamorphism the ultramafics now consist predominantly of amphibole and chlorite. It is considered that the ruby-corundum formed during this metamorphism. Ruby-corundum occurs only where the anorthositic and ultramafic lithologies are closely intermixed as the result of folding and boudinaging during CD_1 or CD_2. "Desilicification" by the ultramafic of the anorthositic compositions is thought to be responsible for the development of excess Al in the anorthosite, thus facilitating the crystallisation of corundum.

The relative depths of the crystallisation environments of basement and cover would appear to have been marginally different, viz. ca 23-30 Km (7-9 Kb) in the case of the basement and ca 23 Km (7 Kb) in the case of the cover. Whether the contrasing indicative mineralogy represents an original difference, incurred during synchronous metamorphism in the two environments, or whether it represents the difference between basement metamorphism and metamorphism of an originally unconformable cover, is uncertain.

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ISOTOPIC RECORD OF PROTEROZOIC CRUSTAL EVENTS IN NORTHERN AUSTRALIA

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In order to trace the principal tectonic and petrogenetic trends of early to middle Proterozoic terrains we need to be confident of the database that portrays the growth of the Proterozoic blocks, and their changes through time. This paper reviews such geochronological information, and attempts to establish such a framework of events in the major Proterozoic inliers of northern Australia. Over the past 10 years, increasingly precise isotopic studies have been focussed in these terrains by workers from BMR, CSIRO, ANU, University of Adelaide, and AMDEL. The resultant chronological framework is thus being continually refined, leading to firmer continent-wide correlations of major orogenic events, lithological suites, and their geochemical trends.

Late-Archaean Elements in northern Australia

Relatively small inliers of late-Archaean granitic rocks, gneisses and metasediments are identified as structural basement to early-mid Proterozoic successions in the Pine Creek Inlier. These include Archaean rocks about 2400 Ma old identified in the west near Rum Jungle, and granitic gneisses in the Nanambu Complex in the east having similar Rb-Sr total-rock and U-Pb zircon ages of 2470 Ma. Recent U-Pb measurements of sub-surface granitic rocks of similar age in the central part of the Inlier (Woolner Granite) confirm the antiquity and continuity of late-Archaean cratonic crust in this region (McAndrew and Compston, pers. comm.). Previous suggestions that the Litchfield Complex (western Pine Creek Inlier) and Halls Creek Group (oldest sequence in the Halls Creek Inlier in the Kimberley region) were Archaean in age are no longer considered valid.

Reconnaissance Sm-Nd studies in the Tennant Creek and Georgetown Inliers (Black and McCulloch, 1984) suggest that some of this crust was derived from mantle source regions 2300-2500 Ma old, but the structural and other isotopic evidence indicate that most of the material in these two inliers evolved in the early to mid Proterozoic.

Early Proterozoic orogenic metamorphism and magmatism

In northern Australia, as elsewhere in the world, a relative dearth of upper crustal events in the earliest Proterozoic between 2500 and 2000 Ma was broken with the advent of a major crustal-forming event. There is mounting isotopic and structural evidence from parts of the Pine Creek, Halls Creek, Tennant Creek, and Mount Isa Inliers, that this event was initiated as widespread metamorphic/deformational processes 1850-1900 Ma ago. Early Proterozoic metasediments ('Nullaginian' or cycle 1 of Etheridge et al., 1984) were involved in this orogenic deformation. Its age is defined by regional Rb-Sr studies of the Tickalara Metamorphics in the east Kimberley area (1920 ± 27 Ma), of pre-Warramunga Group amphibolites near Tennant Creek (1920 ± 60 Ma), and of the Bradshaw Gneiss in eastern Arnhem Land (1902 ± 75 Ma). In the Pine Creek Inlier, this event is tightly constrained in the time interval 1870-1880 Ma (the age of the unconformity between the cycle 1 South Alligator Group volcanism and cycle 2 El Sherana Group volcanism), and further substantiated by the U-Pb zircon age of 1886 ± 5 Ma for granulitic rocks in the Nimbuwah Complex. The earliest recognized metamorphism/deformation in the Mount Isa Inlier basement is also in this time interval, at 1850 to 1860 Ma.

The most substantial early Proterozoic tectonothermal event in northern Australia closely followed, and in some cases must have overlapped with, the 1850-1900 Ma orogenesis of the cycle 1 sediments. This event produced large volumes of I-type, K-rich felsic magma, which, as indicated from Sm-Nd studies was initially extracted from continent-wide mantle source regions between 2000 and 2100 Ma ago (McCulloch and Hensel, 1984).

Stratigraphically, this material marks the initiation of cycle 2 sedimentation, or the 'Carpentarian' of Dunn et al. (1966). Felsic supracrustal rocks and comagmatic intrusive bodies over each of the major northern Australian terrains have U-Pb zircon systems that closely define the age of this magmatism with a peak between 1860 and 1880 Ma. In a few cases the Rb-Sr total-rock systems are undisturbed and reflect the same ages, but mostly the Rb-Sr systems are profoundly disturbed as a result of younger metamorphic or hydrothermal alteration events. The isotopic record of this early Proterozoic magmatism contains no substantial evidence of crustal recycling or remelting of evolved Archaean crust. Rather, this protolithic growth at 1.87 ± .01 Ga was largely achieved by the addition of primitive material from the mantle or juvenile lower crust, having been initiated in earlier mantle fractionation processes at around 2.0 to 2.1 Ga.

Early to mid Proterozoic Events

The coherent age and geochemistry of orogenic felsic magmatism between 1860 and 1880 Ma over northern Australia contrasts with that of younger anorogenic felsic and mafic magmatism. The latter differs significantly in age from province to province, but could be bracketed in the interval 1650 Ma to 1790 Ma, as gleaned from combined U-Pb zircon and Rb-Sr total-rock studies. In the Georgetown and Mount Isa Inliers, detailed Rb-Sr work has given the ages of discrete mid Proterozoic deformational events at 1570 ± 20 Ma and 1470 ± 20 Ma (Georgetown), and 1610 ± 13 Ma, 1544 ± 12 Ma, and 1510 ± 13 Ma (Mount Isa). Post-tectonic granitic rocks in the eastern Mount Isa Inlier have geologically consistent U-Pb zircon results indicating emplacement ages between 1480 and 1550 Ma.

This chronological framework of the early to mid Proterozoic provinces of northern Australia and their relationship to known mineral deposits indicates that the pre-1840 Ma terrains and the post-1840 Ma terrains appear to contain quite an unbalanced share of the known economic mineral deposits. The former are essentially devoid of mineral deposits. In contrast, the latter, especially time-equivalents of the anorogenic magmatic suites, whose ages lie in the interval 1790 to 1500 Ma, have a disproportionately large share of rich and varied mineralization episodes.

Intracratonic sedimentation

The ages of early to mid Proterozoic intracratonic platform cover sedimentation in northern Australia such as in the Kimberley, Birrindudu, Victoria River and McArthur Basins, are generally not as well known as those now available in the preceding orogenic provinces. However, certain age limits can be applied. For example, the Kimberley Basin, a relatively undisturbed cover of clastic sediments and volcanic rocks, rests unconformably on 1815-1920 Ma Halls Creek Inlier rocks. A younger age limit for this Basin is 1762 ± 15 Ma, the age of the Hart Dolerite which intrudes most of the sequence. Direct dating, by U-Pb zircon means, of tuffs in the McArthur Basin yield a relatively precise age for the McArthur Group deposition of 1690 ± 27 Ma. In the other platform cover sequences of northern Australia there is little direct geochronological control, other than K-Ar and Rb-Sr glauconite ages which usually provide only minimum ages.

TECTONIC DEVELOPMENT OF THE GAWLER CRATON, SOUTH AUSTRALIA

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The Gawler Craton is a major Early Proterozoic tectonic block consisting of Late Archaean to Early Proterozoic sediments, volcanics and intrusive granites deformed and metamorphosed during two orogenic cycles, the Sleafordian Orogeny c. 2450-2300 Ma and the Kimban Orogeny c. 1850-1600 Ma.

Garnetiferous quartzo-feldspathic gneisses of presumed Archaean metasedimentary origin are widespread through central and western Gawler Craton and are associated with cordierite gneiss and iron formation (Parker et al., in press). Rb-Sr isochron ages range from 2520-2412 Ma (Webb et al., in press; Fanning et al., 1980) defining a minimum age for their formation. Various granitoids, collectively referred to as the Dutton Suite, intruded the gneisses c. 2350-2300 Ma and these are characteristically adamellites with tabular K-feldspar-bearing granites.

The garnet gneisses, granitoids and a quartz-feldspar-biotite gneiss on eastern Eyre Peninsula define basement to the Hutchison Group metasedimentary sequence. A Rb-Sr isochron for the quartz-feldspar-biotite gneiss gives a metamorphic age identical to ages determined from Hutchison Group schists (Webb et al., in press) however a recently determined zircon U-Pb age for the same gneiss is c. 2010 Ma (C.M. Fanning, pers. comm.) which is believed to represent a maximum age for deposition of the Hutchison Group. Metasediments of the Hutchison Group consist of, in ascending stratigraphic order, quartzite (with local calc-silicate and sillimanite gneiss at the base), dolomitic marble, thin-bedded graphitic quartzite and banded iron formation, semipelitic schist fine-grained garnetiferous gneiss, amphibolite, banded iron formation, and finally more schist (Parker and Lemon, 1982). Sedimentary facies changes within the quartzites and, in particular within the iron formations, infer a westerly source with a coastline that migrated back and forth, west to east across central and eastern Eyre Peninsula, and gradually deepening to the east.

Acid volcanics are not known within the Hutchison Group but various deformed acid volcanics with U-Pb zircon ages in the range 1795-1735 Ma (C.M. Fanning, pers. comm.) occur on eastern Eyre Peninsula and Yorke Peninsula. Their precise relationships with the Hutchison Group have not yet been clarified but since the Hutchison Group appears to be intruded by 1813 Ma granitoids (Mortimer et al., 1980) the volcanics appear to be associated with early Kimban Orogeny metamorphism and plutonism and hence are younger than the iron formation bearing sequence.

Precise dating of the Kimban Orogeny has not yet been achieved. D_1 is believed to be c. 1820-1800 Ma, but D_2 and D_3 could have occurred anytime from 1800-1600 Ma. Rb-Sr systematics on syn-D_2 and syn-D_3 granitoids give ages c. 1700-1650 Ma whereas the U-Pb zircon results cited above, along with a Rb-Sr age for pegmatite in a D_3 mylonite suggest ages 50-100 million years older than that.

Dolerite dykes were emplaced around the southern margins of the Gawler Craton during the waning stages of the Kimban Orogeny (c. 1600 Ma), whereas in the centre of the craton widespread acid volcanics, the Gawler Range Volcanics, and granite plutons (the Hiltaba Suite) were formed. The subsequent evolution of the craton has been largely of an epeirogenic nature with little deformation evident except adjacent to the eastern and northern margins (the Adelaide Fold Belt and Musgrave Orogenic Belt respectively).

The broad tectonic evolution of the Gawler Craton defined by a Late Archaean gneissic basement, an Early Proterozoic iron-formation-bearing sedimentary sequence, a late-Early Proterozoic (c. 1850-1600 Ma), fold-belt forming orogeny, and post-tectonic acid igneous activity, together define a relatively common pattern of Early Proterozoic crustal evolution. There are certainly many parallels between the Gawler Craton and the southwestern Superior Province of North America and this is evident not only in similar stratigraphic components (e.g. iron-formation-bearing sequences) but also in igneous and tectonic activity.

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PRECAMBRIAN MAFIC DYKE SWARMS OF AUSTRALIA

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Mafic dykes have been relatively poorly studied in Australia even though they represent major lithological components in all principal tectonic provinces ranging in age from Archaean to Recent. With few exceptions Australian dyke swarms have been emplaced into continental crustal rocks and therefore record crustal tectonic processes typical of cratonic blocks. The data upon which this review is based are presented as a poster display on a simplified 1:2.5 million scale tectonic map of Australia. The data have been derived from published and unpublished geological maps produced mainly by state geological surveys. For the purposes of this review only the outcropping or confirmed dyke swarms will be discussed.

Western Australian Orogenic Province

In the West Australian Orogenic Province mafic dyke swarms are spectacularly developed and range in age from Archaean to Late Proterozoic. Mafic and ultramafic intrusives though not shown on the poster display constitute up to 60% of Archaean greenstones in both the Yilgarn and Pilbara Blocks. The intrusives are mostly sills which were comagmatic with mafic and ultramafic volcanics of the greenstone belts. However, porphyritic gabbro and lamprophyric dykes are common. Both dykes and sills have been variously deformed and metamorphosed.

Amongst the most striking mafic dyke swarms of Australia are the very long, wide E-W dykes of the Yilgarn Block. These are the Widgiemooltha Suite of sykes dated at c. 2420 Ma. The largest of these dykes is about 585 km long, up to 3 km wide, has chilled margins and contains a subvertical magmatic layering. The Widgiemooltha Suite dykes may be tectonically related to basal Early Proterozoic basalts and intercalated dolerite sills of the Hamersley and Nabberu basins. The N-S trending Black Range Dyke Suite of the Pilbara Block has also been correlated to basal basalts of the Hamersley Basin but recent age estimates in the range 2500-2600 Ma throw some doubt on this correlation.

Throughout the Proterozoic, mafic dykes were intruded into the Yilgarn and Pilbara blocks indicating that the blocks were essentially semirigid cratonic blocks that have not been significantly tilted or deformed since the Archaean. Palaeomagnetic evidence suggests that there were at least six periods of dyke intrusion in the Western Gneiss Province of the Yilgarn during the Proterozoic and furthermore that the Yilgarn and Pilbara blocks have not moved significantly relative to each other since the Early Proterozoic. Dolerite dykes are particularly abundant around and subparallel to the southern and western margins of the Yilgarn Block, particularly within 20 km of the Darling Fault. While the latter is a relatively young Phanerozoic feature, the dykes are probably of Middle Proterozoic age c. 1000-1400 Ma, and many are altered and extensively sheared.

Late Proterozoic mafic dykes are present in the NW Yilgarn Block and in other areas of the West Australian Orogenic Province particularly in the Bangemall Basin where they occur as feeders to the extensive dolerite sills intruded prior to folding of the Bangemall Group (c. 1100 Ma), and as later NE trending intrusions transecting the folds and sills (hence younger than 1100 Ma).

North and Central Australian Orogenic Provinces

Proterozoic dyke swarms in the North and Central Australian Orogenic Provinces are widely distributed within both Archaean and Proterozoic host rocks. In nearly all metamorphic complexes irrespective of age, conformable amphibolite or mafic-granulite bodies occur intercalatead with metasediments and felsic gneisses. In the Halls Creek Block c. 2000 Ma, mafic sills and minor narrow dykes (the Woodward Dolerite) were intruded into similar-age sediments, then deformed and metamorphosed during the c. 1961 Ma orogeny. 2000-1900 Ma intrusives are also present in the Pine Creek Block, where they are known as the Zamu Dolerite, in the Arunta Block of central Australia, and in the Gawler Craton, Mt Painter Inlier and Willyama Block of South Australia. All are conformable, deformed and metamorphosed and, except for the Woodward and Zamu Dolerites, are of uncertain origin. They are not shown on the poster display.

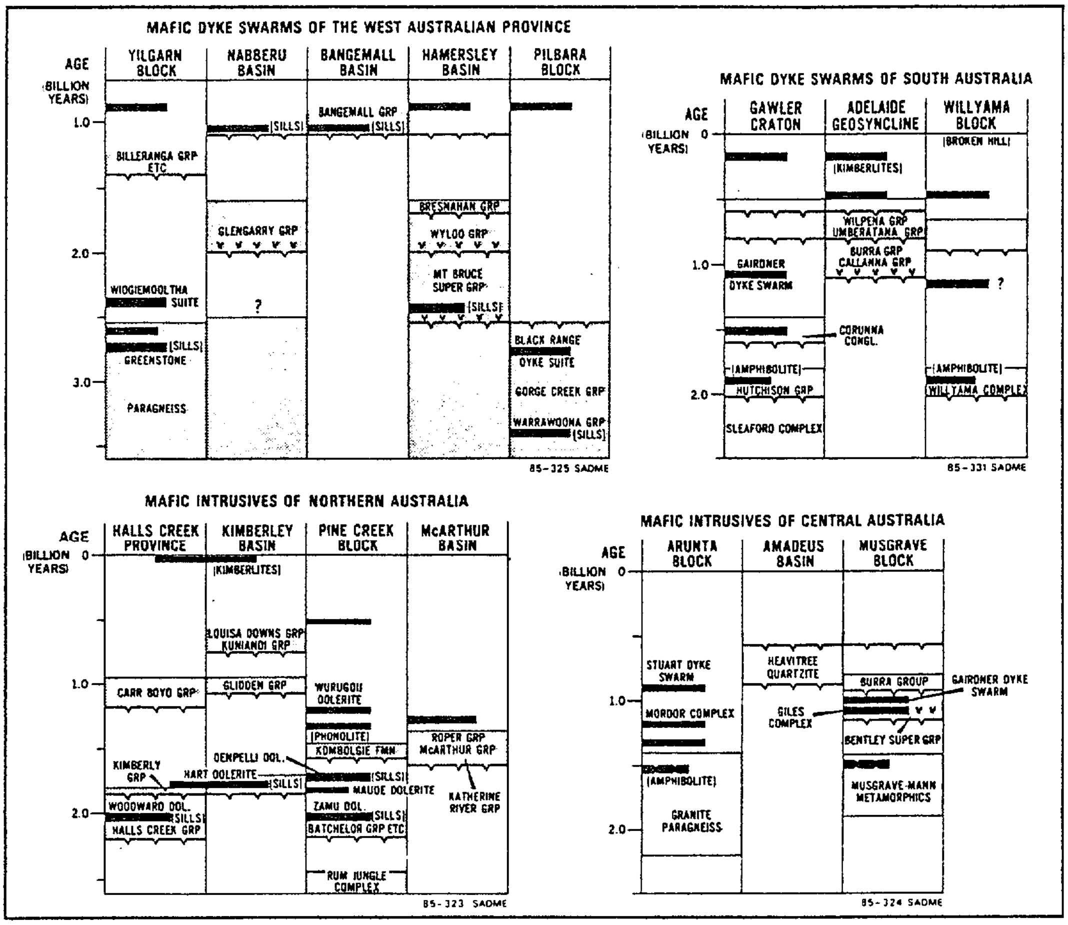
Slightly younger, Early to Middle Proterozoic mafic intrusives are also widely distributed in the North Australian Orogenic Province. The Hart Dolerite and equivalent Fish Hole Dolerite are tholeiitic dolerite/gabbro sills c. 1760 Ma which underlie the entire Kimberley Basin. Similar, thick undeformed sills (or lopoliths) of continental tholeiite composition occur in the Pine Creek Block (the Oenpelli Dolerite) and in the McArthur Basin. They were likely emplaced at depths c.1-2 km below the surface.

By contrast, in the Mt Isa Inlier c. 1800-1700 Ma, pre- or syn-metamorphic mafic intrusives were emplaced mainly as northerly trending dykes. Several suites can be recognized on the basis of petrology, intrusive relationships and distribution. All however are typically of continental tholeiite composition and all appear to antedate the major mafic volcanic successions of the Mt Isa Inlier.

Dykes of post-tectonic age are present throughout the North and Central Australian Orogenic Provinces. In the Gawler Craton they can be subdivided into two groups: a N-S trending group c. 1450-1500 Ma, and a very prominent NW trending group known as the Gairdner Dyke Swarm. The latter is c. 1100-1050 Ma in age and as a swarm extends in length for at least 1000 km. The NW dykes are of similar age to mafic volcanics preserved at the base of the Adelaide Geosyncline and as such represent the earliest phase of intra-continental rifting associated with formation of the Adelaide Geosyncline.

Separating the West, North and Central Australian Orogenic Provinces are the late-Middle Proterozoic Albany-Fraser, Musgrave and Paterson orogenic belts. These were active mainly c.1100 Ma but thrusting continued intermittently through to c. 600 Ma. In the Musgrave Block at least four phases of dyke intrusion can be identified, the first commencing late during the main orogenic phase and corresponding to the NW extension of the Gairdner Dyke Swarm. In the Albany-Fraser and Musgrave Belts the dyke intrusions are closely allied to and often parallel to narrow but long shear zones. NE trending, 1100 Ma dykes cross-cutting regional structures are present in the Mt Isa region where they are represented by the Lakeview Dolerite.

Late Proterozoic mafic dykes younger than 1000 Ma are not well known in Australia. There are NE trending dykes possibly of this age in the West Australian Province but few in the Central and North Australian Provinces. However, the Stuart Dyke Swarm of the southern Arunta Block is well known and dated (897 ± 9 Ma) and is unusual in that it is a very broad swarm of quite limited strike length.



MAFIC DYKE SWARMS OF THE WEST AUSTRALIAN PROVINCE

85-325 SADME

MAFIC DYKE SWARMS OF SOUTH AUSTRALIA

85-331 SADME

MAFIC INTRUSIVES OF NORTHERN AUSTRALIA

85-323 SADME

MAFIC INTRUSIVES OF CENTRAL AUSTRALIA

85-324 SADME

CENTRAL AUSTRALIAN OROGENY - AND HIMALAYAN COMPARISONS

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This paper compares the distinctive polymetamorphic terrains of Central Australia, which separated older cratons and were reactivated over hundreds of Ma, with the the Himalaya and Tibet Plateau.

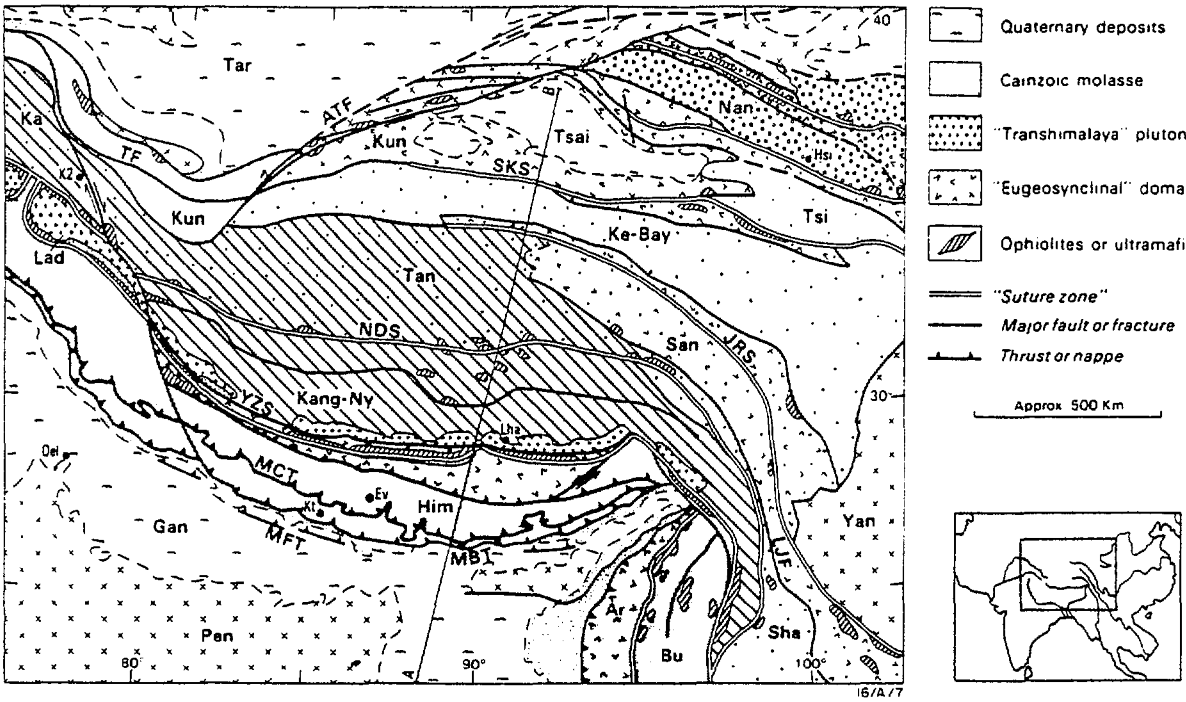

Figure 1.Tectonic sketch map of the Himalaya - Tibet Plateau region

AGE	TECTONIC EVENT	LOW HIMALAYA & SUB HIMALAYA	SOUTH TETHYS-HIMALAYA	NORTH TETHYS-HIMALAYA	YARLUNG ZANGBO SUTURE ZONE	KANGDESE-NYAINQENTANGHLA
QUATERNARY	ISOSTATIC UPLIFT	Siwalik Molasse *UNDERTHRUST-MBF, MFT* Folds, thrusts in Siwalik Uplift	*ISOSTATIC UPLIFT OF HIMALAYA AND TIBET PLATEAU* Conglomerate moraine fluvioglacial deposits (UNCONFORMITY)			
LATE MIOCENE TO PLIOCENE	INTRACONTINENTAL CONVERGENCE	*UNDERTHRUST-MBF* Overthrusts in Low Himalaya	*PENEPLANATION OF TIBET PLATEAU SURFACE* Lake deposits karstic weathering			
OLIGOCENE TO EARLY MIOCENE		*UNDERTHRUSTING– MCT* Intense recumbent folds overthrusts and Barrovian metamorphism in Low Himalaya	South-vergent recumbent folds thrusts Barrovian metamorphism and S-type granite in High Himalaya	Upright folding	Upright folding, Northward counterthrusts (Retrocharriage) Oligocene-Miocene molasse 500m 4000m (UNCONFORMITY)	North counterthrusts S-type granite
EOCENE (To Oligocene ?)	CONTINENTAL COLLISION	*REGRESSION* (Middle-Late Eocene) *TRANSGRESSION* Early-Middle Eocene limestone shale 400 m (Granite ?)		*UNDERTHRUSTING OBDUCTION* South-vergent folds thrusts S-type granite metamorphism	Ophiolite nappe emplacement onto Tethys-Himalaya Underthrusting metamorphism	S-type granite
LATE CRETACEOUS TO PALEOCENE	CONTINENTAL CONVERGENCE	(Hiatus)	*CONVERGING MARGIN* Paleocene hiatus. Shelf limestone shale sandstone 465m	Wildflysch olistostromes pelagic and argillaceous matrix 1100m (UNCONFORMITY)	*ARC-TRENCH COMPLEX* OPHIOLITES Radiolarite pelagic limestone shale 1100m FLYSCH WEDGE Turbidite conglomerate pelagic limestone Marginal molasse 2500m	I-type granite-granodiorite gabbro Low-P metamorphism Calc-alkaline volcanics 2000m (UNCONFORMITY)
MID JURASSIC TO EARLY CRETACEOUS	WIDENING NEOTETHYS	Sandstone limestone 2000m	*PASSIVE MARGIN* Shelf limestone sandstone shale 2800m	Bathyal(?) calcareous and siliceous shale marl turbidite dacite 2500m	Harzburgite, gabbro pillow basalt	Sandstone shale coal limestone 2400m
TRIASSIC TO EARLY JURASSIC	INDIA-KANGDESE RIFTING OPENING NEOTETHYS	Limestone shale 2000m	Shelf sandstone [illegible] limestone 1600m	Calcareous and argillaceous turbidites 1400m	*RIFT* Siliceous and calcareous shale radiolarite flysch basalt local shelf limestone ~1000m	Shelf limestone sandstone shale andesite 2400m

16/05/3

Table 1. Summary of stratigraphy and tectonic evolution of Nepal-Tibet Himalaya

The Tibet Plateau comprises several microcontinents which accreted throughout the Phanerozoic (younging N-S) (Fig. 1). Most foldbelts incorporate considerable Precambrian basement and platform sediments, and each collision reactivated older belts. The Tanggula, Kangdese, and Indian blocks each rifted from Gondwana, and then collided with Pal-Asia in the Late Triassic, Early

Cretaceous, and Eocene respectively. Since the Eocene there has been 1500-2000 kms of intracontinental convergence (still continuing), accommodated by either internal deformation or underthrusting of India beneath Tibet.

Important points from Table 1 are: Most exposed rocks are ensialic. Relicts of oceanic separation and convergence - ophiolites, flysch, melange, and high-P metamorphics - are only preserved in a discontinuous narrow belt of imbricated nappes and thrusts, unlikely to survive future convergence and erosion. The Kangdese block produced arc-type volcanics and granite during convergence, S-type granite after collision, and low-P metamorphics throughout. The Himalaya to the south displays post-collisional southward migration of deformation, Barrovian metamorphism, S-type granite, and major underthrusts (A-subduction).

ARUNTA BLOCK			
EVENT	NORTHERN ZONE	CENTRAL ZONE	SOUTHERN ZONE
900-300 Ma	PLATFORM COVER SEDIMENTATION IN AMADEUS (UNCONFORMITY)		
LATE TO POST OROGENIC 1000-900 Ma	Granite 930 ± 190 Ma	Granite 900 ± 13 Ma	Stuart Dykes 897 ± 9 Ma Basalt flows (UNCONFORMITY)
ORMISTON EVENT 1100-1000 Ma	Local retrogression Weldon Tectonic Zone		Retrogression, amphib. grade; granite 1053 ± 50 Ma
ANMATJIRA EVENT 1500-1400 Ma	Local metamorph - Weldon T Z Acid volcanism gran - 1490 Ma (UNCONFORMITY)		
AILERON EVENT 1700-1600 Ma	High-gr. met S & I-type granite	Local metamor south margin	Amphib metam. I-type gran. Mafic intrus.
STRANGWAYS EVENT 1800-1750 Ma	Post-orog gran 1775 Ma Low-grade met	Granul metam. Anatec gran. 1790 ± 35 Ma	

MUSGRAVE BLOCK			
NORTHERN ZONE	CENTRAL ZONE	SOUTHERN ZONE	EVENT
NGALIA - GEORGINA - OFFICER BASINS (UNCONFORMITY)			900-300 Ma
Dolerite dykes Bimodal volc Granite	Bentley Sgp: ignimbrite-gran. cauldrons; bimodal volcanics (UNCONFORMITY)	Dolerite dykes	LATE TO POST OROGENIC 1000 -900 Ma
Northward thrusting, folding Pottoyu Cplx: granite retrogression Olia Gneiss 1050-1170 Ma	Giles Cplx: gabbro emplac Kulgeran (charnock) granites 1070-1120 Ma	Tollu Volcs 1040 Ma (UNCONFORMITY)	KULGERAN EVENT 1150-1000 Ma
Olia Gns: refolded amphib; south margin	Musgrave-Mann Cplx: granulite; thrusts?	Refolding; trans-granul; north margin	REGIONAL METAMORPHISM 1200 Ma
Metamorphic prehistory; age unknown	Acid-intermed igneous emplacement		"MASSIVE GRANULITES" 1330 Ma
	Qtz-felspath aren, pelite, mafic intrus.		"Layered Granulites" 1560 Ma
		Wateru Gneiss Granul metam. 1620 ± 120 Ma	KIMBAN OROGENY 1800-1650 Ma

18/12

Table 2. Synthesis of tectonic evolution of Arunta and Musgrave Blocks

The Arunta and Musgrave Blocks of central Australia underwent repeated orogeny, of Himalayan scale, from at least 1800-900 Ma. They form a single mobile belt which continues in the subsurface to at least the West Australian coast. They separate cratons of quite different histories. Palaeomagnetic data on the positions of these cratons is equivocal. Related structures extend 1000 km into the adjoining craton. Very little of the total mobile belt is exposed.

The Arunta Block has long been divided into three zones possessing distinctive assemblages of rocks and geological histories (Table 2), and separated by major structures extending to the mantle. Unconformities divide the stratigraphy into three Divisions, but correlation between Zones is uncertain. Metamorphism is mostly of low pressure-intermediate facies style. The Northern Zone is continuous with the North Australian Province. The Central Zone is characterised by upthrust mafic and acid granulites of the 1800-1750 Ma Strangways Event. The Southern Zone is the main site of the 1700-1600 Ma Aileron and 1100-1000 Ma Ormiston Events, both of which caused local reworking to the north; it is separated from the Central Zone by the north-dipping Redbank Zone.

The Musgrave Block is similarly divided herein into three zones (Fig. 2, Table 2). The Southern Zone is the reworked northern extension of the Gawler Craton. The Central Zone is characterised by two unique sequences - 1560 Ma-old sediments and 1330 Ma-old igneous(?) rocks - metamorphosed in the medium to high pressure granulite facies and upthrust, along with the mafic Giles Complex intrusives, during the 1200-1000 Ma Musgrave Orogeny. The zone is bounded by the south-dipping Woodroffe Thrust and Hinkley-Mann-Ferdinand Fault System. The Olia Gneiss of the Northern Zone lithologically resembles the Southern Zone, Arunta Block, with which it displays geophysical continuity beneath the Amadeus Basin. Small relicts of pre-Musgrave Orogeny low-pressure metamorphic rocks are preserved.

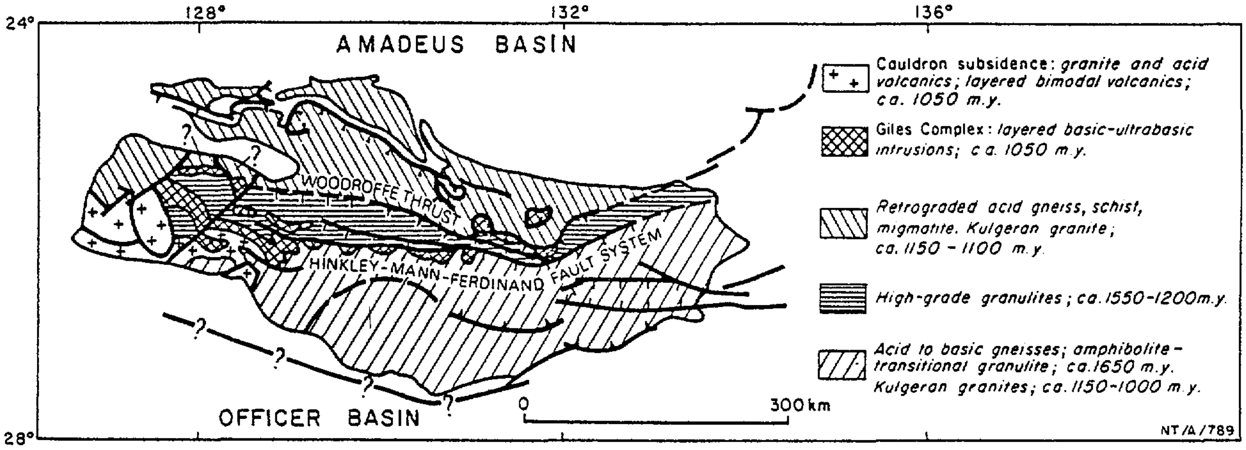

Figure 2. Tectonic sketch map, Musgrave Block.

DISCUSSION

Totally ensialic orogeny is almost indisputable in some Proterozoic terrains, but collision models can not yet be totally discarded. Lack of preserved oceanic crust and abundance of sialic basement is not a problem. The Southeast Asia pattern of microcontinents and sutures is an attractive analogue for Precambrian cratons and mobile belts. The most useful analogue from the Himalaya itself may yet be the intracontinental convergence (A-subduction), but such convergence still requires massive plate movements, difficult to conceive without some continental separations.

Much remains to be learnt about the complex central Australian terrains, particularly the critical Musgrave Block. But the differences between histories of the zones before the Kulgeran Event in Table 2, and between the North Australian and Gawler Cratons farther afield, is very striking. The 1200 Ma metamorphism heralds a progressive merging of all these terrains, culminating in the continuous platform cover from south to north Australia after cratonisation at 900 Ma. Are these blocks/zones exotic terrains accreted during one or more collision events?

Any collision must have occurred at about 1200 Ma, at the Mann Fault between the Musgrave Central and Southern Zones (subject to the relationship between the Musgrave-Mann granulite metamorphism and thrusting), or later, as the extensive post-Giles thrusting. A third alternative combines both: accretion/collision of the Central Zone with the Southern Zone/Gawler Craton at 1200 Ma (Mann Fault), and then post-Giles collision of this block with the Northern (Musgrave) Zone/Arunta Block/North Australian Craton around 1050 Ma. Similar collisions might explain earlier events in the Arunta Block (e.g. Aileron Southern/Central collision at the Redbank Zone), but are not currently favoured by workers in this area.

Progressive northward migration of deformation, and medium-high pressure metamorphism in the underthrust (northern) blocks fits the Himalayan model. Bimodal volcanism on the southern (upper) plate agrees with tensional grabens, high heat flow, and volcanoes recently discovered on the Tibet Plateau. The two-stage ("Tollu" and "Bentley") volcanism could favour two collisions.

PROTEROZOIC OROGENY WORLDWIDE - DIACHRONOUS, RANDOM, OR EPISODIC?

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Opinion on whether orogeny occurs at the same time worldwide, or whether it is random and diachronous, can impose important constraints on some tectonic models.

In the Phanerozoic most recognise that orogenies have occurred at very similar times over widely dispersed areas; the Caledonian, Hercynian, Alpine, and so on, although such cycles do tend to overlap in detail. At a finer scale orogenic peaks migrate with time, even along a single foldbelt, and so orogeny can be deemed to be diachronous or random.

These arguments are not immediately relevent here, because they involve time resolutions beyond that presently available in most Precambrian terrains. However, the length of Precambrian time is important in assessing longer cycles, each perhaps as long as or longer than the whole of the Phanerozoic.

Long-term episodicity has been popular since Gastil (1960) demonstrated worldwide peaks of mineral ages at about 2700-2500 Ma, 2200-2000 Ma, 1850-1650 Ma, 1500-1300 Ma, 1100-900 Ma, and 600-300 Ma. This theme has been followed by many authors since, with frequent reference to worldwide correlation of cycles such as the Hudsonian or Grenvillian, concepts of long-term cyclicity such as Sutton's (1963) chelogenic cycles, and identification of evolving styles of orogeny through time.

The IUGS Subcommission on Precambrian Stratigraphy has been compiling worldwide time-stratigraphic charts from data supplied by national representatives, as the database for their primary task of recommending a time-subdivision scheme for the Precambrian; these charts have now been submitted for publication (Plumb & James, in press). Because so many Precambrian sequences are deformed and metamorphosed, major tectonomagmatic cycles have been commonly used for local subdivisions of the Precambrian, and this approach has been followed on the Subcommission's charts. Stratigraphic sequences and tectonic events have been classified in accordance with the scheme developed for the Tectonic Map of Australia (GSA, 1971):

(1)sedimentation/magmatism preceding orogenesis;
(2)intense deformation, metamorphism, and plutonism (orogenesis);
(3)transitional domains;
(4)platform cover.

Such a compilation can provide a useful, objective, and up-to date database in the context of this meeting, to assess the distribution through time of major geological/tectonic events, and perhaps constrain or enhance some models.

The Subcommission itself has no intention of proving worldwide orogeny; indeed, it has proceeded on the assumption that geological events are essentially diachronous. The original Subcommission compilation grouped the stratigraphic columns regionally, but this obscures some interregional patterns. For the purpose of this paper the interregional patterns and correlations have been enhanced by rearranging the original columns on a second chart, in the order of their terminal or principal orogeny or time of cratonisation.

DISCUSSION

Allowance must be made when assessing such charts for differing reliability of data (e.g. zircon vs Rb-Sr ages), and for the local distortion of real rock relationships by space limitations; units have commonly been displayed on the same vertical column when they do not truly overlie each other in the field. Despite these limitations, the charts very clearly confirm and enhance the cyclic patterns and trends already alluded to.

However one interprets the significance of the individual stages, the general tectonic cycle, originally defined from Phanerozoic orogens, of sedimentation, orogenesis, transitional tectonism, and platform cover, can be applied throughout the Precambrian.

The well-known abundance of greenstone belts and their orogenesis in the Archaean, particularly around 2700-2600 Ma, is clear, but is not a topic of this meeting. What is significant is that this episode provided the basement for the earliest widespread Proterozoic platforms, and for (?)ensialic orogens.

The most outstanding feature on the chart is the dominance of orogeny, of apparently very similar style, around 1800±200 Ma; very much a topic of this conference. Where well-constrained geochronologically, these belts commonly passed through parallel cycles of sedimentation, orogenesis, and transitional tectonism/cratonisation in only about 200 Ma. Orogeny and transitional tectonism peaked around 1900-1800 Ma (e.g. North Australia), but gradually tailed off through other belts to 1600 Ma. Some of the latter were "complete orogens", just like those slightly older (e.g. Svecofennian), but others continued upon a "basement" of the earlier ca 1850 Ma event (e.g. Mount Isa). This widespread and distinctive "1800 Ma" orogeny was immediately followed by probably the most widespread development of cratons and platform covers in the Proterozoic.

Similarly striking is the parallel development of the polymetamorphic terrains, so characteristic of the mid-Proterozoic throughout the world; the Grenville, Central Australia, Southwest Gneiss Belt of Sweden, and so on. These belts all display very similar time scales of repeated sedimentation and metamorphism. They invariably incorporate elements of the 1800-1600 Ma orogens, and sometimes Archaean, and also of Gastil's 1500-1300 Ma events. Very few 1500-1300 Ma events stand alone in independent belts. The terrains mostly went through their "terminal" orogeny and cratonisation, via late-tectonic events of transitional character, at about 1000-900 Ma. Interesting is the parallelism of this final orogeny with extensional events on adjacent cratons: the Keweenawan and MacKenzie Dykes during the Grenville in North America; the Bangemall Basin and initial Adelaidean during the Musgrave Orogeny of central Australia. Such a relationship is not yet apparent from older terrains.

This cratonisation event heralded another apparent change in tectonic style: platform covers, such as the Central Australian Platform Cover across most of the Australian Shield and the Sinian of South China, and new orogens such as the Pan-African and Brasiliano. The platform covers and many of the orogens of this interval pass up into the Palaeozoic with little or no break. There is widespread acceptance of Wilson Cycle models for tectonism from this interval. Proterozoic ophiolites are known from the Arabian-Nubian Shield (Shackelton, 1979).

Most of these observations are not new. But this database does graphically emphasise the following:

1) There is certainly a cyclicity in major orogenic events and cratonisation of new platforms, implying a periodic, concurrent, and widespread development of whatever mechanism drives orogeny (cf Gastil, 1960; Sutton, 1963);

2) Certain periods are characterised by similar chronological patterns of orogeny, probably implying an evolution of tectonic style through time (cf Kroner, 1977, 1981; Windley, 1977);

3) Equally, the similar tectonic cycle through which almost all orogens finally pass, in leading up to cratonisation, imply a large degree of uniformity in the basic process of orogeny through time (cf Plumb, 1979).

Finally, although not intended as an aim of this paper, the modified and somewhat more subjective time-stratigraphic chart used graphically supports the Subcommission's recommendation that 1600 Ma and 900 Ma represent significant boundaries for a first-order subdivision of the Proterozoic.

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STRATIGRAPHIC INTERPRETATION OF HIGHLY DEFORMED AND METAMORPHOSED METASEDIMENTS OF CENTRAL BUSHMANLAND, NAMAQUA MOBILE BELT, SOUTH AFRICA

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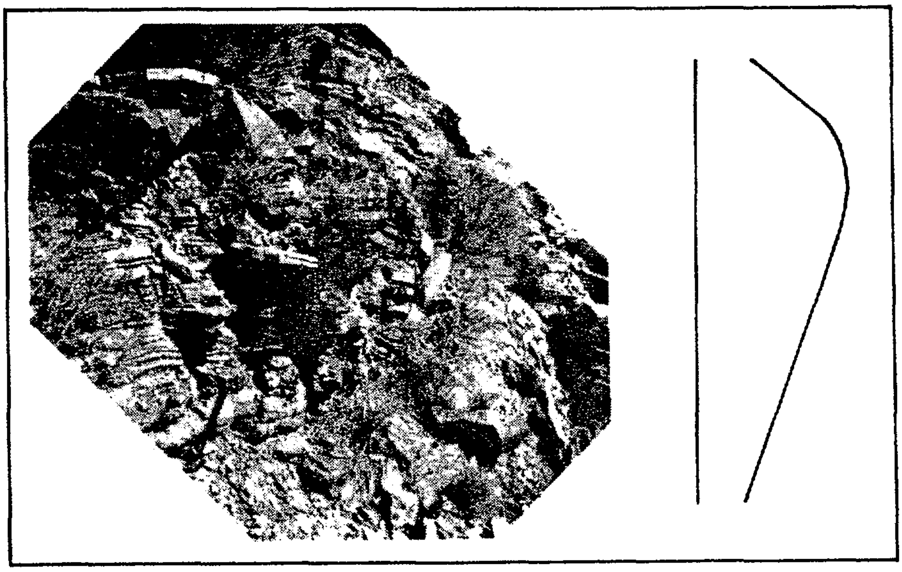
The western part of the Proterozoic Namaqua mobile belt consist of three major stratigraphic domains. In the north there is the Grunau Group (meta-shale and -greywacke), with the Haib Subgroup in the centre (meta-volcanite) and the Aggeneys Subgroup in the south (meta-quartzite, schist, meta-volcanite and banded iron formation). The Aggeneys Subgroup structurally overlies the Haib Subgroup. These two Subgroups belong to the Bushmanland Group, which is a volcano-sedimentary sequence with a possible age around 2000 Ma. The Aggeneys Subgroup, which hosts important base metal deposits, forms the main theme of this paper.

Mapping, with structural and stratigraphic control, was done in critical parts of the study area. Primary sedimentary structures, such as ripple marks and crossbedding, have almost been totally obliterated by metamorphic reconstruction. To overcome this problem a technique (Colliston and Loock, 1984) was developed for the determination of th correct facing direction, using sedimentary cycles. This technique was applied to mapped areas, with satisfactory results (Figure). Application of this method to the stratigraphic reference area (the Haramoep area), yielded results which were consistent with the younging direction previously established.



A first order delta front cycle in the Koeris Formation.

COMPOSITION, AGE AND TECTONIC SETTING OF VOLCANIC ROCKS IN THE CENTRAL BUSHMANLAND GROUP, WESTERN NAMAQUA PROVINCE, SOUTHERN AFRICA

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The Western Namaqua Province (WNP) of Southern Africa is composed of several supracrustal assemblages and intrusive granitoid suites that were formed during the Mid-Proterozoic 2.0-1.0 Ga ago. Two of the older supracrustal suites: (1) the 2.0 Ga old Orange River Group (ORG) and (2) the 1.6-1.7 Ga old Bushmanland Group (BG) have been the subject of intense study recently because of their considerable strategic metal potential, with the ORG containing some of the oldest porphyry Cu-Mo deposits known, while the BG hosts several giant stratiform base metal deposits. We focus attention here on the central part of the BG near Aggeneys and examine the role of volcanism in the evolution of this metalliferous sequence. The original stratigraphy of the BG has been practically obliterated by polyphase folding, shearing and overthrusting, while original lithologies have been rendered almost unrecognisable by medium to high grade metamorphism. At the outset it is important to note that despite tectonothermal modification the BG was probably not a very thick sequence, in contrast with other Proterozoic basins in other continents which host similar ore deposits. Moreover the BG is predominantly sedimentary and the products of proximal volcanism are relatively minor, although their presence in the stratigraphy has enabled useful information to be gained on basin characteristics such as age, tectonic setting, metamorphic history, the source of metals, sulphur and ore forming fluids.

In view of the structural complexity, several structural- stratigraphic models for the BG have been proposed. A currently popular model developed by workers active in the exploration and exploitation of the BG ore deposits (eg. Joubert, 1974, Rozendaal, 1978, Ryan et al., 1982) ascribes to a "working stratigraphy" which consists of a basal leucocratic quartzofeldspathic gneiss suite, followed by pelitic schists, metaquartzite, the ore horizon pelitic schists and chemogenic metasediments, and finally a mixed volcano-sedimentary member consisting mainly of metabasaltic amphibolite, conglomerate and psammitic schists. The upper BG basaltic lavas appear to represent the first onset of major extrusive activity within the sedimentary basin, which effectively terminated the important period of ore horizon development. Acid volcanic precursors are suspected for parts of the basal BG leucogneiss suite, but tectonothermal modification and the ambiguous nature of leucocratic gneisses in general make identification difficult.

Analysis of obviously altered amphibolites amongst our sample suite and inspection of major and trace element variation diagrams have allowed us to assess the degree of compositional modification due to secondary processes, and to subsequently identify several primary characteristics of the original basaltic lavas. The BG amphibolites represent metamorphosed tholeiitic basalts which straddle the silica saturation boundary (ie. Qz or Ol-Hyp normative). MgO contents vary from 9% to 4%, which correspond to Mg numbers of 60-35, and Ni-MgO covariation shows these Proterozoic basalts to be enriched in Ni relative to modern basalts, a feature reminiscent of Archaean tholeiites (Gill, 1979). Incompatible element abundances define two basalt types, with salient differences being Ti/Zr ratios and REE patterns. Overlapping Mg numbers, Ni and Cr contents argue against the two basalt types being linked by fractional crystallisation. Nevertheless, Sm-Nd isochron relationships point to a common initial ^{143}Nd/^{144}Nd ratio, and hence the two types are not distinguishable isotopically.

Various past estimates of the age of BG sedimentation have been based on inferences from long range correlations with other supracrustal assemblages of known age, or from Pb isotope model ages derived from the resident stratiform ore deposits (Koppel, 1978). The amphibolites have yielded a Sm-Nd isochron age of 1.6-1.7 Ga, with an initial ^{143}Nd/^{144}Nd ratio close to bulk earth at that time. We interpret this as the best estimate for the extrusion age of the basalt precursors to the BG ampbibolites. By inference from the stratigraphic position of these metavolcanic rocks, the Sm-Nd age provides a minimum estimate for the age of the BG sequence and resident ore deposits.

Results of a parallel Rb-Sr and U-Th-Pb study of the BG amphibolites indicate strong metamorphic resetting 1.2-1.1 Ga ago, thereby confirming earlier work on the WNP (Nicolaysen and Burger, 1965, Clifford et al., 1975, 1981, Barton, 1983). Of particular interest was the marked domainal response of the BG amphibolites to Rb-Sr resetting, since the various exposures and borehole intersections produced a series of parallel isochrons indicating similar closure ages but different initial ^{87}Sr/^{86}Sr. The magnitude of the initial ^{87}Sr/^{87}Sr roughly correlates with average Rb/Sr of each amphibolite unit. It follows that Sr isotope equilibration occurred after the major phases of deformation which resulted in extensive dismemberment of the original basaltic lava horizons into a series of thickened fold closures, attenuated limbs and boudinaged lenses.

In contrast the BG amphibolites conform to a single Pb-Pb isochron but which yields the same metamorphic age of 1.2-1.1 Ga. Extrapolation of the Pb-Pb isochron to less radiogenic compositions causes it to pass through the tight field occupied by the ore galenas, thereby pointing to a common Pb isotopic composition. In view of the older Sm-Nd age, we interpret the coincidence as the BG amphibolites being affected by Pb mobilised from the ore deposits during metamorphism. Such swamping is not confined to to the amphibolites, because we have seen the same effect on the Pb isotope systematics of other lithologies in the BG, and also parts of the pre-BG gneiss basement. In other words, despite the likelihood of diverse source regions and U-Th-Pb fractionation histories, practically the entire spectrum of lithologies in the immediate vicinity of the BG ore deposits attained a common Pb isotopic composition during metamorphism 1.2-1.1 Ma ago.

Characteristics of the source region to the BG basalts have been inspected with normalised trace element abundances using the methods of Pearce (1982). The least fractionated BG basalts have pronounced negative Ta and Nb anomalies, but with Zr,Hf,Ti,P and Y contents similar or slightly enriched relative to MORB. Affinities with arc basalts as suggested by the Ta-Nb anomalies are confirmed by Ce-Ta-Th covariation, which indicate that the source region for the BG basalts experienced variable geochemical modification similar to that proposed for the mantle wedge overlying subduction zones. In order to reconcile the requirement of subduction related metasomatism in the source to tholeiitic basalts erupted within what appears to be a cratonic sedimentary basin, we suggest that back arc continental extension could provide a satisfactory tectonic setting, as such an environment is intrinsically linked to subduction. Back arc basins often contain basalts with mixed geochemical affinity, displaying trace element and isotope patterns that span the range from MORB to arc-type. The associated 1.7-1.6 Ga old arc environment that developed adjacent to the back arc Bushmanland basin has not been recognised but certain plutonic components of the Vioolsdrif granitoid batholith, which follows the Orange River volcanic belt for most of its extent across the northern margin of the Bushmanland basin, and which have radiometric ages of ~1.7 Ga, represent magmatic activity significantly younger and unrelated to the older 2.0-1.9 Ga Orange River magmatism (Reid, 1979). It is suggested that the Bushmanland basin represents part of a 1.7-1.6 Ga old arc - back arc tectonic regime superimposed on an older arc complex, now represented by the Orange River belt.

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INDIAN RIFT VALLEYS AS THE SITES OF FORMER OROGENIC BELTS

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Peninsular India contains a number of structural joins, many of which are of uncertain magnitude and significance (Fig. 1). Three of the major joins are present rift valleys (Godavari, Mahanadi, and Son-Narmada) along which structural activity began at least as early as the middle Proterozoic. Two of the rifts (Son-Narmada and Mahanadi) are associated with major thrust faults (Fig. 1) that juxtapose terrains of markedly different metamorphic grade and presumably were the sites of former orogenic belts. No associated orogenic structures have been found along the Godavari rift. Extensive strike-slip faulting occurred along the Son-Narmada rift. The relative ages of compressive orogeny and rifting have not been fully established, but it is clear that at least some rifting is younger than thrusting, and it is likely that the rifting events began on former orogenic belts (discussed below).

The rift valleys, plus the major thrust zone (front) along the western margin of the Eastern Ghats (Fig. 1), divide the Indian Precambrian shield into a number of separate cratons with somewhat dissimilar geologic histories. Other structures shown on Figure 1 are probably of lesser displacement, although the distinction is not clear. These smaller zones include the Singhbhum thrust zone, which occurs wholly within an oceanic volcanosedimentary suite between two sialic regions of the Singhbhum craton, the Great Boundary fault in the Aravalli craton, and a thrust and several lateral shear zones (not shown on Fig. 1) in southernmost India.

The three areas shown on Figure 1 in southern India (Western Dharwar, Eastern Dharwar, and Granulite terrain) have different geologic histories, but there is no evidence of an orogenic join between them. In particular, the contact between the granulite-facies area and the amphibolite-facies areas (Western and Eastern Dharwar cratons) shows no evidence of thrusting, no gravity anomaly, and complete lithologic gradation from amphibolite-facies gneiss to charnockite. The Indian shield south of the Godavari rift and Deccan basalts and west of the Eastern Ghats front is regarded as having been a single cratonic block since 3,000 to 2,500 m.y. ago and possibly earlier.

Ages of activity along the various joins are only moderately constrained. Relationships of the Great Boundary and Son valley faults (Fig. 1) with middle Proterozoic and younger sediments in the Aravalli craton indicate that movement began on these faults about 1,500 m.y. ago. Granulite metamorphism in the Eastern Ghats occurred about 1,500 m.y. ago, and the Eastern Ghats front andSukinda fault zone probably have the same age. Mineralization along the Singhbhum thrust also occurred about 1,500 m.y. ago. Southeastern outcrops of sediments of the Godavari rift were metamorphosed along the Eastern Ghats front, indicating that the Godavari rift was in existence 1,500 m.y. ago. Apparently, the present area of the Indian shield, and possibly adjacent areas of Gondwanaland, became a stable unit approximately 1,500 m.y. ago. Controversy exists as to whether the joins represent closure of ocean basins between the cratons or were essentially intracontinental.

The relationship between the rift valleys and orogenic belts is interesting in view of recent proposals that orogenically thickened continental crust is weaker than normal crust and more susceptible to fracturing. As mentioned previously, age relationships between thrusting and the beginning of rifting are not clear along the Son-Narmada and Mahanadi rifts, and no thrust has been detected along the Godavari rift. Nevertheless, the association of two rifts with orogenic structures suggests a causal relationship.

The preceding observations raise several questions. One is why rift valleys are not associated with all of the major thrusts in the Indian shield. For the Singhbhum thrust zone, a possible answer is that the orogenic belt involves only supracrustal rocks formed ensimatically, and thus did not have a continental crust capable of being rifted. For the Great Boundary Fault and Eastern Ghats front, a highly speculative answer can be based on their orientations, which are mostly parallel to each other. During the middle Proterozoic, India was probably incorporated in Gondwanaland, with only its present northern margin adjacent to oceanic lithosphere. If the Eastern Ghats front and Great Boundary fault were perpendicular to this oceanic margin, then expansion across the fault zones would have been constrained by surrounding continental material and may have been impossible, and rifting occurred only in orogenic belts with some orientation parallel to the margin.

A second question is why present valleys occupying the sites of middle Proterozoic rifts are so much more common in India than in other shields. A possible answer to this question lies in the relative production of heat in different shields. High content of radioactive elements and high heat flow have been proposed for India by several previous investigators. Table 1 supports these suggestions by comparing data on the Th and U contents of typical Archean tonalite/trondhjemite "gray" gneisses in the Western Dharwar craton of India with equivalent rocks in the Superior province of the Canadian shield.

The principal observation from Table 1 is that both Th and U are more concentrated in the Indian gneisses than in the Canadian suites. The U content is particularly high in the Indian suites, making the Th/U ratio much lower than the normal 3 to 6 for igneous and meta-igneous rocks. This low ratio implies U metasomatism, and more detailed evidence presented elsewhere indicates metasomatic addition of U to the craton about 3,000 m.y. ago.

The data presented in Table 1 refer only to one area in the Western Dharwar craton. They do, however, support other observations of high heat flow and radioactivity in various parts of India. The continued activity of rift zones since the middle Proterozoic in India is consistent with a high content of radioactive elements in the shield. The consequent high heat flow weakened the crust and promoted rifting, with preferential separation along those former orogenic belts with favorable orientations. This high heat flow may be largely the result of extensive U metasomatism. It is possible that this metasomatic activity was more intense in India than in other Archean shields.

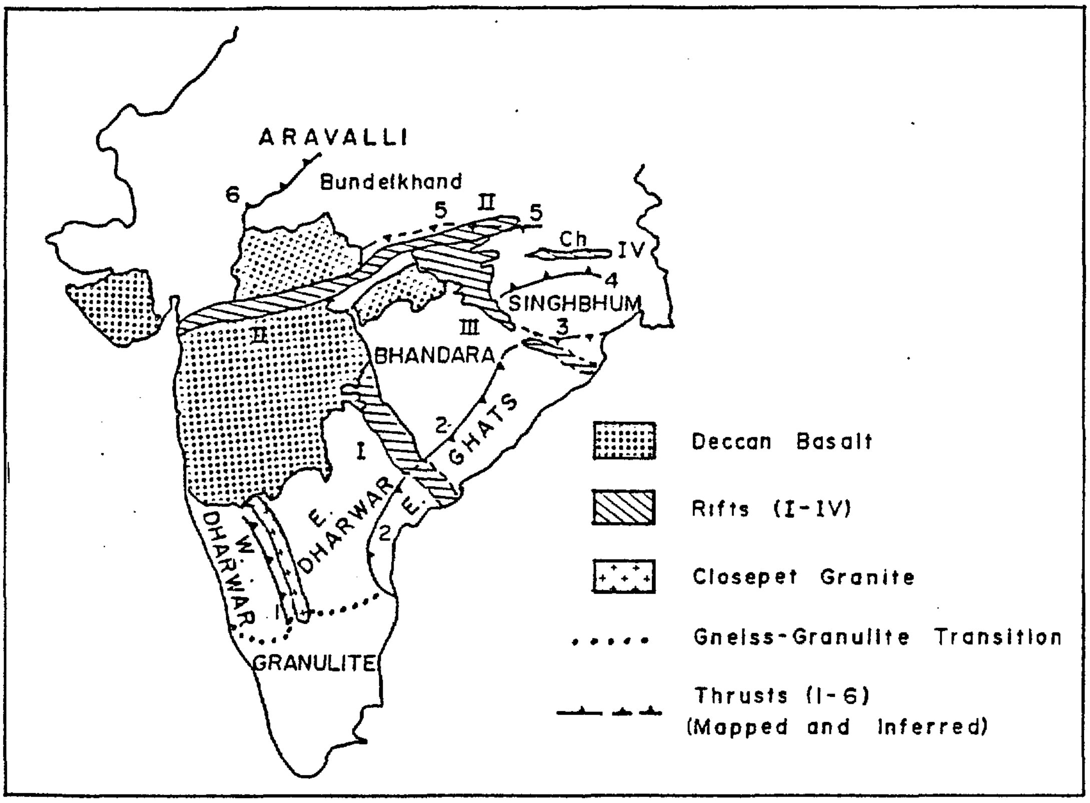

Figure 1. Cratons and joins in peninsular India. Rift valleys are: I - Godavari; II - Narmada-Son; III - Mahanadi; IV - Damodar. Thrusts are: 1 - small thrust in Western Dharwar Craton; 2 - Eastern Ghats front; 3 - Sukinda; 4 - Singhbhum (Copper Belt); 5 - Son valley thrust, inferred westward; 6 - Great Boundary fault.

Table 1. Comparison of Th and U Concentrations in Archean Suites

	Th ppm	U ppm
Dharwar craton		
low-Al gneiss	10.6	4.6
high-Al gneiss	10.5	3.3
trondhjemite	1 - 3	0 - 1
Canadian shield		
gneiss (Unit 7 of Eade and Fahrig, 1970)	11.8	1.5

THE GEOCHEMISTRY OF MAFIC-ULTRAMAFIC ASSOCIATIONS FROM THE HARTS RANGE

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The chemistry of mafic-ultramafic granulites and amphibolites comprising basement and cover sequence metatholeiite series of the eastern Arunta Block, Harts Range, central Australia, reflect a complex multistage geochemical evolution for the attendant Archaean(?) - early Proterozoic mantle and derivative basaltic magmas. A model is presented which attempts to reconcile both magmatic and tectonic aspects of the early development of the Arunta Block.

In the Harts Range area basement gneiss complexes of the Strangways Metamorphic Complex, including the Oonagalabi and Entia gneiss complexes, are structurally overlain by a supracrustal cover sequence consisting of the Irindina supracrustal assemblage and the Harts Range meta-igneous complex (HRMC) (Ding & James 1985). Mafic-ultramafic granulites and amphibolites are interlayered with the predominantly quartzofeldspathic basement gneisses on a meso- and macroscopic scale (Fig. 1). The contiguous HRMC consists mainly of metabasaltic amphibolite, leucoamphibolite, anorthositic gneiss and ultramafic rocks (Sivell & Foden 1985; Sivell et al. in press).

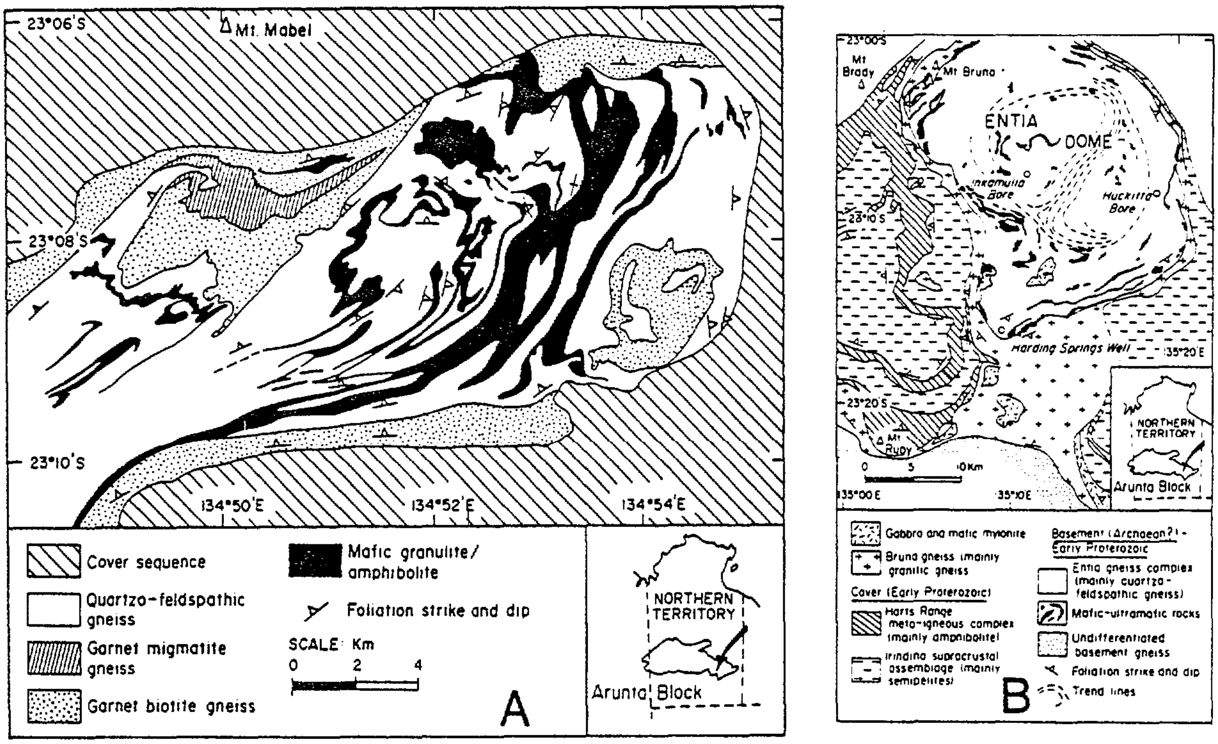

Fig.1. Geological maps of (A) Oonagalabi Tongue and (B) Entia Dome areas of the Harts Range, central Australia, showing major mafic granulite and amphibolite bodies interlayered with host basement gneisses as well as structurally overlying cover sequence lithologies.

Within the Oonagalabi gneiss complex, extremely fractionated basaltic to ferrobasaltic amphibolites and transitional granulite-amphibolites comprise two geochemically and spatially distinct mafic tholeiitic suites (deformed sills/dykes) The metatholeiites are characterised by high to very high FeO, TiO_2 and P_2O_5

contents, and variable depletion in CaO and Al_2O_3. A more primitive metanorite with high Cr and Ni levels constitutes a third petrographically distinct metabasite type. High-grade (granulite facies) metamorphism, and in particular, subsequent limited (amphibolite facies) retrogression, appear to have affected only abundances of certain highly mobile elements (e.g., K_2O) in these rocks which otherwise preserve remarkably-well their pristine igneous major and trace element signatures (Fig.2A,B). Despite similar Zr/Nb ratios the rocks from the three Oonagalabi suites show different degrees of enrichment in LREE and other immobile elements. The data suggest that the primary basaltic liquids were derived by different degrees (15-30%) of partial melting from essentially similar undepleted source regions. Clinopyroxene in the residual mantle assemblage exerted the main control on the composition of the segregating melt at the lower degrees of melting.

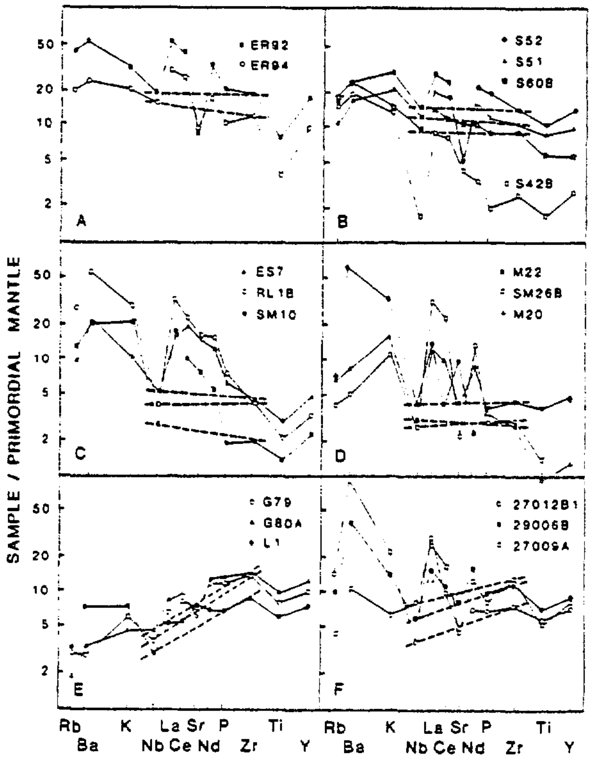

Fig.2. HYG-element variation diagram for basic granulites and amphibolites from (A,B) Oonagalabi gneiss complex; (C,D) Entia gneiss complex and (E,F) Harts Range meta-igneous complex lower and upper metabasite series respectively.

Basaltic amphibolites comprising mafic layers within the Entia gneiss complex show geochemical trends (from Mg-rich to more Fe, Ca and Al-rich compositions) mainly indicative of a metacumulus origin. Petrogenetic modelling indicates that the Entia amphibolites may be analogues of the large amounts of (clinopyroxene-rich) abstracted cumulates required to generate the basaltic to ferrobasaltic spatially and temporally associated Oonagalabi metabasites. Associated relatively iron-enriched Entia amphibolites are less accumulative and overlap in composition with the least differentiated Oonagalabi metabasites. They show compositional affinities with typical continental tholeiites. Both the Oonagalabi ferrobasalts and the (metacumulate) Entia amphibolites imply extensive low-pressure crystal fractionation of mantle-derived magma during long residence times in shallow-level, infrequently replenished differentiating tholeiitic sills and/or magma chambers in a mature rift environment. The mafic Entia rocks probably suffered granulite grade metamorphism prior to the pervasive amphibolite facies retrogression that caused variable enrichment in LREE and mobile LIL-elements (K, Rb and Ba). However constant ratios of immobile high-field-strength (HFS-) elements (e.g., Zr/Nb) indicate melting of a relatively undepleted mantle source similar to the source for the Oonagalabi basalts (Fig.2C,D). Geochemical data for metabasalts from other undifferentiated eastern Arunta basement gneiss terrains confirm that a common homogeneous mantle with some chondritic characters yielded many of the basement tholeiite sequences.

Voluminous metabasaltic amphibolites and related rocks comprise geochemically distinct lower and upper HRMC suites within the early Proterozoic supracrustal cover sequence. The lower metabasites exhibit LREE depletion, low Rb, Ba and K contents and high Zr/Nb ratios (Zr/Nb=65)(Fig.2E) and display tholeiitic differentiation features. They show some similarities to abyssal tholeiites (N-MORB) produced at modern spreading ridges. The upper metabasites are enriched in LREE, Rb, Ba and K and have lower Zr/Nb ratios (Zr/Nb=36) (Fig.2F). These metabasalts possess close geochemical affinities with typical continental tholeiites. Geochemical and field data indicate that the HRMC metabasites were formed in an intracratonic rift environment. The trace element characteristics imply strongly depleted source region(s). Younger noritic intrusives in the cover sequence preserve in part a chondritic incompatible element signature. Variable, selective and progressive LIL-element re-enrichment of depleted HRMC basalts is attributed to contamination of parental magmas by granulite facies basement leucogneisses (± metasomatism of their source region(s)).

The sequence of metasomatic and magma-generating events proposed to account for the temporal geochemical variation of tholeiitic magmas in the eastern Arunta Block is compatible with a tectonic model for the ensialic evolution of the Proterozoic mobile belt involving (1) early addition of an essentially chondritic basaltic component to primitive "relatively-mafic" crust; (2) incompatible element depletion of upper mantle during extraction of "cratonising" basement granitoid magmas; (3) shallow emplacement of depleted mantle beneath a broad zone of a rifting basin and large-scale crustal contamination (+ mantle metasomatism) of voluminous basaltic magmas; (4) spontaneous subcrustal delamination along a thermally-weakened crust-mantle boundary; and (5) subsequent orogenic deformation via crust-restacking and A-subduction resembling modern Cordilleran-style collisional tectonics.

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DISTRIBUTION OF ZAMBIAN GOLD OCCURRENCES IN ZAMBIAN PART OF ZAMBEZI MOBILE BELT

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Nearly 300 occurrences of primary gold mineralisation are known in Zambia. They are fairly broadly distributed in the Central and Eastern regions of the country. The majority (about 190 occurrences), including all the bigger and richer prospects, are located within the pre-Katangan formations (older than 1150 Ma) known as Muva Supergroup (c. 1150-1850 Ma) and Basement Complex (1850-2400(?) Ma). These rocks were affected by intra- and post-Katangan orogenic events (mainly Pan-African) as well as Irumide (c. 1350 Ma) and, in some places, earlier orogenies. In a broad geotectonic sense these formations, where located south of the distinct Mwembeshi dislocation zone, may be treated as northern margin of Zambezi mobile belt.

The gold occurrences are developed as relatively small, iron-rich, gold quartz lodes forming vein- or stockwork-systems. They are emplaced along deep-seated, steeply dipping faults. In exceptional cases mineralised, stratabound ironstones have been encountered.

The lodes display common mineralogical and geochemical characteristics. Abundance of iron and positive correlation between gold and iron content is one common feature. Other similarities include relatively high copper content (up to 10000 ppm in some cases), low silver content and similar mode of gold occurrence; gold is distributed generally as fine particles (below 40 micron diameter)mainly in sulphides (pyrite) or less commonly in greyish quartz. The prospects are low-grade and most of them are subeconomic but some 15% are considered to be of interest.

These occurrences extend along a distance of about 500 km in an East-West striking belt running from Central to Easternmost Zambia. The prospects occur withon country rocks metamorphosed usually to low- or middle- amphibole facies. The prospects reveal a good spatial correlation with intermediate (or less often mafic) metavolcanics and volcanic-related iron-banded rocks, commonly seen as magnetite banded garnetiferous quartzites. Stratabound massive sulphides, although not directly related to the gold occurrences, have also been encountered within this formation. The age and geological position of these volcanics is uncertain and disputable. In the author's opinion they may all be correlated as belonging to a similar period on lithological grounds. In the absence of geochronological radiometric data, dating deduced from tectonic evidence is inconclusive; most evidence indicate an early Irumide time, but an older Ubendian (c. 1850 Ma) age may be also possible.

It seems to be clear, that the initial source of gold mineralisation is related to this volcanic event.

A tentative genetic model is proposed: Gold in low concentration had been initially introduced by an intermediate - mafic submarine volcanism, during Irumide (or earlier) sedimentation in the intracratonic basin, along the northern margin of the Zimbabwe craton. Subsequent high grade Irumide metamorphism significantly remobilised (or drove away) the existing metal. Later stages of the Pan-African orogeny (c. 500 Ma) have been responsible for originating large scale hydrothermal systems which leached and finally re-distributed the gold. Large scale, deep-seated Pan-African faults (perticularly the Mwembeshi dislocation zone and complementary faults) provided appropriate channels for circulation of the fluids.

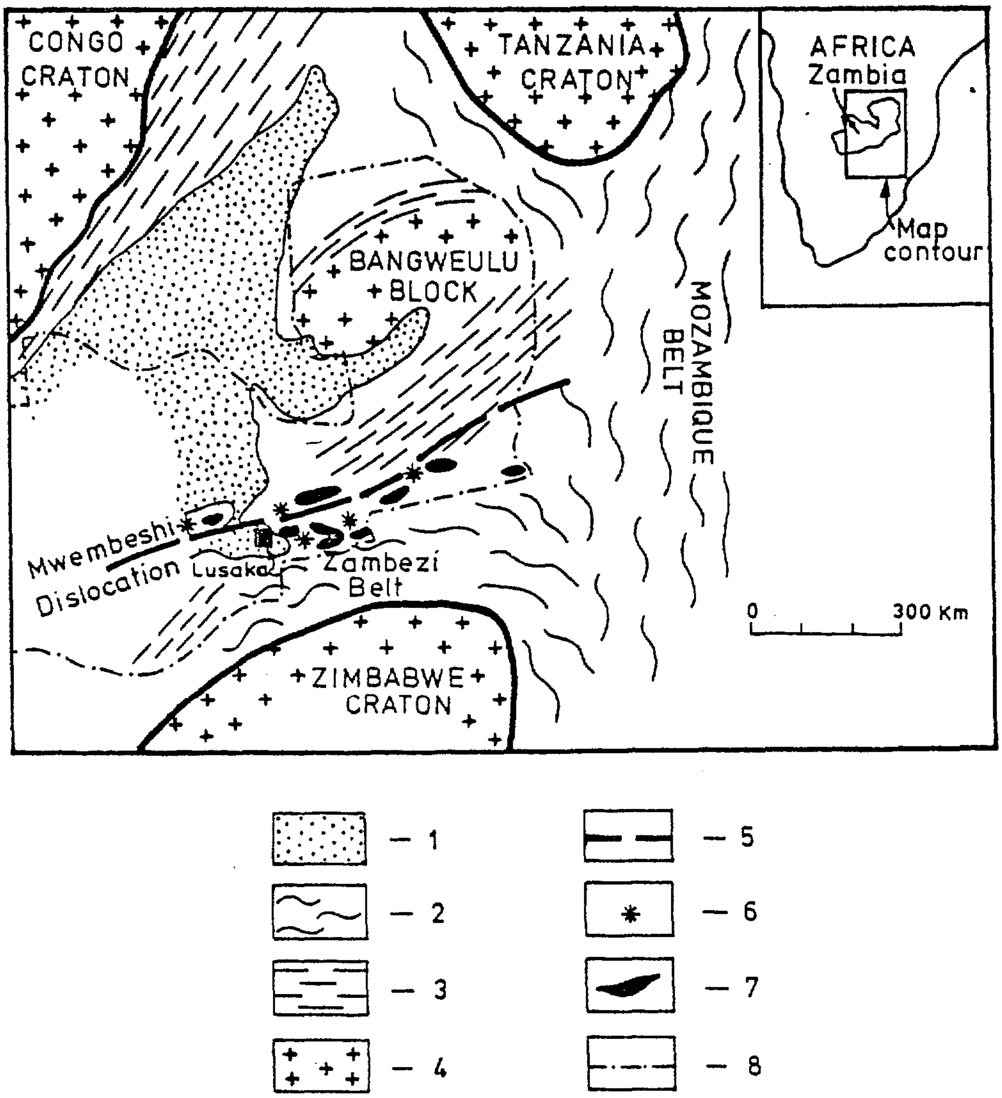
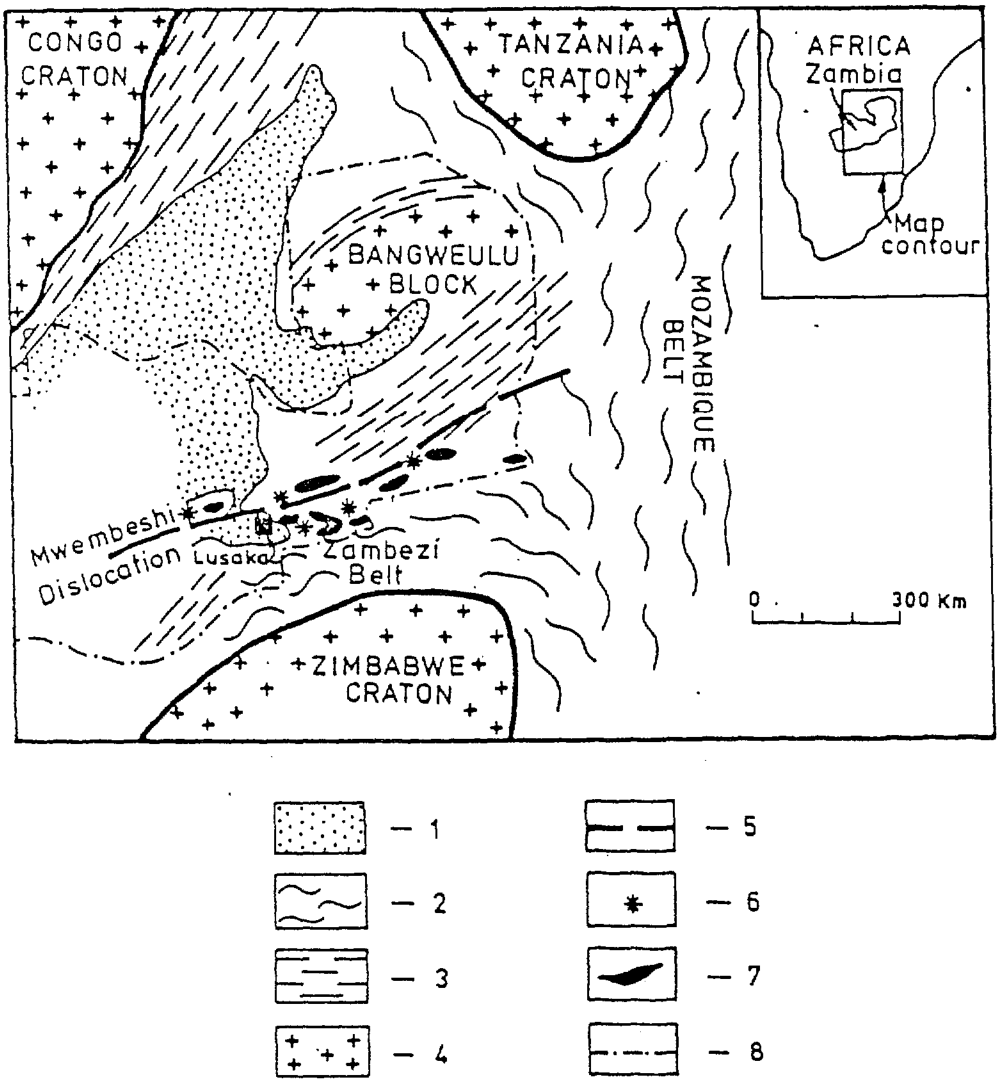


Fig. 1. Distribution of major Zambian gold occurrences and related metavolcanics with respect to main geotectonic features. (major tectonic units after Cahen, Snelling, Delhal, Vail, 1984; modified).

1. Katangan matasediments
2. Pan-African mobile belts affecting pre-Katangan formations
3. Kibarides and Irumides
4. Areas cratonic from at least 1800 Ma
5. Major Pan-African dislocation
6. Important gold occurrences
7. Metavolcanics
8. International boundary



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STRUCTURAL-STRATIGRAPHIC RELATIONS OF THE PROTEROZOIC METASEDIMENTS IN THE VICINITY OF THE BROKEN HILL MINE, AGGENEYS, SOUTH AFRICA

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The metasedimentary successions of the Bushmanland region with its associated stratabound sulphide deposits, forms part of the Namaqua-Natal mobile belt. Outcrops of the stratigraphically very diverse metasediments, are displayed only in inselbergs seperated by plains covered by superficial deposits (Figure). These polimetamorphosed rocks are highly deformed as a result of successive deformation events including large scale thrusting, of which the Namaqua episode (1100-1200 Ma, Blignault et. al. 1983) was the most important.

A novel approach was devised for the unravelling of the structural-stratigraphic complexities, including simultaneous mapping of lithostratigraphic markers and first order flatlying structures. The region under discussion is wellknown owing to the discovery, in the late seventies, of stratabound massive Pb-Zn-Cu sulphides: Black Mountain 81,6 million tons, Broken Hill 85 million tons, Gamsberg 150 million tons (Ryan et. al. 1982, Rozendaal 1982). The initial mapping and lithological classification of the metasediments in the Swartberg area near to the Broken Hill mine (Stedman 1980), included the recognition of a macro scale antiformal isocline, which duplicates the ore. Large scale thrust faults orientated parallel to the regional fabric, have now been recognised and were emplaced syngenetically with respect to two isoclinal fold phases. The most important faults have been named the Zuurwater, Noeniepoort and Swartberg thrusts. Small scale structures such as imbricates, sheath folds and minor isoclinal folds, are associated. The resulting flatlying structures were folded by later deformation, characterized by large open antiforms and synforms.

The stratigraphical succession was divided into three formations (Zuurwater, Kouboom and Soutkloof). The Kouboom formation has an average thickness of 80 m and consists of persistent quartzite units, quartz-muscovite-biotite schist and a diamictite marker horizon. The overlying Soutkloof formation has an average thickness of 40 m and is mainly a ferriferous sequence consisting of garnet - biotite quartzite, iron formation, rhythmites with massive barite, and gossan. Primary sedimentary structures (cross bedding, ripple bedding, original grain size) are nearly always obscured owing to the metamorphic transformations. However, enough relict sedimentary features were found to make a facies analysis possible. According to these observations the Kouboom and Soutkloof formations (the Aggeneys sequence), could represent a shallow beach-to-offshore depositional environment, followed by proximal fan conditions and deposition of the more distal horizons of a trench.

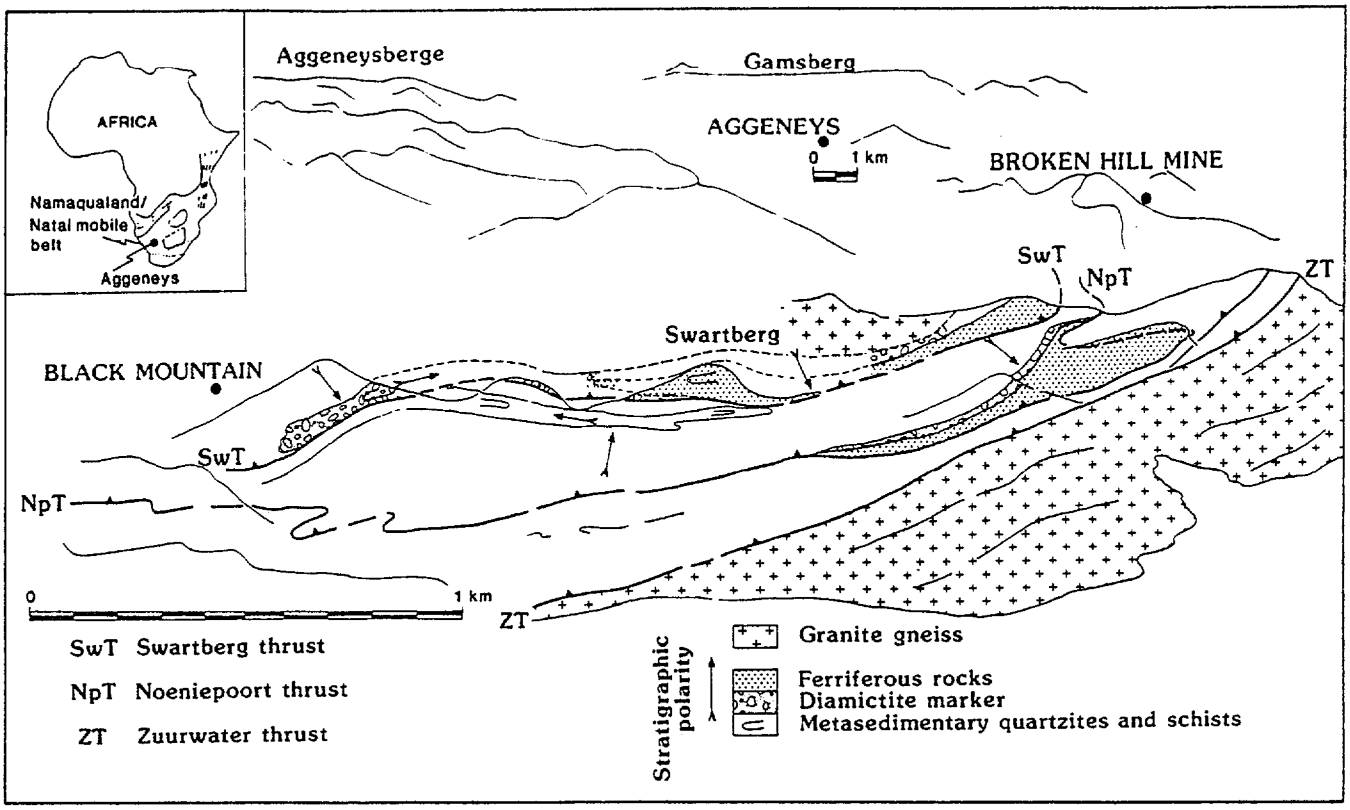

Figure. Oblique easterly view of the north-central Bushmanland terrane (based on an oblique aerial photograph), illustrating the positions of major thrust faults in Swartberg. The scale in the east-west direction varies, owing to foreshortening; the distance between Gamsberg and Aggeneys is approximately 10 km, the same as the distance between Aggeneys and Black Mountain.

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GEOCHEMISTRY AND MINERALISATION OF THE PINE CREEK GEOSYNCLINE NORTHERN TERRITORY

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The Early Proterozoic Pine Creek Geosyncline sequence is floored by Archaean rocks which are exposed in the west and northeast as the Rum Jungle, Waterhouse, and Nanambu Complexes. The complexes consist of several varieties of muscovite-biotite granite, biotite granite and leucogranite, as well as lesser gneiss, schist, migmatite, metasediments and metabasics. The composition of the basal clastic sequences indicates that the complexes are representative of provenance areas of the geosynclinal sequence (Ewers & Higgins, 1985). The Archaean granitoids, enriched in uranium by 2 to 4 times world abundances (Ferguson & others, 1980), were probably the ultimate source of U for the major stratabound U and U - base metal deposits in the region, which show a close spatial relationship to the Archaean complexes.

The geochemistry of the Early Proterozoic geosynclinal sequence reflects major lithological and mineralogical variations, in particular the dolomitic nature of pelites and the volcanic affinity of pelites within parts of the sequence (Ewers & others, 1985). Concentrations of Th, U, Zr, Y, Nb, Ce, and La in clastic sediments of the Finniss River and South Alligator Groups are probably related to the presence of felsic volcanics. High levels of several metals in the South Alligator Group, which hosts disseminated and stratiform precious and base metal deposits, support a syngenetic, possibly exhalative origin for these deposits. Noticeably marginal, reduced and partly evaporitic sequences which host the major U deposits of the region (Needham & Stuart-Smith, 1984), show no significant enrichment of U above normal background values (Ewers & Higgins, 1985).

Extensive granitoid plutons intruded the Early Proterozoic geosynclinal sequence during the Top End Orogeny between 1870 and 1780 Ma. Granitoids older than 1840 Ma are located in the medium to high grade metamorphic terranes of the Alligators Rivers Region in the northeast and in the Litchfield Block in the west. These granitoids intruded at deep levels, were derived from both igneous and sedimentary sources, and are not associated with significant mineralisation. Syn-orogenic felsic volcanic and sub-volcanic suites formed at this time in the South Alligator Valley area are similar in composition and show similar trends to the granitoids, however they characteristically have lower Sr and Al_2O_3, and higher TiO_2, Zr, and Y. The volcanics were probably the source of U and Au in fault - related deposits in the South Alligator Valley.

The younger granitoids (1840 - 1780 Ma) are higher level, derived soley from igneous sources, and are commonly associated with precious and base metal mineralisation. Most Au, Ag, Pb, Cu, Sn, and W deposits are small hydrothermal vein deposits in the contact aureoles of the 1840 - 1780 Ma granitoids. Metal zonation around the Cullen Batholith, the largest granitoid body in the geosyncline, indicates that the mineralising fluids were generated during granitoid emplacement, and that temperature was an important control on metal precipitation (Ewers & Scott, 1977; Stuart-Smith & Needham, 1984). A magmatic source for some metals is indicated by the trace element distribution in the granitoids; this distribution shows a spatial relationship between U , W, Cu, and Ag-Pb deposits and granitoids enriched in U, W, Cu, Pb, and to a lesser degree Zn. There is little evidence for any such relationship involving Sn and no relevant data available to establish any such relationship for Au.

The younger granitoid suites are highly differentiated with silica contents ranging between 50 and 80 percent. Inter-element variations are mostly regular and linear. All the major elements except the alkalis show a negative correlation with silica; the alkalis show a wide range in value independent of silica. The highly fractionated nature of the suites is reflected by marked enrichment of Rb, Li, Y, U, Sn, W, Pb, and Th in the most felsic phases, which commonly occur as small cusps and stocks peripheral to the main granitoid bodies.

Compositionally the felsic igneous rocks of the Pine Creek Geosyncline resemble those of other similar 1870-1800 Ma suites of northern Australia. Estimates of the source age of the granitoids are in the range 2000-2300 Ma (Page & others, 1985) which is in keeping with the source ages of other Proterozoic terranes (Wyborn & Page, 1983), and possibly indicates a major mantle underplating event at about 2000-2300 Ma in the Pine Creek Geosyncline.

Mafic rocks which intruded the Early Proterozoic rocks between 1880 and 1870 Ma and at 1690 Ma are of continental tholeiitic affinity and are not associated with any mineralisation.

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Chemical and Nd isotope study of late Archaean to Middle Proterozoic mafic volcanic rocks in northern Australia

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Secular chemical and isotopic variations are reported for mafic volcanics of late Archaean to middle Proterozoic ages from N. Australia. The purpose of the study is to define the timing of crustal formation and mantle heterogeneity in the lithosphere beneath this region, and development of source rocks for diamond bearing lamproites and kimberlites. Sr, Nd and Pb isotope studies of the latter rocks suggest that their mantle sources (likely to be within the lithosphere) were enriched in LIL elements prior to 2,000 m.y. and probably in the Archaean (McCulloch et al, Nature, 302, 400, 1983; Nelson et al, GCA, in press). This study is also relevant to the search for favourable host rocks for platinum group elements in mafic layered complexes.

Two major types of trace element abundance patterns have been observed among Archaean and Proterozoic mafic volcanics. One has light REE depleted or flat patterns similar to modern MORB. These are common among Archaean komatiites and tholeiites and pre-1860 m.y. rocks in Arunta, Central Australia, Einasleigh metamorphics, Georgetown and Woodward dolerites from the Hall's Creek area. The other type has light REE enriched patterns with depletions of Nb and Ti. The Middle Proterozoic Eastern Creek Volcanics (Queensland) and Hart Dolerites (Northern Territory) are good examples. Some samples of this type are siliceous high magnesian basalts with chemistry similar to boninites from modern island arc environments. Examples include late Archaean hanging wall basalts in Kambalda, Millindina layered complex and Negri volcanics in Pilbara; whereas Proterozoic Lamboo Complex in the Hall's Creek, Eastern Creek volcanics and Hart dolerites have chemical affinity to modern continental flood basalts.

Mafic volcanics of the first type have positive ε_{Nd} initial values and fall on or near the depleted mantle evolution curve; whereas samples of the second type (LREE enriched) commonly have negative ε_{Nd} values (0 to -2). This is in contrast to ~1,700 m.y. greenstone volcanic successions with "island-arc" affinity in south-western North America (Nelson and De Paolo, Nature, 312, 143, 1984), where samples with LREE enriched and depleted patterns all have positive ε_{Nd} values (+3.3 to 6.5) suggesting derivation from depleted convecting mantle. The negative ε_{Nd} values and LREE enrichments of the second type samples from Australia may be a result of melting of evolved mantle sources produced by lithospheric subduction in an analogous manner to modern boninites or interaction of magmas derived from depleted convecting mantle with Archaean crust and/or lithosphere. Ion probe U-Pb age study of zircon xenocrysts recovered from ~ 2,700 m.y. old hanging wall basalts from Kambalda (with "boninite-affinity") by Compston et al (EPSL in press) gave igneous source age of 3,450 m.y. lending support to the crustal contamination model.

If subduction models are not considered applicable to the geological development of Early-Middle Proterozoic crust in Australia then the Nd isotope data supports the suggestion of unexpected Archaean crust adjacent to and/or beneath some of the Proterozoic mobile belts.

U-PB GEOCHRONOLOGY OF THE TRANS-HUDSON OROGEN IN NORTHERN SASKATCHEWAN, CANADA

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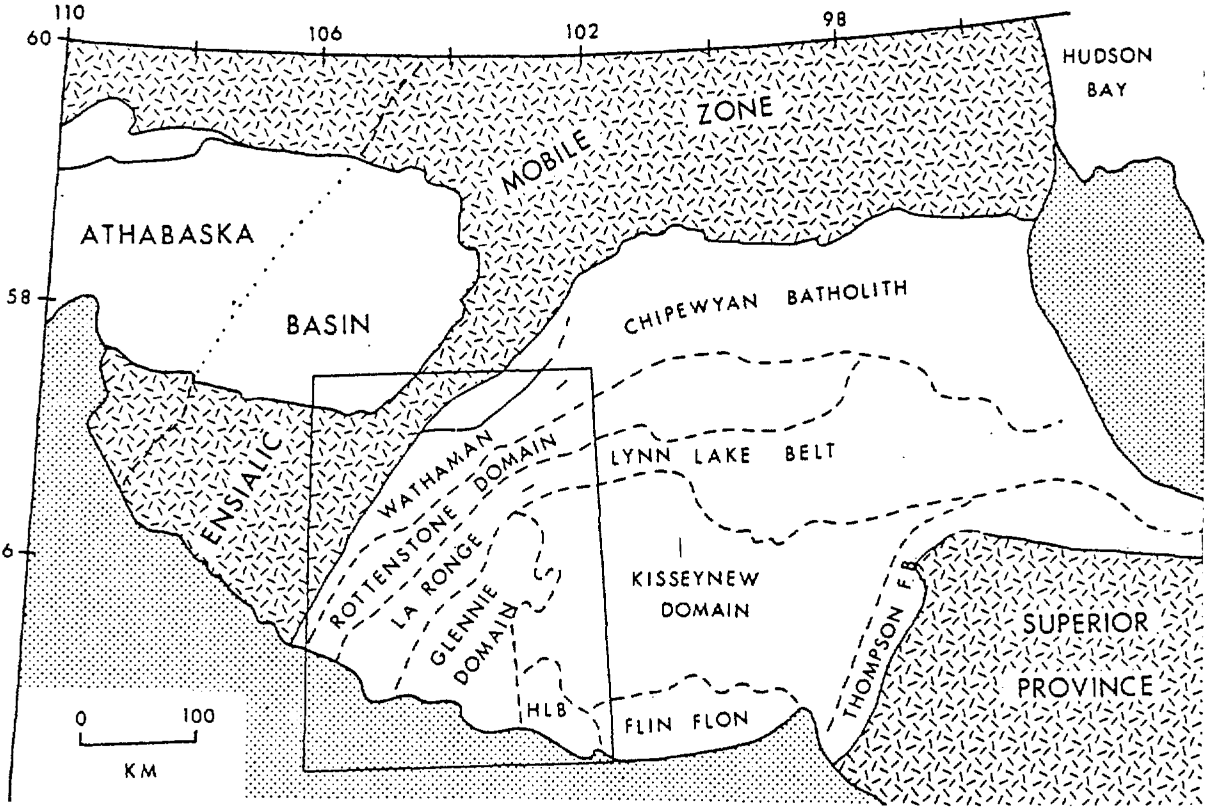
The Trans-Hudson orogenic belt is a major Early Proterozoic tectonic feature of North America that is exposed from northern Alberta, Saskatchewan, and Manitoba to Greenland, with subsurface extension into the north-central United States. In northern Saskatchewan and Manitoba, the Trans-Hudson Orogen lies between the reworked Archean basement and associated Proterozoic cover of the northwestern part of the Churchill Province and the Archean Superior Craton to the southeast. Within this belt several apparent tectonic provinces, or domains, have been recognized. These include the Wathaman-Chipewyan Batholith, the Rottenstone Magmatic Belt, the La Ronge-Lynn Lake Volcanic Belt, the Glennie Domain, the Kisseynew Domain, and the Flin-Flon Domain, with smaller segments such as the Hanson Lake Block, as shown in the figure.



We have obtained U-Pb ages on zircons separated from several units within the Wathaman Batholith, Rottenstone Domain, La Ronge Volcanic Belt, Glennie Domain, and Hanson Lake Block. These data have aided considerably in reconstructing the orogenic history during the Early Proterozoic, in improved understanding of the relationships of the various terranes to one another, and the relationship of the Trans-Hudson Orogen to other Early Proterozoic orogens in North America.

Although earlier interpretations of the Glennie Domain and the Hanson Lake Block inferred the existence of substantial Archean cratonic basement to the Proterozoic supracrustal rocks (Lewry, 1981), we have found indications of Archean ages in only one unit, the Sahli Granite of the Hanson Lake Block. The data are equivocal, but the simplest interpretation is that granitic rocks about 2500 Ma old were subjected to granulite facies metamorphism about 1900 Ma ago, with substantial resetting of zircons. All other units originally thought to be Archean have proven to be Early Proterozoic, suggesting that Archean crust is a minor component of these two terranes.

The oldest apparent age for the Lower Proterozoic rocks is for a tonalitic gneiss (Davin Lake Tonalitic Gneiss Complex) in the Rottenstone Domain. Zircons from this unit suggest an age of about 1900 to 1950 Ma, but they are a complex population with distinct cores, so that the true age of this tonalite may be younger than 1900 Ma. Another, probably equivalent unit, yields a "clean" age of 1863 ± 12 Ma, consistent with the apparent age of 1900 to 1950 Ma being too old due to inherited zircon cores. This belt is just to the southeast of the reworked Archean craton, and inherited components would be expected if a rifted edge of the Archean craton or detrital material from it were involved in formation of these gneisses.

All other units studied in the region until now yield zircon ages of 1835 to 1890 Ma. Four metarhyolites from volcanic sequences yield ages of 1877 ± 8 to 1888 ± 12 Ma and include samples from the La Ronge Belt, Glennie Domain, and the Hanson Lake Block. Several of the associated gneissic and plutonic units yield similar ages and probably represent pre-volcanic and syn-volcanic plutons. The volcanic and syn-volcanic units are all strongly deformed. Later plutons, such as the Wathaman Batholith and other smaller units, yield ages of 1850 to 1870 Ma, constraining the peak of tectonic activity to about 1870 ± 10 Ma ago. A small, undeformed, discordant pluton yields an age of 1836 ± 7 Ma and represents the youngest unit dated at present. The results so far do not show any clear distinction in age among volcanic units or plutons of the La Ronge Volcanic Belt, the Rottenstone Domain, the Glennie Domain, or the Hanson Lake Block, suggesting that the distinction among these terranes is probably mainly lithologic and tectonic, rather than age.

All zircon ages are slightly older than recently reported Rb-Sr isochron ages on equivalent or the same units, suggesting some open system behavior in the Rb-Sr systems. The zircon ages for the main period of igneous and tectonic activity, 1890 to 1835 Ma ago, cover virtually the same age range as found for igneous units of the Penokean Orogen in northern Wisconsin of the southern Lake Superior region (Van Schmus, 1980) and are similar to the ages of 1900 to 1840 Ma found for igneous units of Wopmay Orogen in the Northwest Territories, Canada (Hoffman and Bowring, 1984). Thus, all three major Early Proterozoic orogens in the western part of North America formed at virtually the same time and probably record tectonic and igneous events associated with an Early Proterozoic assembly of that continental mass.

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GEODYNAMIC INTERPRETATION OF CHEMICAL AND ISOTOPIC DATA ON GRANITOIDS FROM MID-PROTEROZOIC OROGENIC BELTS, SWEDEN

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Granitoids of the "Svecokarelian" and "Post-Svecokarelian" orogenic belts in northern and eastern Sweden were intruded in three main periods: 1.89-1.84 Ga, 1.80-1.75 Ga and 1.75-1.65 Ga. The early granitoids have a wide range of compositions, epsilon Nd values near that of LREE-depleted mantle (DePaolo model) and "igneous" oxygen isotope ratios. Those granitoids intrusive into a volcanic arc at a major palaeogeographic (marine to continental) transition have a calcic alkali-lime index and low contents of Y, Nb, Ta and Yb, similar to subduction-related volcanic arc granitoids in the Phanerozoic (Pearce et al, J. Petrol. 1984). 50 km on the "continental" side of the volcanic arc lie a series of alkali-calcic to alkalic granitoids with moderately high Y, Nb, Yb and Ta contents, though not as high as in anorogenic "A-type" granites such as in Nigeria. They are more similar to the type of granitoids developed in ensialic spreading zones in the Andes, on the continental side of the subduction-related calc-alkaline belts (e.g. Brown et al. J. Geol Soc. Lond. 1984), which may be mechanically but not chemically related to subduction. Their trace element enrichment is not related to crustal contamination nor to long-term enrichment of the sub-continental lithosphere. If it is related to the geochemistry of basic precursors derived from the mantle, then the mantle must have been enriched during or shortly before magma generation.

The 1.80-1.75 Ga granitoids have high SiO_2, Rb and K contents, have epsilon Nd values ranging from slightly positive to strongly negative and have oxygen isotope ratios ranging from +6 to +12%. They are interpreted as having a major crustal component. Their geochemical and isotopic characteristics relate to those of nearby crustal sources.

The 1.75-1.65 Ga granitoids form part of a major volcanic/plutonic belt with many geological similarities to the Andean environment. The granitoids have a wide range of composition, but have alkali-calcic or alkalic alkali-lime indexes (not calc-alkalic), though calc-alkalic rocks of similar age do occur further to the west of a major structural line (Lindh & Gorbatchev, Geol Rund 1984). They hve epsilon Nd values of between 0 and +1 and "igneous" oxygen isotope ratios. Their Y and Nb contents are moderately high. As with some of the earliest granitoids, it is suggested that this is an ensialic spreading zone magmatism, with "within-plate" characteristics, on the continental side of a zone of subduction related magmatism. However, the Nd (and Sr) isotopic data cannot distinguish between two possibilities: 1. rapid derivation from mantle with REE composition similar to CHUR, or slightly LREE-enriched. 2. derivation from LREE-depleted mantle followed by a crustal residence of about 200 Ma prior to granitoid generation.

This data does not "prove" that plate tectonic processes were responsible for Mid-Proterozoic orogenies in Sweden, but the geochemical similarities with granitoids from controlled Phanerozoic plate-tectonic environments are striking. Integration with geological data leads to the suggestion that the early period granitoids formed in response to subduction of ocean crust under a continental margin, the middle-period granitoids in response to continental collision and the late-period granitoids in response to a new period of subduction.

The isotopic data was determined by P.J. Hamilton, A.E. Fallick and M. Aftalion at SURRC, Scotland and is reported in Wilson et al, Earth Planet. Sci Lett. March 1985. The geochemical data is reported in a paper submitted to the ILP Midterm Report, to be published by AGU.

EVIDENCE OF THREE WEAK FOLDING EVENTS WITHIN THE IRREGULLY FORMATION AT IRREGULLY GORGE, BANGEMALL BASIN, WESTERN AUSTRALIA.

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Two previously unrecognised folding events can be interpreted within the Irregully Formation in the Irregully Gorge by making use of a variety of criteria. The Irregully Formation near the base of the Middle Proterozoic Bangemall Group consists of interbedded well-laminated dolostones and othoquartzites. Ripple marks and mudcracks within the sequence suggest a generally shallow-water depositional environment.

Macro and mesoscale folds are very abundant within the Irregully Formation exhibiting many geometries and styles. Poles to bedding in the formation (Fig. 1a) lie roughly on a great circle suggesting that the macroscopic folding is close to cylindrical, in which the fold axis plunges at a shallow angle to the NW. The geometry of mesoscopic folds within the Irregully Formation (Fig. 1b & 1c), exhibits a maximum of fold axis orientations plunging 10° NW, and maximum of axial planes oriented vertically, trending NW-SE. Most folds are consistent with an orientation that could give rise to the S_0 distribution shown in Fig. 1a. However there is a significant number with axial planes trending NE-SW, E-W and NNE-SSW. They may have been produced 1) during stages of the regional folding event, 2) in the one event where they developed considerable variation in orientations due to the extreme incompetency of the metasediments or 3) in a number of unrelated folding events.

As no obvious overprinting between the different fold orientations has been noted, there is no easily recognised criterion for placing folds in a sequence. However other criteria such as 1) the timing and geometry of syntectonic veins, 2) the geometry of folds and 3) the tightness of folds and the amount of shortening they have undergone, can be used to establish a sequence of folding events.

Within the Irregully Formation many dolomite and syntectonic quartz veins have been observed, most of which can be related to the regional folding event. At some locations dilational offsets between extensional quartz/dolomite and dolomite/dolomite veins indicate a sequence of vein dilation (similar to that noted by Winsor, 1983). At least three intervals of vein dilation can be recognised, one related to the macroscopic folding, and others before and after this event. Removing the effect of the regional folding on the earlier veins has revealed (Fig. 2) two sets at about right angles and 65° or 25° to the regional folds. Using the geometry of the undeformed earlier veins it is possible to separate folds geometrically related to these veins, from those considered a result of the regional folding event. Style is also used to assign folds to F_1 or F_2, noting that F_1 folds usually trend NW-SE and are commonly tighter than those assigned to F_2. As indicated in Figure 2 there is a large variation in the fold-axis orientation of possible F_1 folds, perhaps indicating refolding about a NW (F_2) axis. A third folding event is suggested (Fig. 3) by the deformation of a D_2 dolomite vein in a small shear zone. Folds (F_3) which may be a result of this later event trend E-W.

Further support for the postulated deformation sequence is indicated by an increase in dihedral angle in F_1 to F_2 folds. Also F_1 folds have apparently been shortened to a greater extent than F_2 folds, which have been shortened more than F_3 folds.

The sequence of folding events described above can in part be correlated with previous interpretations in the area. Macroscopic folds in the Irregully Formation have been assigned by Gee (1979) & Muhling , et al. (in press) to the Edmundian Tectonic Event, which resulted in open, concentric, NW-SE trending folds. These folds are the F_2 folds of the present study. Large scale dome and basin structures have also been recognised in other parts of the Bangemall Basin and interpreted to be result of passive (i.e. not involving any compressive forces) drape over reactivated basement faults. The sequence of folding outlined above disputes this notion of purely passive drape suggesting that a degree of compression and possible tightening of basement folds accompanies the reactivation of basement faults.

Sedimentological studies made within the Irregully Formation in other parts of the Bangemall Basin have indicated that a NE-SW basement trend may have been active during deposition. Although the present study does not necessarily disagree with that interpretation it does provide evidence that the NE-SW trend was active at least after deposition.

This article is concerned with definition of the macrostructure in the Irregully Gorge. Future research will investigate the relationship between macro, meso and micro-structure in greater detail and examine the association between mineralogy, rock type, texture and structure at all scales.

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Figures

Fig. 1 a) 244 contoured poles to bedding Irregully Fm. Contour interval .41,.82,1.64,3.28,6.56% max 11.9%. Approx. fold axis 040/8W, approx. axial plane 130/90W.

Fig. 1 b) 118 contoured mesoscopic fold axes Irregully Fm. Contour interval .85,1.70,3.39,6.78% max 8.47%. Contour max 035/10W.

Fig. 1 c) 118 contoured poles to mesoscopic fold axial planes Irregully Fm. Contour interval .85,1.70,3.39,6.78% max 11.86% Contour max. 120/90E.

Fig. 2 a) Geometry of dilationally offset veins (1-7) Irregully Fm. Early quartz vein EQ, later quartz vein LQ, early dolomite vein ED, later dolomite vein LD. Axial plane 130/90E.

Fig. 2 b) Undeformed early veins unrelated to regional folding event, rotated about fold axis 040/8W. Quartz vein Q, dolomite vein D. Postulated D_1 axial plane 059/90W, D_2 axial plane 130/90W.

Fig. 3 Dolomite vein (044/86W) deformed within a small shear zone. Veins within the shear zone are oriented 004/87W.

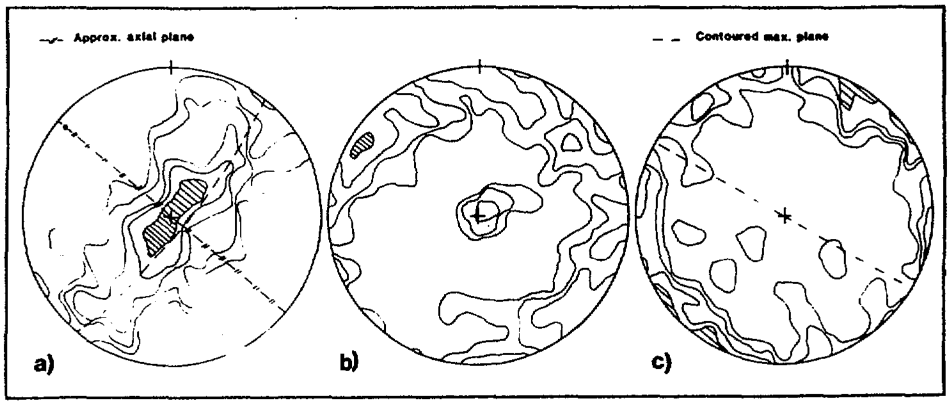

Fig. 1

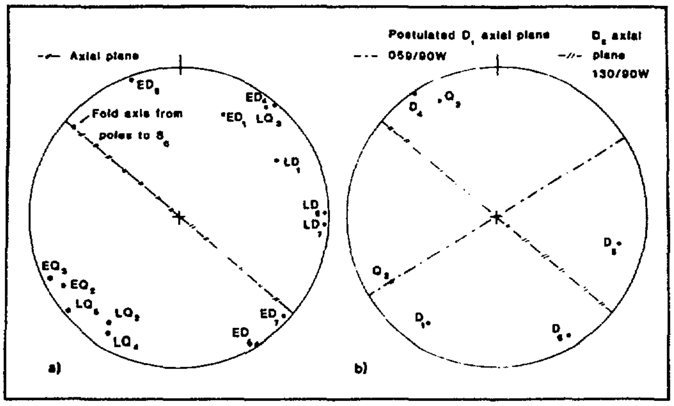

Fig. 2

Fig. 3

GEOCHEMISTRY AND ORIGIN OF A MAJOR EARLY PROTEROZOIC FELSIC IGNEOUS EVENT OF NORTHERN AUSTRALIA AND EVIDENCE FOR SUBSTANTIAL VERTICAL ACCRETION OF THE CRUST

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In the early Proterozoic of Northern Australia, a major period of felsic volcanism and granite emplacement occurred between 1800-1920 Ma. The volcanics and granites cover at least 30,000 km^2 and are compositionally uniform over large areas. These felsic magmas are predominantly I-type, being derived from infracrustal sources which have never been exposed at the surface of the earth. Compositionally they have distinctively high levels of K_2O, Rb, Zr, La, Ce, Th, U, and low MgO and CaO, even at relatively low SiO_2 levels of 60-65%. The rocks are also characterised by low $^{87}Sr/^{86}Sr$ ratios, and chemical and isotopic modelling suggest that the source of these volcanics and granites formed during a major mantle accretion event from 2000-2300 Ma. It is suggested that as a result of small scale mantle convection, extensive underplating occurred during which large volumes of incompatible element enriched mantle material accreted to the base of the lower crust, and fractionated significantly. The more felsic fractionated part of this source was remelted during subsequent orogenesis between 1800-1920 Ma to produce the voluminous felsic volcanics and comagmatic granites present in nearly every Proterozoic terrain of Australia. The geochemical data support models of episodic additions of mantle material with time, and there is no evidence of a major Archean component in these felsic igneous rocks. When these Early Proterozoic felsic igneous rocks are compared with Phanerozoic I-type analogues there appears to be a systematic decrease in K_2O, Th, and U, with time, suggesting progressive degassing of these elements from the mantle. The composition of these felsic magmas and the tectonic setting operating during their emplacement cannot be related to subduction of oceanic crust either at a continental margin or an island arc. The data are consistent with a two-stage development of new continental crust in the Early Proterozoic involving initial underplating followed by later vertical redistribution in the upper crust during partial melting of the underplated layer.