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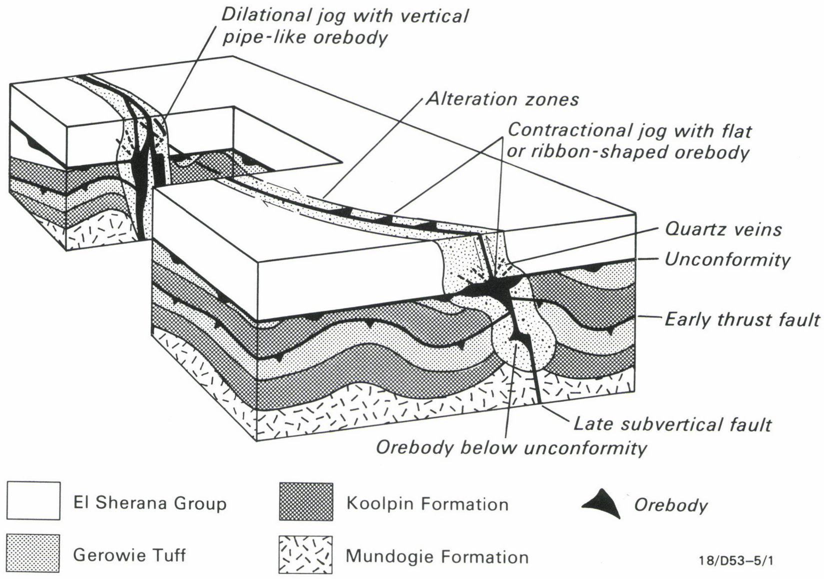
# Localisation of mineralisation in the Coronation Hill and related deposits, South Alligator Valley Mineral Field, NT

**Recent studies carried out as part of the BMR Kakadu Conservation Zone project have led to an improved understanding of the formation of the Au-PGM (platinum-group metal) and uranium deposits of the South Alligator Valley Mineral Field (Needham, 1988: Geology and Mineralisation of the South Alligator Valley Mineral Field, 1:75 000 Map, BMR) and their regional geological setting. A distinct combination of host lithologies, highly oxidised mineralising fluids, and dilational structures within a dextral strike-slip fault system all combine to suggest that Coronation Hill (Au-PGM) is an unusual style of deposit. Figure 1 shows the important geological features that are considered to control the mineralisation.**

The deposits lie close to the unconformity between (1) the little-deformed 1860 Ma felsic volcanics and sandstones belonging to the Coronation Sandstone of the El Sherana Group and (2) the underlying highly folded and deformed Koolpin Formation of the South Alligator Group (for illustrative purposes the folding has been 'subdued' in Figure 1). The uranium mineralisation generally occurs in cherty ferruginous units of the carbonaceous Koolpin Formation below the unconformity, whilst the Au-PGM mineralisation occurs both below and above the unconformity and is hosted by a wider range of rock types. Uranium mineralisation is not known deeper than 100 m below the unconformity or more than a few metres above it. On the other hand, the Au-PGM mineralisation appears to be much more widely distributed both above and below the unconformity.

Detailed structural studies carried out by Dr R.K. Valenta of Monash University at all of the main deposits from Rockhole to Coronation Hill, and also on a regional scale for the whole of the original (2300 km$^2$) Kakadu Conservation Zone, have shown that the mineralisation is contained within a major northwest-trending dextral strike-slip fault system, most of the deposits being on or near the Rockhole-El Sherana-Palette fault system (Fig. 2). Almost all mineralisation is localised around fault zones that are clearly associated with dilatancy, and the deposits are of basically two types. The first type occupies sites related to contractional jogs. In this case, the extension is in a vertical sense, so tensile fracturing and dilatancy is favoured on planes which are close to horizontal and the resultant mineralisation occurs in subhorizontal pipe-or ribbon-like bodies, e.g. Rockhole, and possible also Saddle Ridge and Sleisbeck (off map, to southeast). In contrast, the other type occurs in features that are formed as a result of dilational jogs. These produce tensile stresses in the horizontal plane perpendicular to the maximum principal stress and consequently the mineralisation occurs as subvertical pipe-like features, extending to greater depth, e.g. Coronation Hill, Palette, and Skull. Figure 3 illustrates the differences in shape and orientation of the two types of orebodies.

**Fig. 1. Schematic block diagram showing geological features controlling mineralisation in the South Alligator Valley Mineral Field.**

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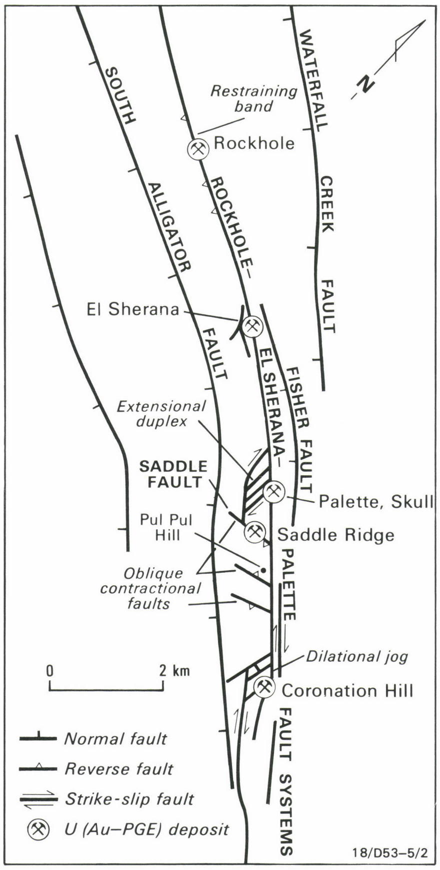



**Fig. 2. Location of deposits in the major northwest-trending dextral strike-slip fault system, South Alligator Valley Mineral Field.**

All known deposits are surrounded by alteration zones that may extend for over 1 km away from the mineralisation; the zones have also been found on other faults well away from the known deposits. The alteration is characterised mineralogically by muscovite (sericite)-chlorite ± kaolinite ± biotite ± hematite. Hematite, which formed late in the alteration process, is the most extensive type of alteration. At some of the deposits (e.g. El Sherana) the rocks are strongly desilicified at the unconformity and consist of predominantly chlorite-rich felsic volcanics that still retain some primary volcanic textures such as flow-banding and quartz phenocysts. In other places, generally at higher stratigraphic levels above the unconformity, the volcanics are silicified and quartz-veined (e.g. parts of the Coronation Hill deposit, Pul Pul Hill). Chemically the alteration is characterised by loss or gain of $SiO_2$, very high $Fe^{3+}/Fe^{2+}$ and U/Th ratios, and almost complete depletion of $Na_2O$, CaO, and Th. There is some enrichment of U, but U rarely exceeds 50 ppm, even in the old uranium pits. Studies of the altered rocks suggest that they were formed by interaction with relatively low-temperature, oxidised, low-pH, saline fluids.

On geological grounds the mineralisation is younger than 1860 Ma (the age of the El Sherana Group host rocks) and, as it is controlled by faults that also cut the Kombolgie Sandstone (~1650 Ma) nearby, it may be younger than 1650 Ma. One of the earliest papers on U-Pb geochronology in Australia was on uraninites from the El Sherana, Palette, and Sleisbeck mines (Greenhalgh & Jeffrey, 1959: *Geochimica et Cosmochimica Acta,* **16,** 39–57) which yielded ages of between 500 and 900 Ma. New ion microprobe U-Pb data on hydrothermal zircons in a wide variety of altered rock types along the Rockhole–El Sherana–Palette fault system and elsewhere in the region give similar ages (R.W. Page, pers. comm.). Current work is aimed at establishing the significance of these young zircons relative to the mineralisation.

Structurally, the deposit model described here and shown in Figure 1 is similar in many respects to that proposed by Johnson & Wall (1984: *Abstracts of the Geological Society of Australia,* **12,** 285–287) for the major unconformity-related uranium deposits of the Alligator Rivers Uranium Field to the north (Jabiluka, Ranger, Koongarra, Nabarlek). Although these deposits contain much more U than those of the South Alligator Valley Mineral Field, the Jabiluka and Koongarra deposits also contain significant Au reserves, although the only PGMs recorded are at Jabiluka, which contains palladium (Wilde & others, in press: *Economic Geology,* Monograph **6**).

Johnston & Wall (op cit.) suggested that, in this context, the essential role of an unconformity is simply to provide a significant contrast in permeability and rheology between the cover and basement rocks. Thus, it follows that 'unconformity'-style deposits could form well below the unconformity within the basement sequences at locations where there is a strong rheological and lithological contrast (Fig. 1). This concept could be applied to some of the small uranium deposits that occur in the basement sequences well below the projected level of the El Sherana Group/Koolpin Formation unconformity on the northwestern extension of the major fault structures northwest of Rockhole (Coirwong Gorge area). None of these prospects have been tested for Au or PGM concentrations.

Despite the similarities in structural style between (1) the Coronation Hill deposit and other deposits of the South Alligator Valley Mineral Field and (2) those of the Alligator Rivers Uranium Field, there are several important differences:

— In the Alligator Rivers Uranium Field the host rocks below the unconformity are the carbonate and carbonaceous schists of the lower Cahill Formation or the Myra Falls Metamorphics and the unit above the unconformity is (or, where missing, is inferred to have been) the Kombolgie Formation (predominantly quartz sandstone).

— In the vicinity of the South Alligator deposits there are much lower volumes of U-enriched rocks (see p.5, this issue).

— Au and PGMs have been found to be well above the crustal average in a greater proportion of country rocks in the South Alligator Valley Mineral Field, particularly the black shales and mafic igneous rocks, e.g. Koolpin Formation, Shovel Billabong Andesite, Zamu Dolerite, and Birdie Creek Volcanic Member.

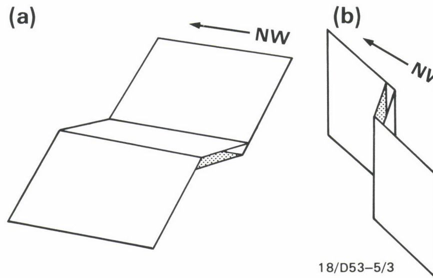



**Fig. 3. The two contrasting orebody styles, South Alligator Valley Mineral Field (end-member spatial variations in the geometry of dilatant sites): (a) steep reverse fault with flat dilatant site (e.g. Rockhole, ?Saddle Ridge, ?Sleisbeck); (b) steep strike-slip fault with steep dilatant site (e.g. Coronation Hill, Palette area, Skull).**

— If the geochronological results do confirm that the mineralisation is as young as 600–900 Ma, then these solutions would be much younger than the ~1600 Ma age proposed for the Nabarlek, Koongarra, and Jabiluka deposits (Maas, 1989: *Economic Geology,* **84,** 65–90) and the solutions may have parameters that are more favorable to Au and PGM dissolution and transport.

The Coronation Hill type of Au-PGM deposit appears restricted to the South Alligator Valley. Studies carried out by the BMR Proterozoic Framework Project show that Proterozoic stratigraphic sequences, in particular highly folded basement rocks containing carbonaceous and/or ferruginous cherty and/or calcareous units similar to those of the Koolpin Formation of the South Alligator Valley, are more common in northwestern to central parts of northern Australia (e.g. the Biscay Formation of the Halls Creek Mobile Zone, the Mount Charles beds of the Granites-Tanami Block, and parts of the Warramunga Group of the Tennant Creek Inlier). By contrast, alteration patterns caused by interaction with similar highly oxidised, saline, low-pH fluids are more common in northeasterly areas, in the McArthur Basin, Murphy Inlier, and NW Mount Isa Inlier. These two major factors come together in the South Alligator Valley and this may explain why, although the Au-PGMs were found at Coronation Hill nearly five years ago (Noranda Pacific Ltd, 1985: Prospectus) no similar deposit has been found in any other Proterozoic province.

*For further information contact Dr Lesley Wyborn at BMR (Minerals & Land Use Program).*

# High uranium granites of the Kakadu-NW Arnhem Land region

## Are they related to the locally abundant uranium deposits?

**The Kakadu and northwestern Arnhem Land region (Fig. 4) encompasses two major mineral provinces — the Alligator Rivers Uranium Field and the South Alligator Valley Mineral Field. The region is well known for the major uranium deposits of Jabiluka, Ranger, Koongarra, and Nabarlek which together contain about 15% of the world's low-cost uranium reserves. The region also contains at least 138 other uranium mines, prospects, and occurrences and obviously is anomalously enriched in uranium; it corresponds to a regional uranium high containing some of the higher background levels of uranium in Australia.**

As part of the Kakadu Conservation Zone Project, a detailed study has been completed on the poorly known Malone Creek Granite, and the results can now be integrated with the earlier study of Ferguson & others (*in* Ferguson & Goleby (Editors), 1980: URANIUM IN THE PINE CREEK GEOSYNCLINE. *IAEA Vienna,* 73-90) on other granites in the region.

Most of the granites in the region have uranium contents well above the crustal average of 2.8 ppm (based on Taylor & McLennan, 1985: THE CONTINENTAL CRUST: ITS COMPOSITION AND EVOLUTION.

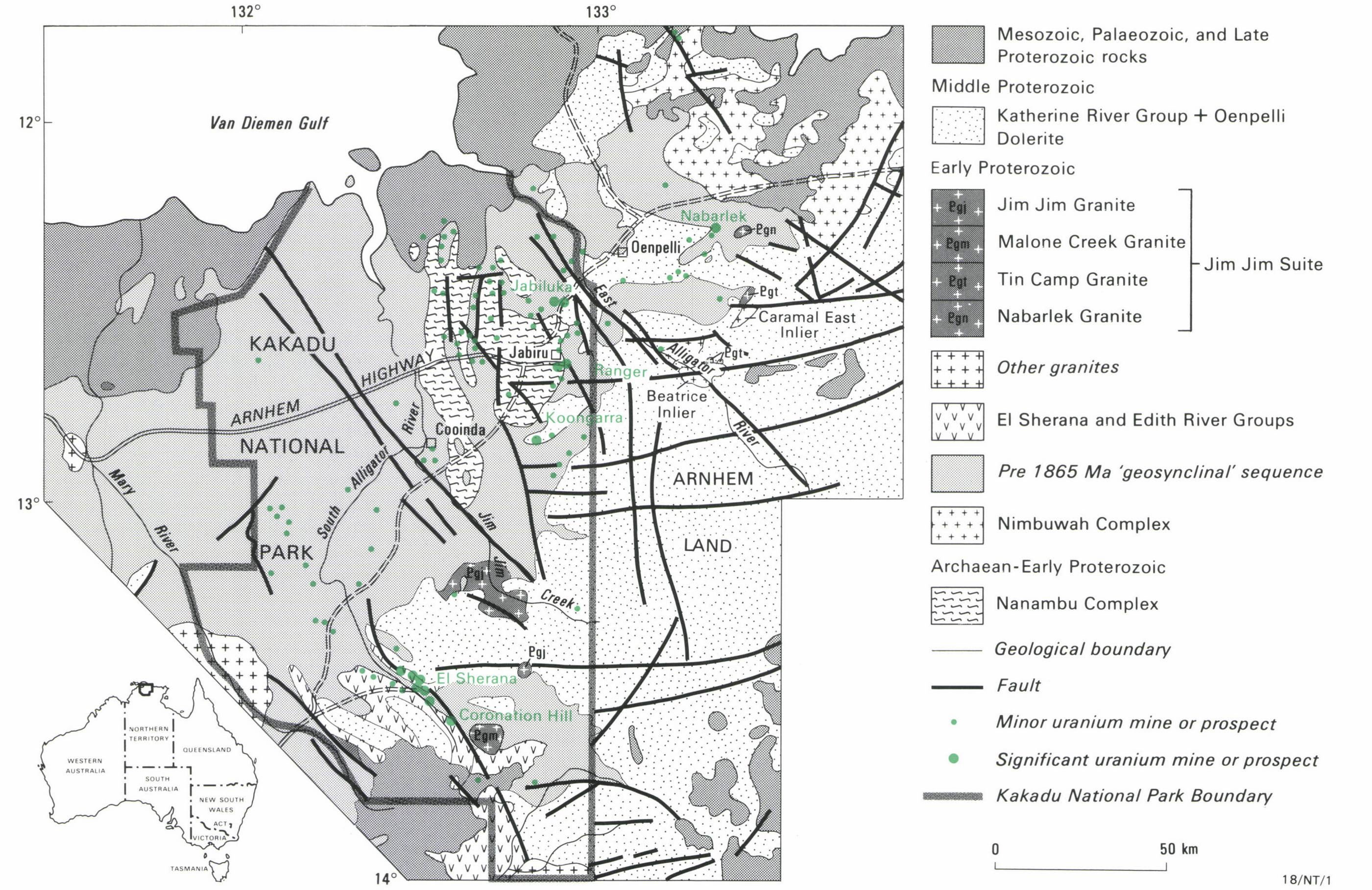



**Fig. 4. Distribution of major granite suites and uranium deposits in the Kakadu-NSW Arnhem Land region (from Stuart-Smith & others, 1983: Geology of the Mary River–Point Stuart Region, BMR 1:100 000 geological special map).**

*Blackwell Scientific Publications).* On the basis of geographical location, age, mineralogy, and chemistry these granites can be subdivided into three suites: the Nanambu Complex, the Nimbuwah Complex, and the Jim Jim Suite.

The Nanambu Complex, which is poorly exposed between the South Alligator and East Alligator Rivers, comprises Archaean granite and gneiss, some of which has a Proterozoic metamorphic imprint (Needham, 1988: *BMR Bulletin* **224**). The uranium values are highly variable and range from 3–50 ppm (Fig. 5). Some of the high values are from samples close to the Ranger and Jabiluka deposits, whilst many of the low-U samples have high Th/U ratios of up to 33, suggesting that U has been lost.

The Early Proterozoic Nimbuwah Complex to the northeast contains biotite-hornblende tonalite and granite gneiss, as well as granitic and granodioritic migmatite (Needham, op. cit.). It has the lowest U value (1–10 ppm) of all of the granites in the region.

The Jim Jim Suite comprises, from north to south, the Nabarlek Granite, the Tin Camp Granite, the Jim Jim Granite, and the Malone Creek Granite. The suite crops out mainly adjacent to the Kombolgie Sandstone or in small inliers within it. Interpretation of gravity data suggests that some of the plutons are connected at depth (Tucker & others, *in* Ferguson & Goleby (Editors), *op. cit.*).

The Nabarlek Granite crops out about 7 km northeast of Nabarlek and has been intersected in drillholes below the Nabarlek deposit. Uranium generally ranges from 3–30 ppm, although higher values (up to 47 ppm) have been recorded from altered granites closer to the mine.

The Tin Camp Granite crops out in the Beatrice and Caramal East Inliers and intrudes the Nimbuwah Complex. Trace-element data are available for two samples and they contain 8 and 13 ppm U.

Gravity data suggest that the Jim Jim Granite may extend south beneath the Kombolgie Sandstone and join up with the Malone Creek Granite. Uranium ranges from 3–20 ppm.

The Malone Creek Granite crops out as a small, zoned pluton east of the Coronation Hill deposit and has an extensive contact aureole. It contains high U values (11–28 ppm).

The ages of the members of the Jim Jim Suite have not been precisely defined. The granites all intrude pre-1860 Ma folded and metamorphosed units of the Pine Creek Geosyncline and appear to be unconformably overlain by the Kombolgie Sandstone (Katherine River Group). Rb-Sr biotite and whole-rock age determinations are available for most members of the suite and range from

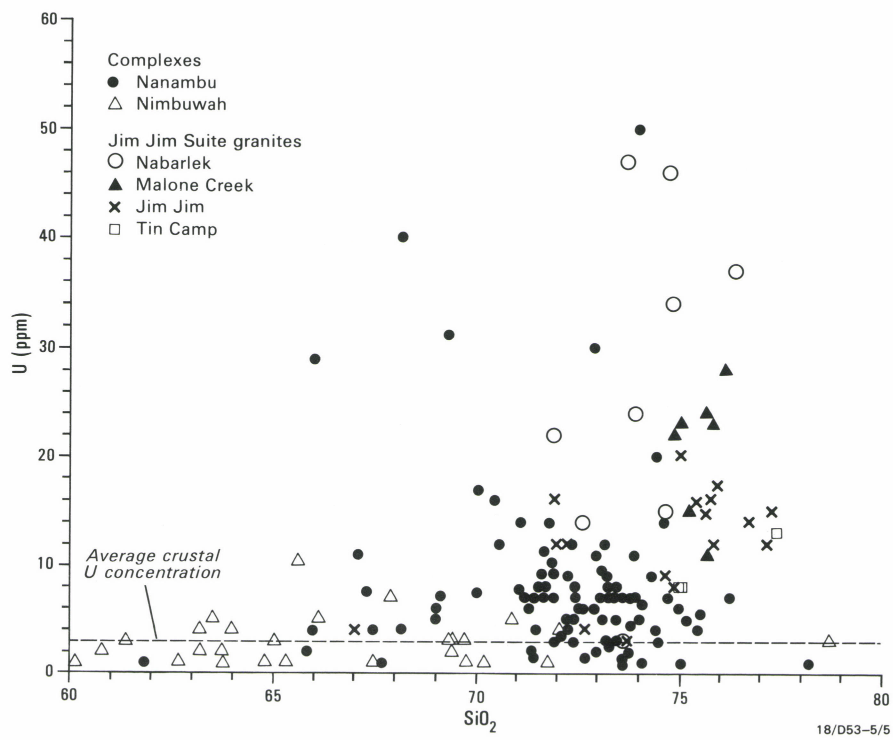



**Fig. 5. Harker variation diagram for the granites of the Kakadu-NW Arnhem Land region (data from Ferguson & others, op. cit. and Kakadu Conservation Zone Project unpublished data).**

1735–1780 Ma (Page & others, *in* Ferguson & Goleby (Editors), op. cit.). These are minimum ages only, as they may have been affected by younger metamorphism and deformation.

Petrographically, all of the granites from the Jim Jim Suite appear to be oxidised and the feldspars are often red; fluorite and allanite are common accessories. Both petrographically and chemically the Jim Jim Suite members closely resemble the A-type granites of Collins & others (1982: *Contributions to Mineralogy & Petrology*, **80,** 189–200) and contain high values of incompatible elements such as Nb, Y, and a higher $Ga/Al_2O_3$ ratio, typical of A-type granites.

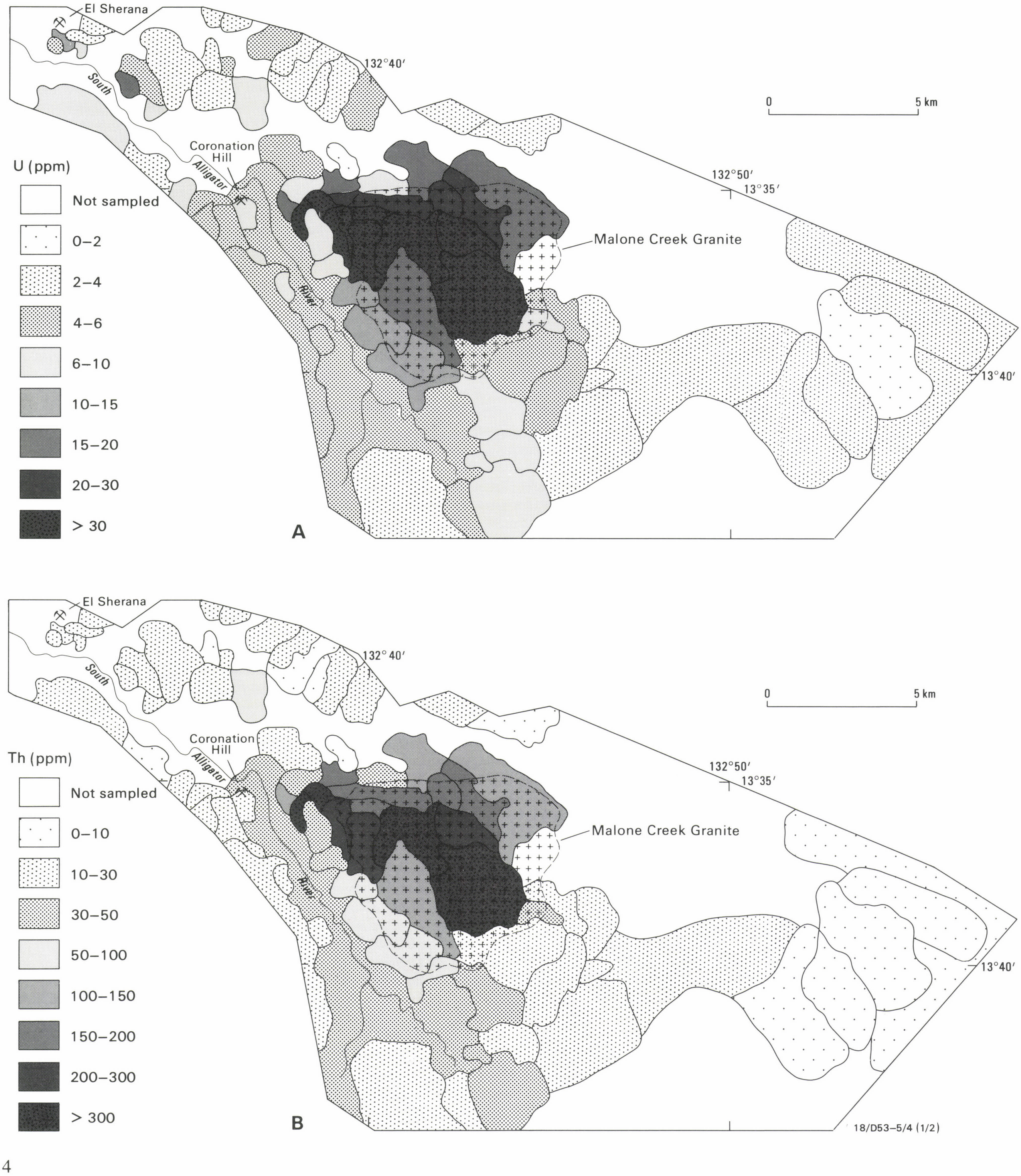
Compared with the generally accepted crustal average for uranium of around 2.8 ppm, the Nanambu Complex and Jim Jim Suite granites are exceptionally enriched in U, in fact they are amongst the most uraniferous granites known in Australia. This then invites the question — is there a genetic connection between these uraniferous granites and the uranium deposits? The same applies to other uranium deposits in Australia that are located near high-uranium granites (e.g. the Whites and Dyson deposits adjacent to the late Archaean Rum Jungle Complex of the Pine Creek Inlier, NT; the Mary Kathleen deposit adjacent to the Burstall Granite, and the Skal, Valhalla, and other deposits near the Sybella Granite, all in the Mount Isa Inlier, Qld; and the Olympic Dam deposit on the Stuart Shelf, SA).

Not all high-U granites are known to have major uranium deposits nearby. Two examples of high-uranium granites that have comparable U values to those of the Kakadu-NW Arnhem Land region but as yet have no known major related uranium mineralisation are the Williams Granite of the eastern Mount Isa Inlier and the Warrego Granite of the Tennant Creek Block, NT. Both of these granites appear to be younger than any major known oxidising mineralisation and alteration events.

The significant feature common to all of these uraniferous granites is their late Archaean to Early-Middle Proterozoic age (2700–1500 Ma), and most of Australia's important uranium deposits, regardless of their age of formation, are hosted by sequences of this age. This then suggests that during this period of time, significant quantities of uranium were introduced into the upper crust by granite intrusion. The Kakadu-NW Arnhem Land region received a particularly high proportion of these granites and hence the underlying crust there is enriched in uranium.

*For further information contact Dr Lesley Wyborn at BMR (Minerals & Land Use Program).*

**Fig. 6. Values in stream sediments from catchments in the original Kakadu Conservation Zone, STOW 1:100 000 Sheet area, NT. (A) U in ppm, minus 0.18 mm mesh; (B) Th in ppm, minus 0.18 mm mesh; (C) Pb in ppm, minus 0.18 mm mesh; (D) Au, bulk leached cyanide method.**



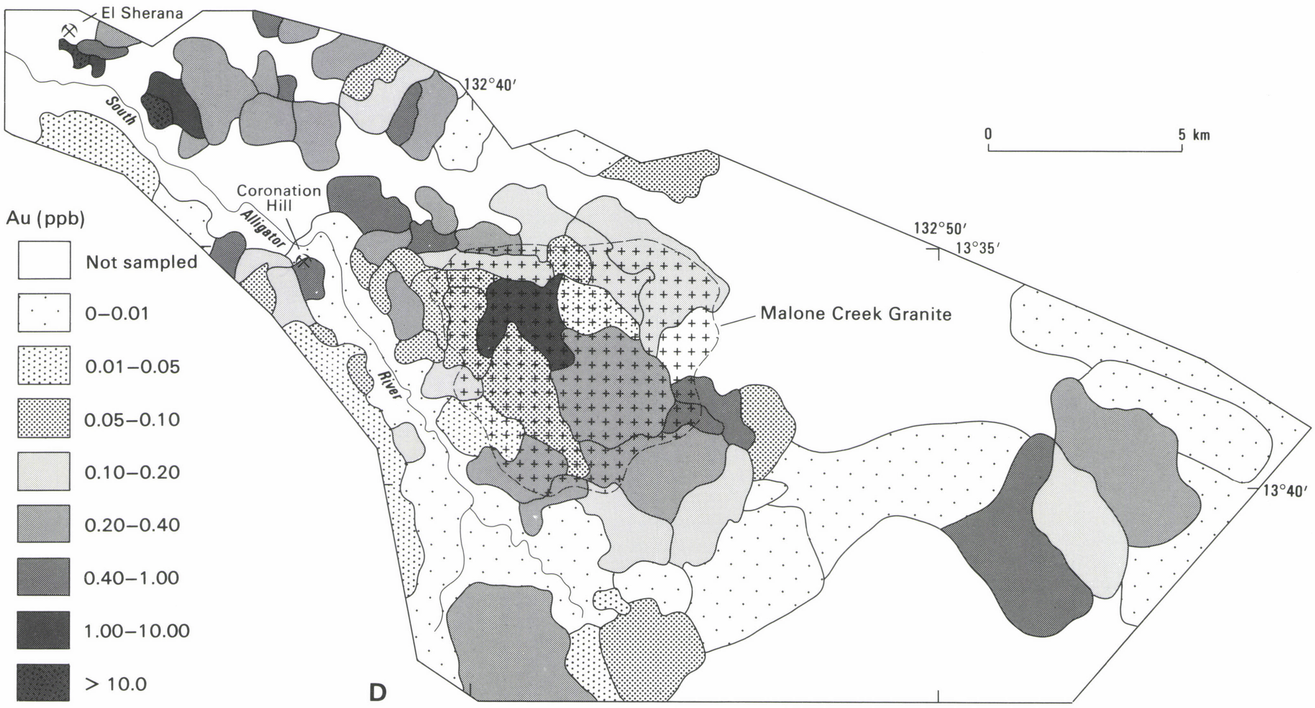
# Stream-sediment goechemistry of the original Kakadu Conservation Zone

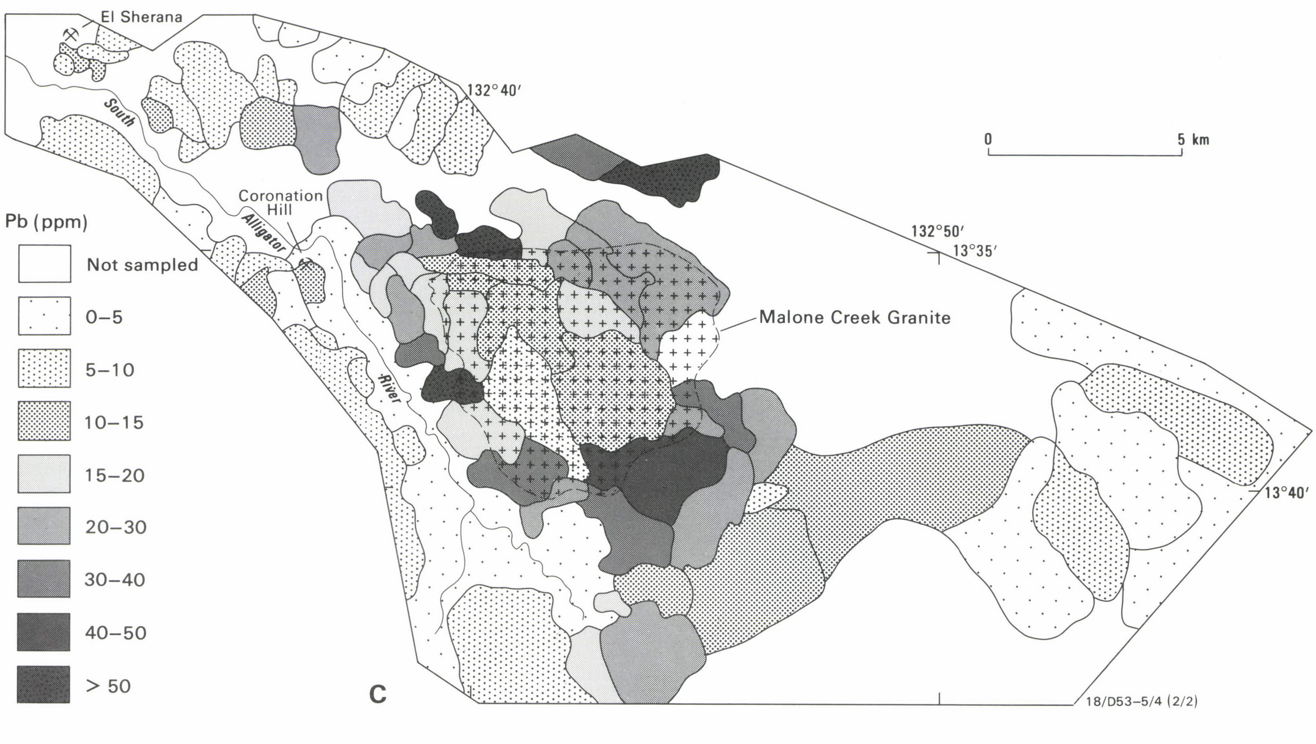
**Stream-sediment samples were collected from 133 sites in the original 2300 km² Kakadu Conservation Zone during 1989 as a combined orientation and regional survey. The survey was aimed at collecting information on the stream-sediment geochemical signatures of the unusual Au-PGM-U style of mineralisation in the South Alligator Valley Mineral Field, as well as investigating possible high concentrations of potentially environmentally harmful elements such as U, Th, As, Pb, Se, and Cr that are known to have well above average crustal concentrations in some of the local rock units. Streams draining known mineralisation, including the Coronation Hill, Palette, El Sherana, and Rockhole mines (U, Au, Pt, Pd) and the Namoona mine (Pb, Zn), were sampled, but the geochemical persistence of the elements of interest could not be determined because most of these sites are drained by short streams feeding directly into the South Alligator River.**

Approximately 10 kg of -1 mm sediment was collected at each site. Two portions of each sample were split off and sent for analysis for Au, Pt, and Pd: a 5 kg portion for bulk cyanide leach separation and AAS analysis (Australian Assay Laboratories, Perth) and a 1 kg portion for grinding, splitting, and fire assay separation for ICP/MS analysis (Analabs, Perth). Approximately 30 g of -0.18 mm sediment was sieved from the remainder of each sample and the oversize material was discarded. These portions were analysed for 30 trace elements (As, Ba, Bi, Ce, Cr, Cu, Ga, Ge, Hf, La, Mn, Mo, Nb, Nd, Ni, Pb, Rb, Sc, Se, Sn, Sr, Ta, Th, Ti, U, V, W, Y, Zn, and Zr, at BMR) by X-ray fluorescence spectrometry. A range of grainsize fractions will be sieved from selected samples and analysed.

The catchment basin for each sample was outlined using the 1:100 000 topographic maps, and geochemical maps have been prepared showing element concentrations represented by a greyscale level filling the area of each catchment basin. Figure 6 covers the eastern half of the survey, in the STOW 1:100 000 Sheet area.

The most obvious feature of these maps is the concentration of U (up to 49 ppm), and Th (up to 527 ppm) in sediments from Coronation Creek and other streams draining the U-enriched Malone Creek Granite (see article on pp.2-4). These high



values are unrelated to the mineralisation at Coronation Hill, because Coronation (Malone) Creek drains a separate area. U and Th also show strong spatial and statistical correlation with Zr, Hf, Nb, and W over the granite, although little correlation with La, Ce, or Nd. The U and Th are possibly concentrated in resistant minerals such as zircon and xenotime. Relatively high U values, although not as high as those in the granite, are also shown in streams draining abandoned workings at El Sherana (13.5 ppm) and Palette (20 ppm). Not shown are a small stream draining the pit area at Coronation Hill (17.5 ppm U) and a stream draining the Rockhole mines (121 ppm U) in the MUNDOGIE Sheet area. Th values were generally low in these streams draining the mineralised areas, as was also the case in the whole-rock geochemical analyses of the ore zones and their related alteration zones (see also article on pp.2-4).

Pb levels are high throughout much of the area.

With the precious-metal results there were discrepancies between the values obtained for the individual elements by the two different techniques, and this is being investigated. With both techniques, Au values were high in the El Sherana and Scinto Plateau areas and in some areas around the Malone Creek Granite.

*For further information contact Dr Bruce Cruickshank at BMR (Minerals & Land Use Program).*

# New results from the Mount Isa Geotraverse

**The Mount Isa Geotraverse is a nearly completed BMR program of detailed investigations into the structural evolution of an east-west corridor some 30 km wide across the structural grain of the Mount Isa Inlier, in northwest Queensland. The geotraverse aims at determining the stratigraphic and structural history of the rock units in the corridor, so as to elucidate the controls on the origin and distribution of copper, zinc-lead-silver, gold, and uranium in the inlier. One of the key areas of the geotraverse is the recently studied Ballara-Mount Frosty area southeast of Mary Kathleen (Fig. 7).**

This area:

— is the continuation of an area to the south where extensional faulting earlier than the first regional folding (at about 1610 Ma) of the Mount Isa Inlier was reported by C.W. Passchier (1986, *Geology,* **14,** 1008-1011); the two areas are separated by some 20 km of strike-slip displacement along the Fountain Range Fault, at the southern margin of the area;

— includes a possible klippe of a major thrust nappe emplaced during the first regional folding (Loosveld & Schreurs, 1987: *Australian Journal of Earth Sciences,* **34,** 387-402);

— illustrates a conformable stratigraphic relationship between the Argylla Formation and the Mary Kathleen Group, hitherto regarded by some as separated by a major unconformity.

Numerous small copper mines, some working, some not, are located in the Ballara-Mount Frosty area, and the eastern half of the area is currently of interest for copper and gold exploration.

## Geology

The stratigraphic sequence in the area is part of Mount Isa Cover Sequence 2, about 1790-1760 Ma old (D.H.Blake, 1987: *BMR Bulletin* **225).** From bottom to top, Cover Sequence 2 comprises the Argylla Formation (felsic volcanics and minor feldspathic sandstone), Mary Kathleen Group (Ballara Quartzite, followed conformably by calcareous and aluminous metasediments of the Corella Formation), and Mount Albert Group (Deighton Quartzite and ferro-aluminous schist of the White Blow Foundation). In the extreme northeast, the Argylla is underlain by the Magna Lynn Metabasalt; the Magna Lynn is separated by a shear zone from an adjoining granite which intrudes the Corella Formation. The area is intruded by many dykes, sills, and irregular masses of metadolerite.

## Stratigraphic results

The most significant stratigraphic results have been:

(1) Establishment of a new unit, the Mount Frosty Sandstone (intended new name). It forms the lowest part of the Mary Kathleen Group, being a correlative of all or part of the Ballara Quartzite, conformably overlies the Argylla Formation, and is in most places conformably overlain by the Corella Formation; in places in the west, however, it is conformably overlain by Ballara Quartzite. The unit has a maximum thickness of 1000 m, and was shown as Ballara Quartzite on the Mary Kathleen 1:100 000 Geological Map published by BMR in 1976, but its sedimentological characteristics — abundant feldspar, or sericite where metamorphosed, abundant heavy-mineral laminae, abundant conglomerate beds and, in the southwest, agglomerate, very thick bedding, and steep cross-bedding — indicate that it was deposited under possibly continental conditions, very different from the shallow-marine environment of the clean, well-sorted Ballara Quartzite. In the west limbs of the Rosebud and Staurolite Synclines (Fig. 7), the Mount Frosty Sandstone passes up through a 200 m thick interval of passage beds — interbedded calcareous sandstone, pelitic granofels, thin-bedded marble, and conglomerate — into the Corella Formation. In the west, the Mount Frosty Sandstone includes a lens several kilometres long of calc-silicate rock and marble, and is overlain by Ballara Quartzite, which appears to represent isolated shallow-shelf areas. On the Duchess Region 1:100 000 Geological Map (BMR 1982), the Mount Frosty Sandstone is shown south of the Fountain Range Fault as a major subunit near the top of the Argylla Formation.

(2) Establishment of stratigraphic conformity between the Argylla Formation and the overlying Mary Kathleen Group. At *locality 1* in Figure 7, purple feldspar porphyry is succeeded by interbedded crystal tuff and friable heavy-mineral-bearing sandstone with siltstone pebbles, and then by more porphyry; these are in turn overlain by cross-bedded friable sandstone originally mapped as Ballara Quartzite on the Mary Kathleen 1:100 000 Sheet, but now separated out as the Mount Frosty Sandstone.

## Structural results

The major structural features of the Ballara-Mount Frosty area can be summarised as follows:

(1) A large folded fault, the Melba Fault, juxtaposes Argylla and Corella Formations in the centre of the area; the fault is folded by the regional north-south-trending $D_2$ folds, and is therefore a $D_1$ fault. A very tight though gently arcuate syncline ($D_1$ because of its northeast-striking axial-plane cleavage), parallel to the fault at its western end (*locality 2),* indicates the fault is contractional.

(2) Blocks of Mount Frosty Sandstone commonly several kilometres in extent are bounded by meridional stratigraphic contacts or by $D_2$ faults, and by northeast- or northwest-striking faults. The latter faults cut and therefore postdate north-trending upright $D_2$ folds inside the blocks, and may be smaller equivalents of the strike-slip Fountain Range Fault. The block at *locality 3* immediately west of Mount Frosty mine is itself a jumble of smaller fault blocks, with the northeast-striking faults generally acting as tear faults where northeast-moving fault blocks terminated.

(3) In several places, e.g. *locality 4* on the western limb of the Rosebud Syncline, and *localities 5 and 6* on the western limb of the Staurolite Syncline, marble, granofels, and calc-silicate conglomerate of the Corella Formation have been injected along post-$D_2$ strike-slip faults for distances of hundreds of metres, indicating the pronounced tectonic mobility of this formation.

(4) The voluminous metadolerite dykes on the western limb of the Rosebud Syncline *(locality 7)* were injected along breccia zones (mapped as faults here) that cut the Mount Frosty Sandstone at a large angle to bedding. The dykes are nowhere brecciated themselves, but are cleaved by the meridional $D_2$ foliation and metamorphosed to biotite schist. Hence the breccia zones predate the dykes, which themselves are pre or early-$D_2$ in age. These observations are similar to those of Passchier 20 km to the southwest, and attributed by him to early extensional faulting followed by dolerite intrusion along the faults. At *locality 7,* however, the faults and breccia zones are associated with a doubling in thickness of the Mount Frosty Sandstone, indicating contractional faulting. The doubled section is succeeded to the north by a 1-km gap in the Mount Frosty Sandstone, indicating extension; it appears that the sandstone underwent north-south pre-$D_2$ extensional faulting, and the fault blocks were later jammed back together during the $D_2$ contraction (cross-section E-F). South of the Melba Fault *(locality 8),* metadolerite-filled extensional faults segment the Argylla Formation and Mount Frosty Sandstone into roughly equant tilt-blocks 1-2 km in extent.

(5) At *locality 9-9'* in the northwest, a fault excises a 4 km strike-length of a prominent feldspathic sandstone bed in the Corella Formation, but fault displacement decreases to nearly zero at the southeast end of the fault where it meets the Deighton Quartzite. Looking 'down-structure', the fault is a late $D_2$ or post-$D_2$ extensional fault 'rooted in the front' (cross-section, A-B. The separate fault blocks of Ballara Quartzite immediately west of locality 9-9' are caused by steeply dipping contractional $D_2$ faults, including a type of 'pop-up'. The fault at the southern end of the Campbell outlier *(locality 10)* is a late $D_2$ extensional fault; it, too, has its displacement dying out toward the front (cross section C-D, Fig. 7).

(6) The Deighton Quartzite on the west side of the Campbell Outlier is in stratigraphic conformity with the Corella Formation (A.J.Stewart, 1989, *Australian Journal of Earth Sciences,* **36,** 405-421), thereby disproving the thrust-nappe hypothesis of Loosveld & Schreurs. The fault on the eastern side of the outlier is a steeply west-dipping normal fault. It has undergone post-$D_2$ movement, but evidence from analogous extensional faults on the eastern sides of other Deighton Quartzite outliers to the north indicates that the faults formed before or early in the $D_2$ deformation.

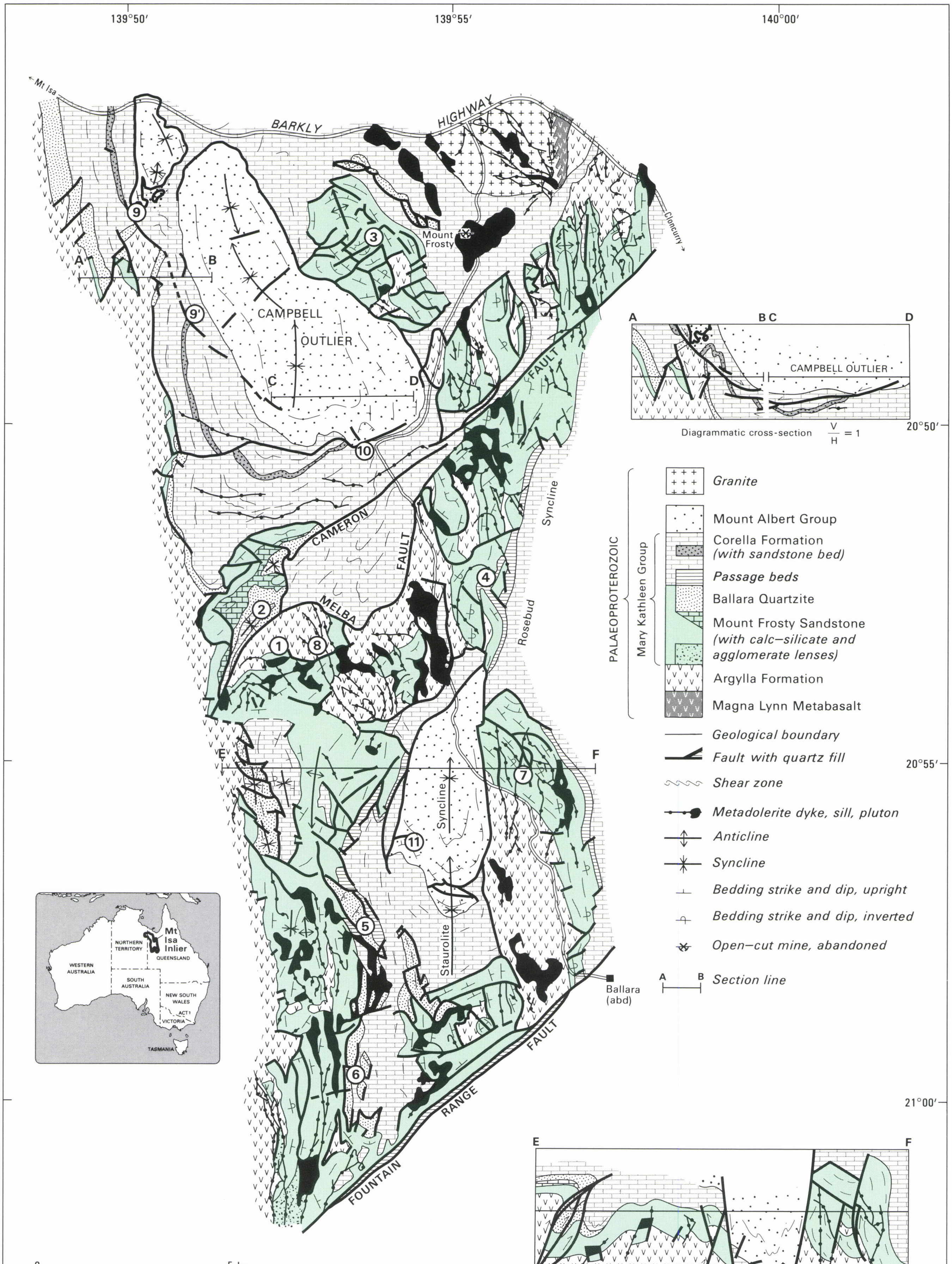



**Fig. 7. Generalised geological map of Ballara-Mount Frosty area, compiled from field data collected by A.J.Stewart (BMR; 1986, 1988) and M.A.Hawkins (Mount Isa Mines Ltd; 1986), and diagrammatic cross-sections. The circled numbers refer to localities described in the text.**

(7) The sense of displacement on the faults at *locality 11* on the west limb of the $D_2$ Staurolite Syncline is inconsistent with an origin by reverse faulting on the limb of the syncline during $D_2$ folding. The displacement is, however, consistent with an origin by pre-$D_2$ normal faulting, the faults being subsequently rotated past the vertical by buckling during $D_2$. Hence the Staurolite Syncline is interpreted as a pre-$D_2$ graben, which drops Mount Albert Group down into Corella Formation.

### Sequence of structural events

The interpreted sequence of structural events was as follows:

**(1) Pre-$D_1$ extension,** oriented approximately northeast-southwest, caused (a) normal faulting which dropped the Campbell and Staurolite outliers of Mount Albert Group into juxtaposition with Mount Frosty Sandstone; (b) segmentation by normal faults of the Argylla and Mount Frosty units at *locality 7* on the future western limb of the Rosebud Syncline at *locality 8* south of the future Melba Fault; and (c) intrusion of dolerite into the faults and breccia zones.

**(2) $D_1$ contraction** at about 1610 Ma (Page & Bell, 1986: *Journal of Geology,* **94,** 365-379), oriented north-south, caused (a) thrusting of Argylla over Corella along the Melba Fault, together with formation of a tight syncline parallel to the western end of the fault; and (b) pushed back together the previously extended fault blocks of Mount Frosty Sandstone at locality 7, and also duplicated the same unit by thrusting.

**(3) $D_2$ contraction** (at about 1544 Ma), oriented east-west, caused (a) formation of north-trending folds such as the Rosebud and Staurolite Synclines; (b) steepened or overturned pre-existing normal faults, e.g. on the sides of the Staurolite Syncline; (c) folded the originally east- striking Melba Fault and its accompanying tight syncline; (d) folded, cleaved, and metamorphosed dolerite intrusions and fault-fillings; and (e) formed steep reverse faults in Argylla and Ballara units in the northwest. Near the end of deformation, late dolerite dykes were injected south of the Campbell Outlier and gently folded. Deformation ended with late $D_2$ relaxation which formed the extensional faults rooted in the front in the northwest.

**(4) Post-$D_2$ strike-slip faulting** (at about 1500 Ma) formed the Fountain Range, Cameron, and other strike-slip faults, the larger ones oriented northeast but many others northwest. Faulting was accompanied by injection of Corella Formation into dyke-like openings between strike-slip fault blocks, and this, together with the abundance of the two orientations of strike-slip faults indicates that the strike-slip faulting formed in response to east-west compression and concomitant north-south extension (Derrick & others, 1977: *BMR Bulletin* **193,** 73).

The Ballara-Mount Frosty area thus contributes evidence on several aspects of Mount Isa tectonics. It:

— confirms the existence of pre-$D_1$ extension, of $D_1$ contraction oriented north-south, $D_2$ contraction oriented east-west, and the origin of the strike-slip faulting by east-west compression.

— disproves the existence of a postulated major thrust nappe; and

— reveals evidence of minor localised extension late in $D_2$, something not previously recognised in the Mount Isa Inlier.

**The results of this investigation of the Ballara—Mount Frosty area will be presented in a BMR Bulletin, now in preparation, on the Mount Isa Geotraverse. The Bulletin will comprise individually authored articles and a folio of maps prepared by BMR and university geologists who have contributed to the current BMR Mount Isa Project since its inception in 1983.**

*For further information, contact Dr Alastair Stewart at BMR (Minerals & Land Use Program).*

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# Sons of Gwalia gold deposit, WA

## Localisation in an Archaean extensional ductile shear zone

**The Sons of Gwalia mine at Leonora, WA, one of the most productive gold deposits in Australia, was operated as an underground mine from 1897 to 1963, and has operated as an open pit from 1982 to the present. Williams & others (1989: *Australian Journal of Earth Sciences,* 36, 383-403) (see also *BMR Research Newsletter,* 10, 1989) reported that the Sons of Gwalia deposit lies in an early, east-dipping ductile shear zone at least 45 km long which contains numerous other deposits and prospects. Examination of a 1.6 km continuous drillcore, from a hole drilled by Western Mining Corporation Ltd 1 km south of the mine, has helped characterise this shear as a regional extensional structure and shown that it marks an abrupt change in metamorphic grade and fluid composition (Fig. 8).**

The drillcore sampled four major rock units (Fig. 8). The top 55 m consists of intensely fissile schists: felsic schists probably derived from felsic volcanics down to 43 m, and chloritic schists with thin felsic intervals from 43 to 55 m. The second major unit, from 55 to 118 m, comprises ultramafic rocks varying from massive to ductilely deformed. The third unit, from 118 to 820 m, comprises sedimentary and felsic volcanic strata, while the fourth unit extending from 820 m to the bottom of the hole at 1605 m, consists of basaltic rocks with ultramafic intervals. Within the fourth unit, a major bedding-parallel ductile shear zone from 1180 to 1380 m separates an upper sequence lacking amphibole and poor in biotite from a lower sequence that contains prominent amphibole porphyroblasts and intervals of biotite schist with local strongly altered aluminosilicate porphyroblasts.

In the third unit, small-scale recumbent folds with wavelengths of a few centimetres have axial surfaces dipping about 40° to the east, parallel to the prominent cleavage. However, the enveloping surface defined by swarms of fold closures dips steeply, indicating the position of larger folds.

Using the vergence of these small-scale folds, the interpreted fold profile (Fig. 8) exhibits third-order-fold closures with wavelengths between 20 and 40 m and second-order folds with wavelengths between 140 and 180 m. Repetition of stratigraphy can be recognised across these folds. There is no clear vergence defined by the second-order folds, but the uppermost closure faces to the west, as does the lowermost clearly defined closure. The inferred first-order fold has a half wavelength of about 660 m, bounded at the top by a major shear zone against ultramafic rocks, and at the base by a thick (200 m) shear zone in basaltic rocks. Second-order folds may also be isolated.

Between 120 m and 1000 m, both thrust and extensional movement is recorded in asymmetric pressure-shadows, oblique carbonate fibres in asymmetric blebs, cleavage asymmetry around porphyroblasts and S-C fabric. The thrust indicators are only on the upper limbs of antiforms whereas extensional indicators are restricted to the lower limbs, suggesting that the fabric asymmetry developed as a result of flexural slip and does not reflect the overall regional sense-of-shear in the upper part of the hole. Below 1100 m, sense-of-shear is determined largely by S-C fabric in deformed basaltic and ultramafic layers. In all instances the cleavage fabric indicates movement of the top side down to the east, i.e. extension. In this part of the hole cleavage is partly annealed by static recrystallisation of hornblende, and in many parts of the core, particularly below 1500 m, cleavage is only poorly defined. However, at several levels cleavage is defined by a strong alignment of fresh hornblende needles.

The core exhibits two contrasting metamorphic assemblages juxtaposed relatively abruptly across the major ductile shear zone from 1180 to 1210 m. The upper part of the hole contains greenschist-facies assemblages: chlorite-muscovite-biotite in semi-pelitic rocks and chlorite-tremolite-calcite-epidote in mafic to ultramafic rocks. Below 1200 m the predominantly basaltic rock contains assemblages in the amphibolite facies, typified by oligoclase-tschermakitic amphibole-biotite (-magnetite-sphene).

For the low-grade rocks, Witt & others (1989: *BMR Research Symposium, Abstracts),* on the basis of fluid-inclusion data, quote a temperature of ~380°C and a fluid phase with $H_2O/CO_2$ ~19. The muscovite-biotite-chlorite geobarometer yields a pressure of 2.2 kilobars. The assemblage epidote-tremolite-chlorite in the ultramafic rocks suggests a temperature of about 365° and a pressure of about 2.5 kilobars. A reasonable peak P-T estimate for the greenschist-grade rocks is about 380°C and 2-2.5 kilobars. The metamorphic fluid was strongly dominated by water. Rock textures indicate that much of the deformation came after this metamorphism.

In the amphibolite-facies rocks coexisting magnetite and ilmenite suggests temperatures of about 580°C at an oxygen fugacity of about $10^{-18.6}$ bars. Amphibole compositions suggest a pressure of about 4 kilobars, and a temperature of 630°. The widespread assemblage ilmenite-sphene-calcite-biotite-kspar-quartz would be stable at 600° and 4 kbars only if $CO_2/H_2O$ were greater than 3. Retrograde chlorite-calcite-plagioclase-amphibole assemblages require $CO_2/H_2O$ greater than 1.

Features observed in drillcore strongly resemble features of the regional Sons of Gwalia Shear Zone, particularly in the area close to the Diorite King Mine. The Sons of Gwalia Shear Zone broadly coincides with the boundary between amphibolite and the Raeside Gneiss; both the amphibolite and gneiss are strongly sheared. In the Diorite King area, numerous shear sense indicators and the local fault geometry are definitive of normal movement on the north-dipping shears.

Amphibolite on the downthrown side is characterised by acicular hornblende needles defining a strong planar fabric which in places is overgrown by optically identical randomly oriented hornblende laths. Within 2–3 km of the boundary with the gneiss the metamorphic grade in the greenstone drops rapidly to greenschist-facies, in weakly deformed to undeformed pillowed basalts. The rocks in both the amphibolite-facies and greenschist-facies zones dip approximately 30° to the north, sub-parallel to the shear zone.

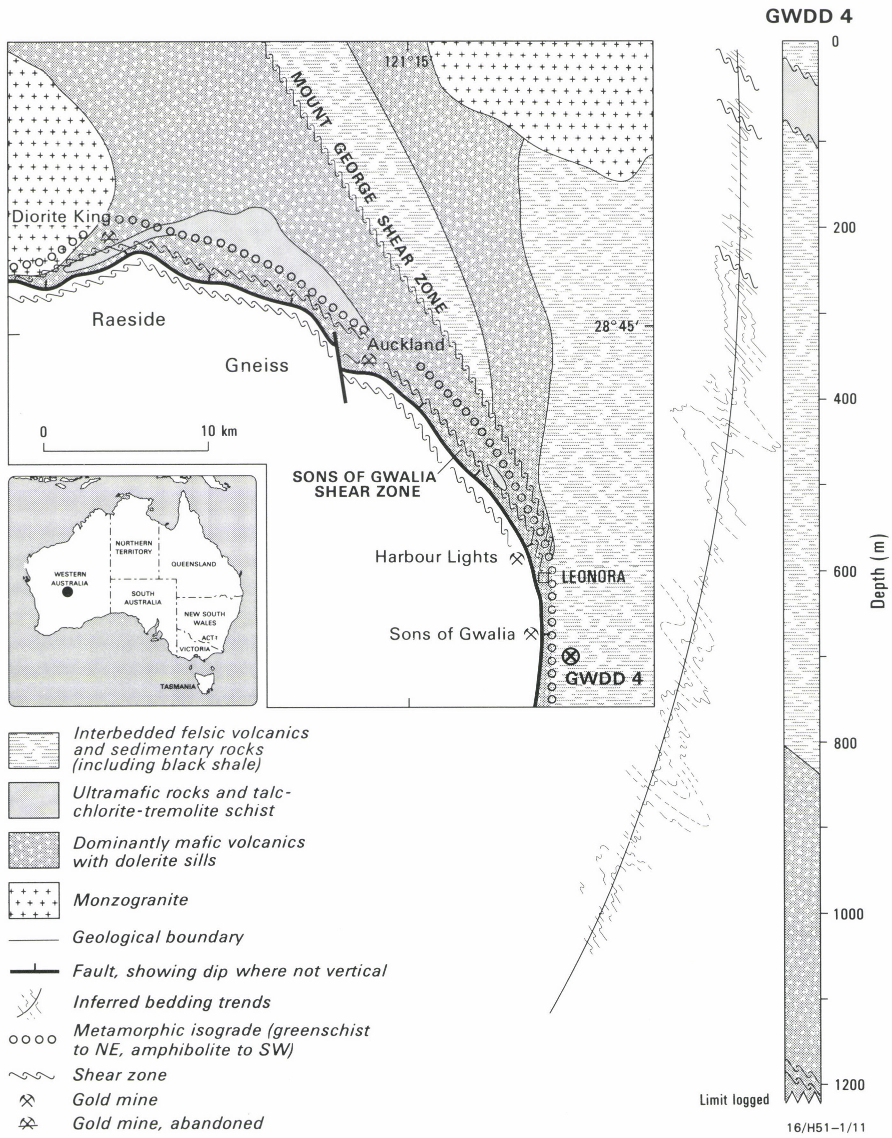
Data on metamorphic grade demonstrate that the ductile shears in the Sons of Gwalia section represent a major break involving loss of section. Even allowing for inaccuracy of the pressure estimates, several km of basaltic section appear to be missing. Estimated thicknesses of the basaltic interval in this greenstone belt are sufficient to allow such a loss.

The documented episode of deformation and metamorphism involved major extension along low-angle ductile shears, and contemporaneous rise of hot, deep-seated rock, i.e. similar conditions to those associated with metamorphic core complexes. Although elevated P/T gradients are evident above the central core, the highest P/T gradients occur at the boundary between the high-grade infrastructure and low-grade superstructure. This boundary also marks an abrupt change in the composition of the fluid phase, although there is little or no change in the character of the host rocks. It seems plausible that localisation of the Sons of Gwalia deposit, and perhaps other deposits associated with the same zone, is related to this change. The pervasive greenschist-facies metamorphism of the greenstones may have been driven by the rising hot rock.

The observed structural and metamorphic features suggest a model which differs markedly from previous models for the Leonora district, and from those involving early thrusting elsewhere.

**Fig. 8. Solid geology and locations of main structures in the Leonora area (in the Archaean Yilgarn Block, WA) including the Sons of Gwalia mine and Western Mining Corporation Ltd's drill-hole GWDD4. Condensed log of drill-hole GWDD4 shows the main stratigraphic and structural features.**

*For further information on BMR work in the Eastern Goldfields, WA, contact Dr Peter Williams at BMR (Minerals & Land Use Program). GWDD4 was kindly made available for examination by Western Mining Corporation Ltd, 55 McDonald St, Kalgoorlie, WA.*




# LEONORA (WA) geological sheets released

**Geological field compilation sheets for the LEONORA 1:100 000 Sheet area, WA, have been completed and are on sale through the BMR Copy Service. The two 1:50 000 sheets cover the northern and southern halves of the LEONORA 1:100 000 Sheet area, together with reference. The maps are a result of a collaborative Eastern Goldfields project of geological mapping and structural analysis by the Geological Survey of Western Australia (GSWA) and BMR.**

The maps emphasise the structural elements of the LEONORA Sheet area and present much new structural information. They build on past geological mapping in the area, providing a sound lithological framework, and show the structural data that led to the identification of early shear zones in the district (*BMR Research Newsletter* **10** [April 1989] and this issue, p.8) and their association with gold deposits. Following GSWA practice, release of these sheets will replace the publication of three-colour preliminary maps for the Eastern Goldfields collaborative project.

The maps are available as either dyeline prints or transparencies for a total price of $75. Individual sheets may be purchased for $50.

# GDA upgrade

**GDA, the BMR's IBM PC-based whole-rock geochemical data analysis system (see *BMR Research Newsletter*, 9, October 1988), has recently been updated. It incorporates several new options, and a number of bugs have been eliminated. The system is written in FORTRAN 77 and uses Media Cybernetics HALO for plotting routines. It was designed to accept data from the BMR *Oracle* database, but any correctly formatted ASCII datafiles can be used as input, or the data may be entered into files directly from the keyboard. The GDA system is particularly designed for producing a variety of plots (XY, triangular, histograms, box-whisker, and spidergrams), and has the facility to add additional plot points, text, and lines or grids such as rock-type or phase boundaries to the plots. It can also calculate statistical functions (e.g. mean, standard-deviation, regression lines, correlation-coefficient matrices, and cluster analysis). A specialised petrological package includes CIPW norms and petrogenetic models (equilibrium batch melting, Rayleigh fractionation, least-squares mixing, etc.). There are also facilities for producing hard-copy plots, tables of geochemical and statistical data, and a utilities program for setting up, editing, and merging datafiles.**

**The FORTRAN source code on 3½ or 5¼ inch floppy disks may be purchased for $750. A comprehensive reference manual is included. Users will need an IBM PC (or compatible) with 640 k RAM, a 10 Mb hard disk, and a Hercules, EGA, or VGA colour-graphics card. An HP-compatible plotter is required for hard-copy graphics, and a printer for reports. Additional software required comprises Microsoft FORTRAN 77 and Media Cybernetics HALO. *Available from: BMR Publication Sales, GPO Box 378, Canberra City ACT 2601. Phone (06) 249 9519, Fax (06) 247 2728. Enquiries to John Sheraton (06) 249 9384 or Doone Wyborn (06) 249 9386***

# Deep-sea polymetallic sulphides (including new discoveries in the SW Pacific)

**Polymetallic sulphides, deposited from hot hydrothermal solutions, are now known from the Red Sea as metalliferous sediments and from the Pacific Ocean as sub-seafloor stockworks and massive sulphides, and seafloor polymetallic massive sulphides (PMS). (Cronan, 1980 UNDERWATER MINERALS, *Academic Press*, provides an excellent review of early discoveries.) The first discovery of hot brines in the Red Sea was made in 1948 and led to the first-ever discovery of deep-sea, unconsolidated stratiform polymetallic sulphides in 1966. The first discoveries of seafloor PMS in the Pacific Ocean were in the Gulf of California in 1977 and on the East Pacific Rise (EPR) in 1978. Since then, many similar discoveries have been made along eastern Pacific spreading centres, together with discoveries of metalliferous sediments in ocean basins next to spreading centres elsewhere in the Pacific and Altantic Oceans (Fig. 9). Operations using submersibles led to the discovery of PMS and stockworks in areas where faults cut the oceanic crust of spreading ridges or nearby seamounts. Recently, new discoveries have been made in the Southwest Pacific Ocean, in back-arc basins.**

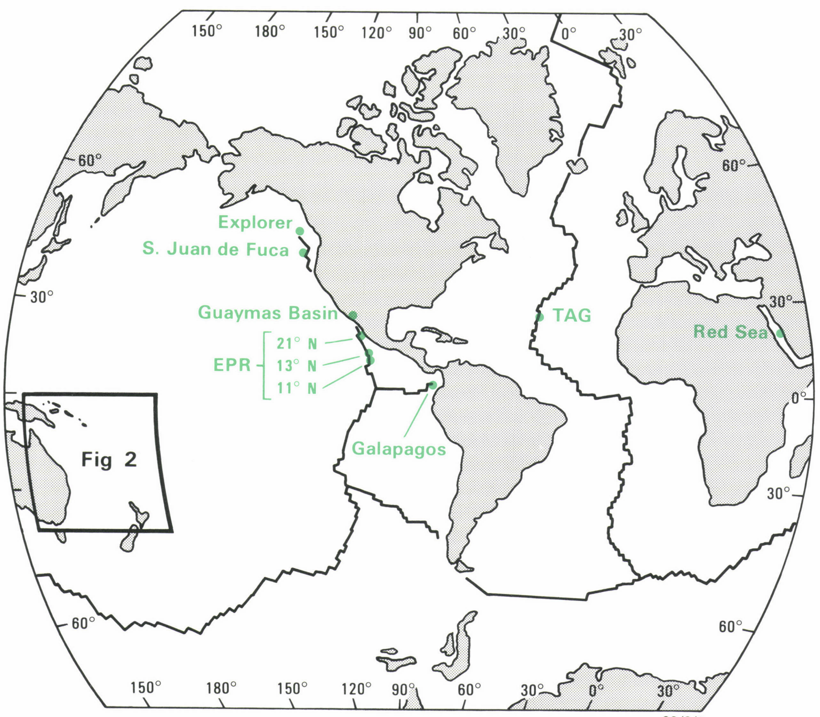
## Eastern Pacific deposits

In the eastern Pacific, massive sulphides on the seafloor typically occur as chimney-like structures formed about hydrothermal vents and rising as much as 30 m above basaltic spreading centres. The chimneys commonly coalesce into much larger composite bodies.

All the Pacific PMS deposits have formed through the circulation of sea water deep into the basalts where it has become superheated and has leached out metals. Where hydrothermal temperatures reach 350–400°C, the mineral-laden water is emitted from the vents as black plumes ('smokers'), and polymetallic sulphides (Cu, Zn, Pb, and Fe sulphides, with appreciable contents of Au, Cd, Mo, Sn and V in places) are precipitated to form the chimneys. At lower temperatures, of 300–350°C, the smokers are white and form chimneys of metal sulphates, anhydrite, and gypsum.

A spectacular association of unique and unusual organisms attends the smokers. Clouds of bacteria feed on methane in the hot water plumes, and these form the basis of a food chain including giant tube-worms, clams, crabs, shrimps, and fish. This unique food chain is seen also where methane escapes from thick sedimentary sequences on active continental margins, e.g off North and South America.

**Fig. 9. Selected seafloor polymetallic sulphide (PMS) locations.**




## Southwest Pacific deposits

In the last few years a number of research cruises have sought evidence of similar smokers and PMS bodies in the back-arc basins of the southwest Pacific, where there are some differences in crustal type from the eastern Pacific and where spreading centres are typically shallower. The search for methane and helium anomalies in sea water, which have helped locate hydrothermal vents elsewhere, has shown that such anomalies are present at least in the Lau Basin, North Fiji Basin, and Manus Basin (Fig. 10). Polymetallic sulphides have been photographed (as smokers) in the Manus Basin, and sampled in the Lau Basin and North Fiji Basin by surface vessels and a research submersible. In addition, lower-temperature hydrothermal deposits, largely of manganese and iron oxides, have been recovered in these three basins and also on the Manus Fore-arc northwest of Manus Island, in the westernmost Woodlark Basin, and on the eastern Lord Howe Rise where cut by the Vening-Meinesz Fracture Zone. Unusually, the latter three occurrences are not on oceanic basalt but on arc, intermediate, and continental crust respectively.

The recent CCOP/SOPAC-IOC Fourth International Workshop on Geology, Geophysics, & Mineral Resources of the South Pacific, held in Canberra in late 1989, included eight papers covering the latest studies of hydrothermal metal deposits in back-arc basins, mostly in the southwest Pacific (the abstracts volume is *CCOP/SOPAC Miscellaneous Report* **79**). BMR is not involved in these studies but CSIRO's Dr Ray Binns has co-authored a paper on the western Woodlark Basin hydrothermal iron-oxide deposits, where rifting is propagating into the crust of eastern Papua New Guinea. The results outlined at the workshop are summarised below.

In the Lau Basin, a great deal of work has been done by German, French, and US scientists. A magma chamber beneath the Valu Fa Spreading Ridge in the southern Lau Basin was identified from a US vessel in 1982. This was considered to be a favourable area for hydrothermal deposits by German scientists, who, using tethered equipment from a surface vessel, later found hydrothermal deposits, including PMS, on the ridge in 1984. More recently, a US research vessel recovered PMS samples from the northern Lau Basin. The research submersible *Nautile* was used by a French-German consortium to extensively survey the Valu Fa ridge in 1989, obtaining abundant photographic, temperature, and sampling evidence of white and black smokers, and associated hydrothermal deposits, in water depths of 1700–2000 m, in and on young andesitic crust. These deposits extend for at least 100 km north-south, and individual sulphide bodies are at least several hundred metres long and 20 m high. Chimneys form on the surface, and stockworks and massive sulphides beneath. Black smokers consist of sulphides, and white smokers of barite. Sulphide mineral assemblages vary, with Cu, Zn, Pb, and Ba important.

In the North Fiji Basin, French, Japanese, German, and US researchers have been active and an initial discovery of polymetallic sulphides from surface vessels was followed up in 1989 by French-Japanese *Nautile* dives. In the axial graben of the North Fiji Fracture Zone, in water 2000 m deep, hydrothermal sites with extinct chimneys are common. The only active vent seen so far has formed a 3 m high chimney of anhydrite.

The biological communities associated with the methane-bearing hydrothermal vents consist of clouds of bacteria, barnacles, gastropods, crabs, shrimps, and fish. The main difference from the east Pacific communities is the apparent absence of tube-worms and clams and the presence of gastropods.

## Size

Systematic, three-dimensional sampling has not been carried out for any seafloor PMS deposit, and, consequently, bulk compositions and vertical extent are very poorly known. The areal extent and thicknesses of some deposits along the Explorer Ridge and EPR (Fig. 9), determined from deep-tow photography and submersible observations, combined with geophysical self-potential measurements (Francis, 1985: *Marine Geophysical Researches*, **7**), are up to 200 by 100 m in plan and 5–10 m thick; the thickness has been measured on faulted sections through deposits. Ten such deposits are estimated to contain about 3-5 Mt in aggregate (Scott, 1987: *in* Teleki & others (Editors): MARINE MINERALS: ADVANCES IN RESEARCH & RESOURCE ASSESSMENT. *D. Reidel Publ. Co.).* The recent results from the southwest Pacific, together with the fact that only a very small fraction of potential sites on the world's ocean floors have been closely surveyed, raises expectations that there are more and larger deposits yet to be discovered.

### Mining and beneficiation

With the exception of the deposits in the Red Sea, neither the mining nor the beneficiation of seafloor PMS have received as close attention as scientific research *per se.* Two broad types of PMS are discernible (Rowland, 1985: *Marine Technology Society Journal,* **19,** 4): (1) unconsolidated deposits in sediments, such as the Red Sea muds, and (2) massive or consolidated deposits such as those in the Juan de Fuca region. The technology to mine unconsolidated deposits was developed in the early 1980s and successful pilot-scale mining has been conducted in the Atlantis II Deep in the central Red Sea at a depth of over 2000 m. The extremely fine grainsize of the Red Sea deposits will require application of a chloride-based hydrometallurgical technique after flotation to upgrade the valuable metals (Carnahan, 1985: *Marine Technology Society Journal,* **19,** 4).

Currently, there is no technology with which to mine consolidated PMS deposits, although a conceptual approach has been proposed by Kaufman (1985: *Marine Technology Society Journal,* **19,** 4). Flotation tests of PMS samples from 13°N and 21°S latitudes on the EPR have been conducted by Preussag AG. The tests required pulp aeration for effective pyrite depression and addition of sodium sulphide for selective copper-zinc flotation (Ergunalp & Weber, 1985: *Erzmetall,* **30,** 5).

Bench-scale testing of PMS samples at the University of Toronto has shown that high-intensity magnetic separation has the potential to produce a bulk copper-zinc concentrate with over 80% recovery of copper and zinc (Alton, Dobby, & Scott, in press: *Marine Mining).* These authors suggest that this type of separation may be possible at sea with the tailings (not containing chemicals) being discharged directly into the ocean, and the bulk concentrate being processed on land into separate copper and zinc concentrates by flotation. It is assumed that such discharge would be beneath the thermocline and hence separated from the surface waters.

Although base metals (primarily Cu and Zn) are the principal economic constituents of seafloor PMS, gold and silver combined may contribute as much as 20% of the in-situ metal value of the deposits (Hannington & Scott, 1988: *Marine Mining,* **7).** The fine grainsize (<10 microns) of gold particles and complex textural associations of silver-bearing minerals are likely to result in recovery problems similar to those encountered during the milling and flotation of massive sulphide deposits on land. Nevertheless the recovery of these metals commonly contributes to the profitability of these deposits, and is likely to be of similar importance for the commercial exploitation of seafloor PMS.

Little can be said at this stage about the costs of mining consolidated PMS except that they would be high relative to those for similar resources on land. Initial expenditure will involve research and development of new mining technology. Exploration costs will be high because of the need to use ships and high-technology sensing equipment. The discoveries to date, coupled with a reasonable expectation that larger deposits are yet to be found, may be sufficient reason to be optimistic that ocean mining of PMS will become viable in the future (Scott, 1987: *in* Teleki, P.G., & others (Editors), *op. cit.);* as yet, however, too little is known about the nature of PMS to make confident predictions about their economic promise and the timing of any development.

### Jurisdiction

Ocean-ridge settings that contain PMS deposits in the Pacific are both within and seaward of the 200 nautical mile offshore zone of coastline countries. Under the provisions of the Convention adopted by the Law of the Sea Conference in 1982, coastal States would have jurisdiction over their 200 mile Exclusive Economic Zone (EEZ) and the part of their legal continental margin that extends beyond that distance. Exploration and mining in the deep ocean beyond this will be under the jurisdiction of the International Seabed Authority (ISA) when the Convention comes into force. Forty-two nations have ratified the Convention and a further 18 are required to ratify it in order to bring it into force. However, parts of the Convention are unacceptable to some countries and it remains to be seen whether the United States, the industrialised states of East and West Europe, Japan, and others can agree on solutions which are generally acceptable and which will enable them to become parties to the Convention.

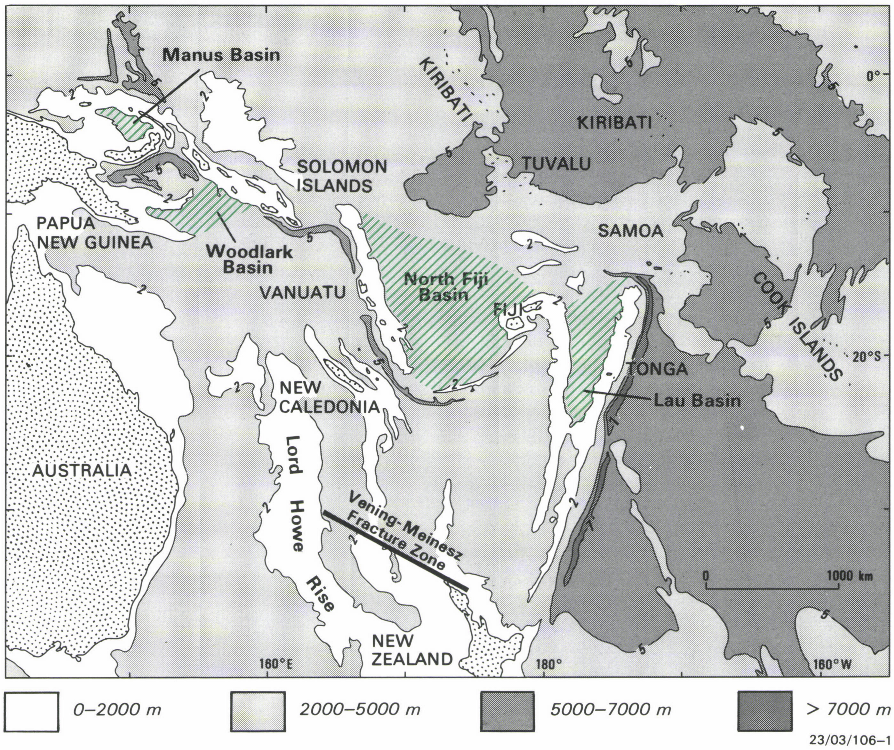



**Fig. 10. Basins recently found to contain seafloor PMS in the southwest Pacific.**

The Law of the Sea Preparatory Commission is currently drafting regulations for the exploration and exploitation of polymetallic manganese nodules (PMN); the Commission's mandate for these activities extends only to PMN. The ISA's executive body (the Council), however, acting by consensus, will be able (on request) to promulgate rules and regulations governing the mining of other minerals. For legislative and economic reasons it seems likely that commercial interest in PMS deposits will focus initially on areas within EEZs. Ridge areas that are within the EEZ of eastern Pacific rim coastal states include Explorer Ridge and the northern part of the Juan de Fuca Ridge, Canada; the northern part of the Gorda Ridge, United States; the Guaymas Basin, Mexico; parts of the EPR, Mexico and Chile; and part of the Galapagos Ridge, Ecuador (McKelvey, 1986: *US Geological Survey, Bulletin* **1689).** In the southwest Pacific they include the Manus Basin, Papua New Guinea; the North Fiji Basin, Vanuatu, France, and Fiji; and the Lau Basin, Tonga and Fiji.

*For further information, contact Dr Neville Exon (Marine Geoscience & Petroleum Geology Program) or Dr William McKay (Minerals Resource Assessment Program) at BMR.*

# The Mud Tank Carbonatite, NT

## An example of metasomatism at mid-crustal levels

**The Mud Tank Carbonatite, 85 km northeast of Alice Springs, NT, was the first carbonatite to be recognised in Australia (Crohn & Gellatly, 1969: *Australian Journal of Science,* 31, 335–336). It yields some of the world's finest gem zircon from alluvial deposits and is presently being evaluated as a potential vermiculite deposit. A number of carbonatite complexes have now been identified in Australia by exploration companies and one of these, Mount Weld, WA has significant reserves of rare-earth elements (REE) and phosphate. Field and geochemical work on the Mud Tank Carbonatite reviewed by Crohn & Moore (1984: *BMR Journal of Australian Geology & Geophysics,* 9, 13–18), concluded that the carbonatite has an unusual geometry, and that sodic metasomatism and high REE and niobium concentrations typical of carbonatite complexes are absent. BMR has carried out a detailed petrologic and geochemical study of Mud Tank as part of its research program on alkalic rocks and related mineralisation. This work shows that an unusual type of sodic metasomatism is present, and suggests that the shape and geochemical signature of the complex may result largely from post-emplacement processes.**

The Mud Tank Carbonatite was emplaced into felsic and mafic granulites of the Strangways Metamorphic Complex about 732 Ma ago. Outcrop comprises three low knolls within a northeast-trending area about 2 km long by 200 to 700 m wide, with another small area lying a further 2 km to the southwest. Each knoll consists of a separate carbonate core surrounded by more magnetic biotite-rich units. The carbonatite is emplaced within a major northeast-trending mylonite zone with a long history of deformation in which early sillimanite-grade metamorphism outlasted ductile deformation, but high-grade assemblages have been repeatedly retrogressed and deformed in increasingly brittle style.

Carbonatite units have been foliated and deformed to various degrees, with foliation generally parallel to regional foliation, but locally wrapping around the carbonate cores, which have been brecciated and rehealed, in some cases repeatedly. The carbonatite contains a variety of boudinaged and fractured inclusions, ranging in size from a few centimetres up to tens of metres and in lithology from pegmatite and alkali syenite to anorthositic and mafic granulite. Contacts of the carbonatitic rocks with both inclusions and host are sharp and commonly strongly sheared.

The carbonatite consists of an early fabric of ferroan dolomite, veined, brecciated, replaced, and cemented by Fe-poor calcite. Apatite, a major accessory, shows the effects of multiple episodes of deformation and recrystallisation. Compared to world averages, Mud Tank carbonatites have significantly high Cu, Ni, and Cr contents, and low Sr, Zr, Nb, Mo, La, and Ce. Micas appear to have a complex history involving hydrothermal and surficial processes. Unfoliated mafic granulites within the complex have been pervasively metasomatised and are enriched in Si, Na, and Ba and depleted in Fe, Zr, and Pb relative to similar country-rock granulites which are a major constituent of the fault slice into which the Mud Tank complex is emplaced. Metasomatic minerals include albite, and amphibole and pyroxene anomalously high in Na and Al.

Thermodynamic calculations based on mineral chemical data indicate emplacement of the carbonatite at >615°C and >5 kb under conditions of high water and fluorine fugacity. We suggest that such P-T conditions, along with the abundance, size, diversity, and boudinaged character of inclusions, together with the widespread brecciation of the carbonates, the early crystallisation of dolomite, and the location of the complex along a major ductile shear zone, indicate that the Mud Tank Carbonatite was emplaced at mid-crustal depths (minimum 15 km) along active faults associated with development of the late Precambrian Amadeus Basin (Shaw & others, 1984: *Australian Journal of Earth Sciences,* **31,** 457-484). During repeated movement, hot carbonate would be remobilised and parts of the metasomatic envelope entrained. Each episode of movement on the ductile shear zone caused the carbonatite to rise and cool slightly, leading to successively more brittle conditions. In the later stages sampled by carbonate-mica pairs, the fluid associated with movement of the intrusion was water-dominated, a condition unfavourable for transport of Nb and REE. Hence any significant concentration of these elements is unlikely.

Among inclusions acquired by the carbonatite during its ascent are syenites which share alkaline character with the carbonatite. It seems improbable that the carbonatite magma would fortuitously sample an unrelated alkaline rock, but the higher Fe/Mg ratio and more depleted REE pattern of the syenite indicate clearly that the two rock types cannot be related to a single parent. Alkaline rocks typically occur in provinces. The carbonatite may have sampled another alkaline body associated with late Precambrian rifting, which suggests that an alkaline igneous province of late Precambrian age is present in this region.

*For further information contact Dr Jan Knutson at BMR (Minerals & Land Use Program) or Dr Ken Currie, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada.*

# Finger-printing diamonds by their nitrogen aggregation state

**Nitrogen is the major impurity in the lattice of diamond and its presence or absence has a marked effect on a diamond's physical properties, particularly colour and conductivity. Most natural diamonds contain substitutional nitrogen in amounts ranging up to 0.5% (atomic) and are termed 'Type Ia'. The substitution of nitrogen in diamond can be determined by infra-red (IR) spectroscopy and such studies have shown that Type Ia diamonds contain nitrogen in lattice defects in several distinct aggregation states. It has been shown that nitrogen aggregation characteristics obtained by IR spectroscopy can provide useful geological information (Evans & Harris, 1989: in KIMBERLITES & RELATED ROCKS, Volume 2: Their Mantle/Crust Setting, Diamonds & Diamond Exploration, 1001-1006. *Geological Society of Australia, Special Publication 14).* As part of an ongoing investigation by BMR of Australian diamonds and their host rocks we have determined the nitrogen aggregation characteristics of diamonds from alluvial sources at Copeton, NSW and Kalimantan, Indonesia and from the Argyle and Ellendale lamproite pipes in Western Australia, with a view to better defining their origin and, in particular, the source of the alluvial stones.**

## Nitrogen aggregation kinetics

The two dominant forms of aggregated nitrogen in diamond are the 'A form' which is a pair of nitrogen atoms, and the 'B form' which consists of four nitrogen atoms arranged tetrahedrally about a vacancy. Experimental studies (e.g. Evans & Qi, 1982: *Proceedings of the Royal Society of London,* **A381,** 159-178) have shown that the A—>B aggregation reaction forms part of an overall sequence that begins with incorporation of singly substituted nitrogen atoms as point defects during diamond growth. These diamonds are termed 'Type Ib' and most synthetic diamonds are of this type. During high-temperature annealing in the mantle, the singly substituted nitrogen atoms migrate and combine to form the more stable A-aggregates with a minor side reaction to form N3 defects (triplets); this process is essentially irreversible at temperatures of ~1200°C. Further aggregation yields B-defects and concurrent generation of large planar defects known as platelets (in cube planes). The platelets may ultimately degrade to form a diamond of pure B character or undergo 'catastrophic' degradation, resulting in platelet-depleted diamonds with mixed A-and B-defects. The extent of A—>B aggregation is a function of the temperature history of the mantle, the mantle residence time, and the nitrogen content of the diamond.

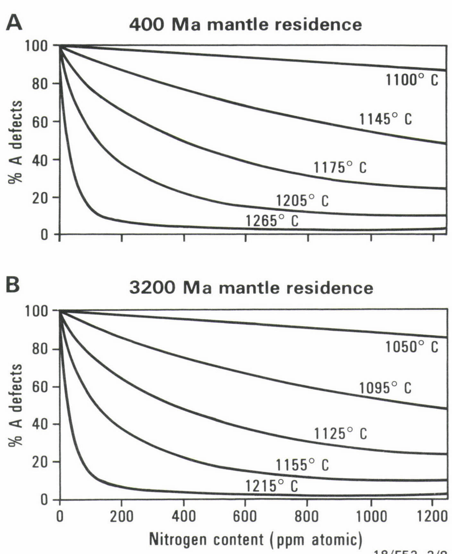



**Fig. 11. Results of modelling of the A—>B aggregation reaction, shown as isotherms % A-defects-versus-nitrogen-content variation diagrams for mantle residence times of 400 and 3200 Ma.**

Isotopic dating of inclusions in Argyle eclogitic diamonds indicates a short mantle residence time for the diamonds (~400 Ma, Richardson, 1986: *Nature,* **322,** 623-626) and this, together with equilibration at the temperatures estimated for Argyle diamonds (~1250°C, Jaques & others, in Evans & Harris, op. cit.) have been used to refine the reaction kinetics and activation energy of the A—>B aggregation. Kinetic modelling shows that the reaction is sensitive to the 'time-averaged' temperatures in the range 1050 to 1300°C. Below 1050°C there is no significant conversion of A-defects, even for Archaean ages, whereas at temperatures greater than 1300°C conversion is nearly complete after only a few hundred million years (Fig. 11).

## FTIR microscopy

In our collaborative study we used the Fourier Transform Infra-red (FTIR) microscope at the Central Science Laboratory of the University of Tasmania to determine the nitrogen content and aggregation characteristics of diamonds from Australia and Kalimantan. The FTIR microscope permits non-destructive direct determination of IR spectra on rough diamonds or fragments of broken diamonds of ~0.5-4 mm thickness using a variable aperture diaphragm. Spectra were recorded in transmission mode over the range 4000-450 $cm^{-1}$ and 'decomposed' into A, B, and D components after subtraction of background using synthesised spectra. The proportion of A- and B-defects was determined with a reproducibility of ± 4% and total nitrogen estimated with an accuracy of ± 6% relative.

## Argyle and Ellendale diamonds

Our data confirm earlier results (Harris & Collins, 1985: *Industrial Diamond Review,* **3/85,** 128-130) which showed that Argyle diamonds, which are overwhelmingly of eclogitic paragenesis, (1) have low nitrogen contents, (2) the nitrogen is dominantly present as B-aggregates, and (3) many show platelet degradation. The temperatures estimated from A—>B aggregation are very close to average temperatures obtained from garnet-clinopyroxene geothermometry. The Argyle diamonds appear unique in being dominated by B-defects and platelet-degradation, and this is attributed to their unusually high equilibration temperatures.

Ellendale eclogitic diamonds differ markedly from Argyle diamonds in having most of their nitrogen in A-aggregate form (Fig. 12). This implies that the Ellendale eclogitic diamonds were resident in cool lithosphere and could not have experienced the high temperatures typical of Argyle. Constraints from inclusion geothermometry indicate that Ellendale eclogitic diamonds must be younger than those from Argyle, and a Phanerozoic age seems likely.

## Copeton diamonds

The source of the Copeton diamonds is unknown. The Copeton stones are notable for their multiple twinning (which makes them hard to cut), their unusually heavy $\delta^{13}C$ values, and an inclusion suite with abundant coesite and Ca-rich garnet (Sobolev, 1984: *in* Kimberlite occurrence &

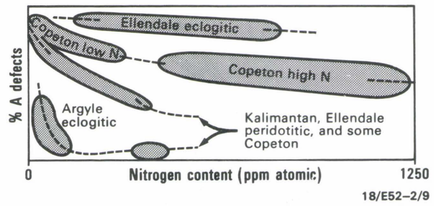



**Fig. 12. Nitrogen aggregation plot showing separation of Ellendale eclogitic and Argyle eclogitic diamonds into low- and high-temperature fields respectively. Copeton diamonds plot on moderate -temperature isotherms. The coincidence of diamonds from Kalimantan, Ellendale (peridotitic), and some Copeton stones could indicate a common thermal history and an origin in old Gondwana lithosphere now tectonically dispersed.**

origin: a basis for conceptual models in exploration. *University of Western Australia, Geology Department & Extension Service, Publication* **8,** 213-226). Copeton stones (kindly made available by Mr A.C. Joris) fall into high (> 500 ppm, yellow) and low (< 400 ppm, mostly colourless) nitrogen groups showing a range of A–B characteristics with no platelet-degraded diamonds present (Fig. 12). The degree of nitrogen aggregation shown by the eclogitic Copeton diamonds requires mantle residence times of at least 20 Ma even for storage temperatures as high as 1300°C. For more moderate temperatures (i.e. ~1100–1150°C) a Proterozoic age is implied for at least some of the Copeton diamonds, even though no Precambrian lithosphere is known within the New England Fold Belt. The nitrogen data therefore militate against an origin in newly subducted (or obducted) cold lithosphere for the eclogitic diamonds from Copeton. These diamonds seem likely to have formed in recycled (subducted) crustal rocks that were accreted onto an old remnant of microcontinental lithosphere and were later carried to the surface by Mesozoic volcanic pipes.

### Kalimantan diamonds

Alluvial diamonds have long been known from Kalimantan but their primary source(s) remain a mystery. Limited data for the Kalimantan stones suggest similarities with the Ellendale peridotitic diamonds and both these suites appear coincident in terms of their nitrogen aggregation temperatures with the geotherm defined for the higher-temperature Copeton suite (Fig. 12). This could be interpreted to indicate that all three suites had a common origin in ancient Gondwana lithosphere that has been dispersed by subsequent tectonic processes, a view consistent with recent palaeotectonic reconstructions of northeastern Gondwana, which includes Australia and parts of Asia (Long & Burrett, 1989: *Geology,* **17,** 811–813).

The unreactive nature of diamond in all but oxidising conditions means that diamonds and their syngenetic inclusions record important information on the subcontinental mantle (*BMR Research Newsletter,* **6** (1987), 15–16). The FTIR microscope offers a powerful new means of rapidly characterising diamonds and obtaining information on the thermal evolution of the subcontinental lithosphere.

*For further information contact Dr Lynton Jaques at BMR (Minerals & Land Use Program) or Dr Wayne Taylor at the Department of Geology, University of Western Australia, Nedlands, WA 6009.*

Announcing a

## One-Day Workshop at BMR on HYDRODYNAMICS OF BASINAL FLUIDS: APPLICATION TO PETROLEUM MIGRATION AND ORE FORMATION

by

**Dr Craig Bethke**

*Department of Geology, University of Illinois at Urbana—Champaign*

Following the successful workshop on Geochemistry of Basinal Brines, presented by Dr Yousif Kharaka (USGS) in April 1989, the working group on basinal fluids and Zn-Pb mineralisation in the Canning Basin is pleased to announce that a one-day workshop on hydrodynamics of basinal fluids will be held on **17 May 1990, at BMR.**

Dr Bethke is internationally known for his research into the hydrodynamics of basinal brines and water/rock interactions in sedimentary basins. He has developed hydrogeologic and geochemical models for major petroleum and mineral companies in the USA, and is currently a recipient of industry grants for computer modelling of fluid flow in sedimentary basins. In 1987 Dr Bethke received the Lindgren Award from the Society of Economic Geologists.

Dr Bethke will visit BMR from 14 to 22 May 1990; during his visit he will work closely with BMR and CRES (Centre for Resource & Environmental Studies, ANU) on the hydrodynamics of basinal fluids in the Canning Basin.

The workshop will bring together representatives from oil and metal exploration companies, and research and higher education organisations to discuss problems related to hydrodynamics of basinal brines and water/rock interactions in sedimentary basins, with special emphasis on carbonate-hosted Zn-Pb deposits and petroleum accumulations.

### PROGRAM

#### Morning

- Overview of fluid migration in sedimentary basins for the non-specialist
- Origin of geopressures in compacting basins; palaeohydrology of the Gulf of Mexico basin
- Long-range fluid migration in interior basins of North America; origin of Mississippi Valley-type ores
- Long-range petroleum migration in the Illinois basin

#### Afternoon

- Quantitative modelling of fluid/rock interactions
- Sediment diagenesis in clastic sediments: case studies from several basins
- Artificial diagenesis: fluid/rock interaction in petroleum reservoirs
- Discussion of future of computer modelling techniques applied to sedimentary basins

**Inquiries to:**
**Dr Hashem Etminan, BMR, GPO Box 378, Canberra City, ACT 2601.**
**Tel: 06-249 9294, Fax: 06-248 8178.**
**Please advise your intention to attend the workshop by 11 May 1990.**

## The BMR Mineral Data Analysis System (MDA)

**MDA is a comprehensive IBM PC-based software package developed by the Minerals & Land Use Program in BMR for the analysis and graphical presentation of mineral analyses obtained by electron-probe microanalyser. MDA is an extension of GDA — the BMR geochemical data analysis system — and uses many of the GDA data-editing and graphics routines. Key features are the colour on-screen graphics capability and the facility for data editing. Output is to HP-compatible colour-pen plotter and/or laser printer. MDA will accept data as ASCII files from a database, or data can be entered directly from keyboard.**

MDA features a comprehensive sample selection/retrieval capability which enables analysis and plotting of several sample groups concurrently. The system enables calculation of mineral structural formulae and cation ratios, and estimation of ferric iron abundance based on stoichiometry. Other programs allow calculation and plotting of end-member components and classification of certain minerals (amphiboles, spinels, garnets, pyroxenes). A similar range of plot types to that in GDA may be produced, and an additional program projects spinel compositions into the reduced or oxidised spinel prism to show the complex chemical variation in spinels.

MDA incorporates the statistical functions employed by GDA, including cluster analysis, and provides output routines for printing data tables of major and trace elements, structural formulae, and derived abundance ratios.

### Diamond exploration

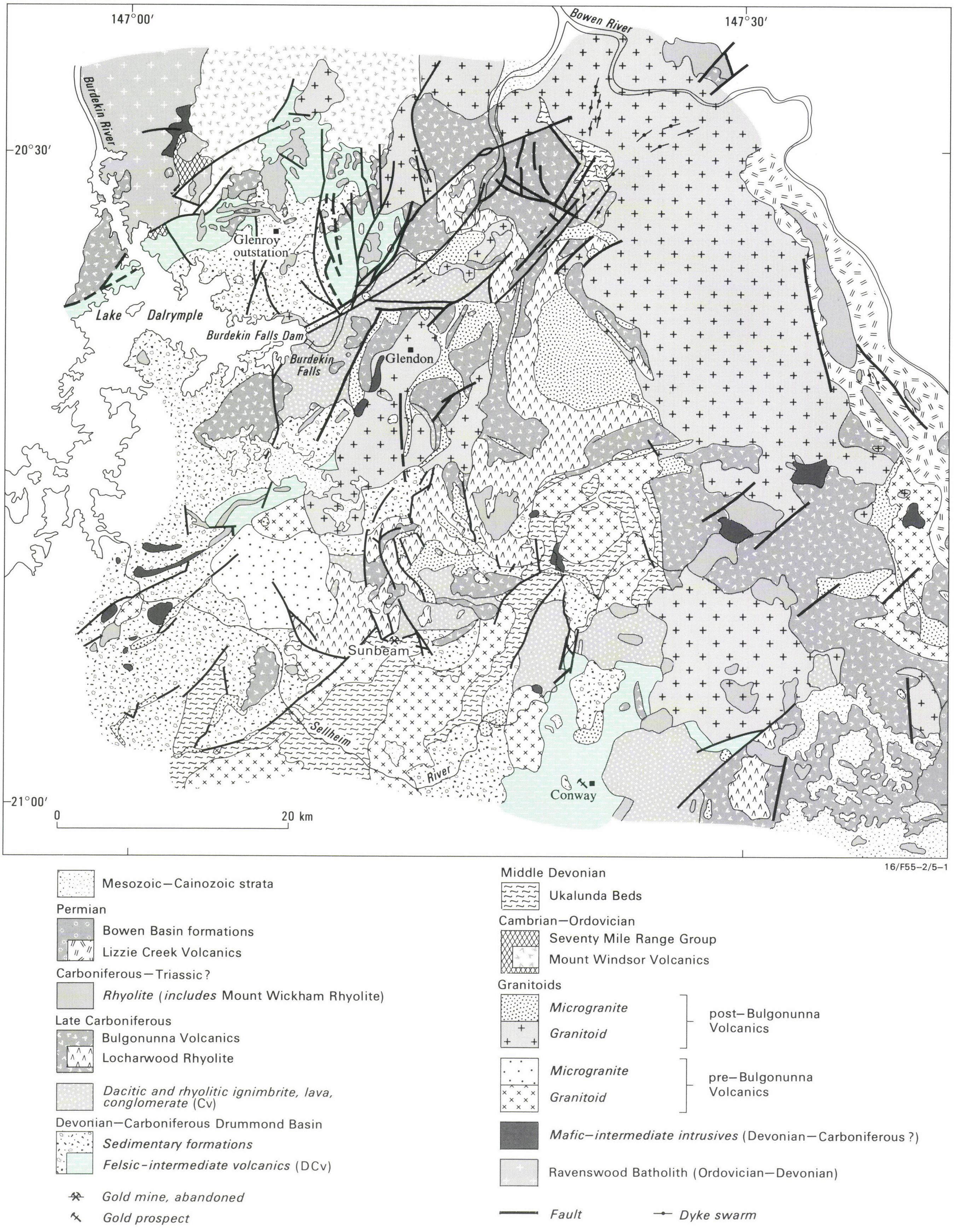
MDA has application in fields requiring systematic reduction and manipulation of mineral chemical analyses obtained by electron probe microanalyser (or similar method). It may be directly employed in operations requiring chemical discrimination of mineral suites. Thus, it is expected to prove useful in diamond exploration which relies heavily on regional variations in the chemistry of certain indicator minerals such as chromite, garnet, and ilmenite to discriminate potentially prospective from non-prospective sources. In BMR, MDA has been employed mainly in mineralogical and petrological studies of diamond-facies rocks and minerals, layered mafic and ultramafic rocks associated with PGE mineralisation, and carbonatites and associated alkaline intrusive rocks.

The source code (available on 3½" or 5¼" floppy disks) and a reference manual are currently being prepared for sale.

*For further information contact Dr Lynton Jaques at BMR (Minerals & Land Use Program).*

# Setting of epithermal gold mineralisation in the northern Drummond Basin further refined

**Fieldwork aimed at elucidating the epithermal gold potential of the northern Drummond Basin in 1988 (*BMR Research Newsletter*, 10, April 1989) resulted in the whole of a widespread assemblage of dacitic ignimbrites and extrusive andesites, with associated sedimentary rocks, being assigned to an already-established but informal unit, DCv. The overlying Bulgonunna Volcanics were regarded as being dominated by quartz-rich rhyolitic ignimbrites. However, a U-Pb zircon investigation gave results shortly before the 1989 field season which indicated that the thick sheet of dacitic ignimbrite exposed at and around Burdekin Falls Dam was probably indistinguishable in its age of about 300 Ma (Late Carboniferous) from Locharwood Rhyolite ignimbrite, which is a key unit for correlation of Bulgonunna Volcanics 'proper'. If geologically**



**meaningful, these U-Pb data would question the basis and validity of DCv, with significant implications for the understanding of mineralisation in view of the earlier identification of the sequence as a preferred host of epithermal gold.**

Careful evaluation of critical field evidence has shown that two superficially similar volcanic sequences lie unconformably below uniformly rhyolitic Bulgonunna Volcanics 'proper'. The upper one of these sub-Bulgonunna sequences contains the 300 Ma-old ignimbrite at Burdekin Falls Dam. This 'Dam' ignimbrite is now thought to be associated with several sheets of quartz-rich Bulgonunna-type ignimbrite, in addition to dacitic varieties. The lower volcanics sequence is a revised DCv, whose precise age is currently being investigated. The new disposition of these and associated rocks in the northern Drummond Basin is shown in Fig. 13.

The Late Carboniferous sequence containing the 'Dam' ignimbrite is conspicuously more heterogeneous than overlying but penecontemporaneous Bulgonunna Volcanics 'proper'. It is also more deformed, mainly by faults but also locally by folds, at least where the two sequences can be directly compared. However, the 'Dam' ignimbrite and associates do not appear to have been affected by the regional folding event which deformed DCv and other Drummond Basin units.

The clear distinctions between late Palaeozoic volcanic sequences in the northern Drummond Basin area perceived originally, when only two were being discriminated, are no longer strictly applicable. Both DCv and the sequence that includes the 'Dam' ignimbrite contain extrusive andesites and quartz-free or quartz-poor dacitic to rhyolitic ignimbrites, and both the latter sequence and the Bulgonunna Volcanics 'proper' contain effectively identical quartz-rich rhyolitic ignimbrites. On the other hand, features which allow isolated and/or areally restricted outcrops to be assigned to one or other sequence include: (1) lack of dacitic or quartz-free rhyolitic ignimbrites, and probable lack of extrusive andesitic rocks, in Bulgonunna Volcanics 'proper'; and (2) presence of a substantial clastic volcanic and sedimentary component in DCv compared to the minor proportion of such rocks in the sequence containing the 'Dam' ignimbrite, and extreme rarity in Bulgonunnas 'proper'.

This revision does not compromise the earlier conclusion that epithermal gold occurrences are hosted in rocks other than those of the Bulgonunna Volcanics 'proper'. The preferred host is confirmed as the DCv sequence, albeit in its now-restricted lithological composition and distribution. The only exceptions seem to be at Ukalunda, where deposits occur in a series of melanocratic granitoid bodies, and at Mount Coolon, where the andesitic rocks that host most of the known mineralisation could either be equivalent to the 'Dam' ignimbrite, or part of DCv. Continuing research into the mineralogy, petrology, geochemistry, and geochronology of late Palaeozoic extrusive and intrusive rocks throughout the area should result in better characterisation of different rock units and more precise assignment of individual lithologies.

The formal nomenclature eventually introduced to accommodate the penecontemporaneous Late Carboniferous sequences in the area will depend on, and reflect, a consensus as to the preponderance of similarities or differences between the sequences.

*For more information, contact Dr Lance Black, Dr Doug Mackenzie, or Dr Brian Oversby of BMR (Minerals & Land Use Program) or Dr Jocelyn McPhie (University of Tasmania).*

# Carbonate-hosted Zn-Pb deposits in the Canning Basin: preliminary chemical modelling

**Thermodynamic mass-transfer modelling using recent experimental data on galena and sphalerite solubility suggests that the zinc-lead deposits of the Lennard Shelf (Canning Basin, WA) could have been formed by a single ore fluid; sulphide deposition does not necessarily require fluid mixing as proposed for some other Mississippi Valley-type deposits. The fluid could have originated from a clay-carbonate source region at temperatures in excess of 150°C, and then have been focused by rapid flow into a lower-temperature deposition site. There, reaction of the acid ore brine with calcite-rich rocks (i.e. the reef limestones) is predicted to have resulted in carbonate dissolution, dolomitisation and chloritisation associated with base-metal sulphide precipitation, in general agreement with geological observation.**

Geochemical models for the genesis of the Devonian-carbonate-hosted Zn-Pb deposits of Mississippi Valley type (MVT) are divided into two camps (e.g. Sverjensky, 1986: Annual Review of the Earth & Planetary Sciences, **14,** 77-199). Some assume a single ore fluid transporting metal and sulphur together (e.g. Mascot-Jefferson City district, USA), a process that is severely constrained by the low solubility of sphalerite and galena at the typically quite low temperatures of ore deposition. The other group of models invoke a mixing process between two different fluids, one carrying high concentrations of base metals, and the other rich in sulphide (e.g. the low-temperature Pine Point deposit in Canada). Indirect support for the two-fluid model has been presented by Kharaka & others (1987: *Applied Geochemistry,* **2,** 543-561) who have found two compositionally distinct types of formation waters in the oil fields of the Central Mississippi Salt Dome Basin; formation waters with high concentrations of zinc and lead (300 mg/L) have extremely low concentrations of $H_2S$, whereas fluids enriched in $H_2S$ (up to 85 mg/L) have very low base-metal concentrations.

**Fig. 13 (opposite). Distribution of 'DCv', 'Dam' ignimbrite and associates ('Cv'), Bulgonunna Volcanics 'proper', and other rocks of the northern Drummond Basin as refined on the basis of the 1989 fieldwork.**

Detailed research on the MVT deposits in the Canning Basin, involving BMR in collaboration with several exploration companies, has not shown any positive evidence of fluid mixing, even though the process is difficult to disprove conclusively (Etminan & Hoffmann, 1989: *Geology,* **17,** 19-22; see also *BMR Research Newsletter,* **11,** 6-8). Thermodynamic model calculations have therefore been carried out to re-evaluate, in the light of the most recent experimental solubility data, the possibility of generating economic concentrations of zinc and lead from a single ore fluid, under conditions that are consistent with geological observations from the Canning Basin deposits.

## Geology of Zn-Pb deposits in the Canning Basin

Several major Zn-Pb sulphide deposits are located in Devonian reef carbonates of the Lennard Shelf (Murphy & others, 1986, and Buchhorn, 1986: *13th Congress, Council of Mining & Metallurgical Institutions,* **2,** 153-161).

At Blendevale, the biggest deposit in the basin (20 Mt ore at 8.3% Zn and 2.5% Pb), the ore occurs as veins and breccia cement in limestone. At Cadjebut the ore occurs in partly dolomitised carbonates. The Wagon Pass and Narlarla deposits contain Zn-Pb sulphides as disseminations and veinlets in dolomitised and chloritised calcareous rocks. Fluid-inclusion studies on sphalerite and dolomite in close association with mineralisation at Wagon Pass, Blendevale, and Cadjebut indicate that highly saline brines at temperatures between 100 and 180°C (after pressure correction for 1-3 km of overburden) were involved in sulphide deposition. Microthermometry of the fluid inclusions indicates salinities around 25 weight-% with an appreciable proportion of calcium chloride. Substantial $CO_2$ in the inclusions has been detected by mass spectrometry, and there is no evidence of vapour separation from the brine during mineralisation. Sulphur isotope analysis indicates that sulphate reduction was the ultimate source of the ore sulphur. However, this probably occurred before the fluids were injected into the ore deposition site, because the estimated temperature of ore formation is too high for biogenic sulphate reduction but too low for efficient inorganic reduction (Lambert & Etminan, 1986: *BMR Record* **1986/3,** 2-8).

Colour alteration of conodont fossils (R.S. Nicoll, BMR, pers. comm.) and preservation of pre-Devonian fission track ages in detrital apatites (Arne & others, 1989: *Australian Journal of Earth Sciences,* **36,** 495-515) indicate that the host rocks for the Zn-Pb deposits were never heated above 70°C for a substantial length of time. This, and the widespread evidence of net carbonate dissolution, dolomitisation of calcite, silicification, and chloritisation of wall rocks during mineralisation, indicates that the invading ore fluids were grossly out of thermal and chemical equilibrium with the limestones at the ore deposition site. This implies relatively rapid fluid migration from the deeper parts of the sedimentary basin to the structural and chemical 'traps' that now host the ores.

## Results of chemical modelling

In a first step of testing various possible chemical processes of MVT ore formation in the Canning Basin, we have used thermodynamic mass-transfer calculations to re-evaluate the possibility of transporting geologically realistic amounts of zinc, lead, and reduced sulphur in a single fluid in contact with minerals observed or inferred to be present, in the source region of the fluids and along their flow path to the ore deposition site. The major-element composition of model ore fluids has been estimated from fluid-inclusion data and from analysis of oil-field brines. Hypersaline formation waters presently found at depth in some parts of the Canning Basin are Na-Ca-Cl rich, have total salinities up to 25 weight-% (*BMR Research Newsletter,* **11,** 6-8) and are compositionally similar to recent brines from other oil basins and to fluid inclusions in the Lennard Shelf zinc-lead ores.

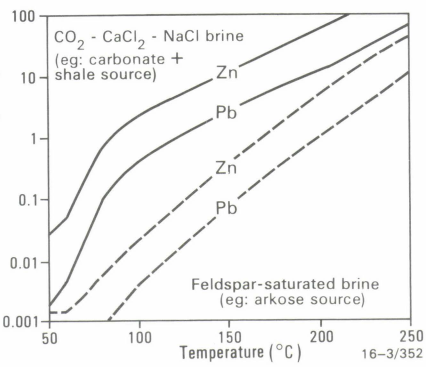
Sphalerite and galena solubilities in such brines are primarily dependent on solution acidity (pH) and temperature, parameters that are controlled by the mineralogy of the source rocks and their burial history in the basin. Over the pH and temperature range of interest, sphalerite is about 5–10 times more soluble than galena (Fig. 14).

The presence of feldspars (sodic plagioclase, orthoclase) in the source rocks restricts the solution pH to near-neutral, and temperatures in excess of 200°C are required to transport lead and zinc at geologically realistic concentrations (1–10 ppm), together with an equivalent (molal) concentration of reduced sulphur. This is shown by the dashed solubility contours in Figure 14.

No direct evidence for such high temperatures exists in the MVT deposits of the Canning Basin. Co-transportation of substantial concentrations of zinc, lead, and reduced sulphur are nevertheless possible down to temperatures as low as 130°C, provided that the solutions are substantially more acid. Higher acidity is possible in $CO_2$- and $CaCl_2$- rich fluids in contact with calcite ± dolomite ± clay minerals, i.e. a carbonate-shale source rock. This is indicated by the solid solubility contours in Figure 14, calculated for the highest concentrations of $CO_2$ and $CaCl_2$ consistent with fluid inclusion data. The calculation is based on the 'optimal' assumption that the fluids at their source were saturated in both sphalerite and galena, and is consistent with the high zinc:lead ratio (typically 6:1) of many carbonate-hosted MVT deposits, including those on the Lennard Shelf. However, depending on source-rock mineralogy, additional limitations may be imposed on the fluid's transporting capacity for base metals and sulphide. Of particular importance are chemical reactions between the fluid and iron silicates (e.g. chlorite) and sulphides (e.g. pyrite), which further limit the concentration of reduced sulphur in the ore fluid. Mass-transfer calculations are in progress (Jaireth & others: *BMR Record,* in preparation) to further constrain the likely composition of a fluid originating from a potential shale-calcite-dolomite source at elevated temperature, and to simulate the effects of reaction of this fluid with a reef limestone at lower temperature. First results indicate that this will lead to precipitation of sphalerite, galena, minor chlorite, and pyrite (or marcasite), associated with conversion of calcite to dolomite and with net carbonate dissolution. This is in qualitative agreement with mineralogical observation and the widespread evidence for collapse breccias in MVT deposits in the Canning Basin and elsewhere.

Further work will be directed towards testing whether this deposition mechanism is in quantitative agreement with observed mineral abundances and ore grades. Comparison between model prediction and geological observation will be used to further constrain the possible ore-fluid composition. This in turn will help to determine whether some special source rocks are essential for the formation of the deposits, or whether an entirely different process such as fluid mixing is required for ore formation.

**Fig. 14. Solubility of sphalerite and galena in chloride brines (ca. 25 weight-% total salinity), with total base-metal concentration in the fluid equivalent to total reduced sulphur (on molal scale). Heavy lines = very acid fluid with high $CO_2$ (0.6 mol/kg) and $CaCl_2$ (0.7 mol/kg) in contact with calcite ± dolomite ± clay minerals. Dashed lines = 10–100 times lower solubility in a less acid brine in equilibrium with orthoclase + sodic plagioclase + muscovite + quartz.**

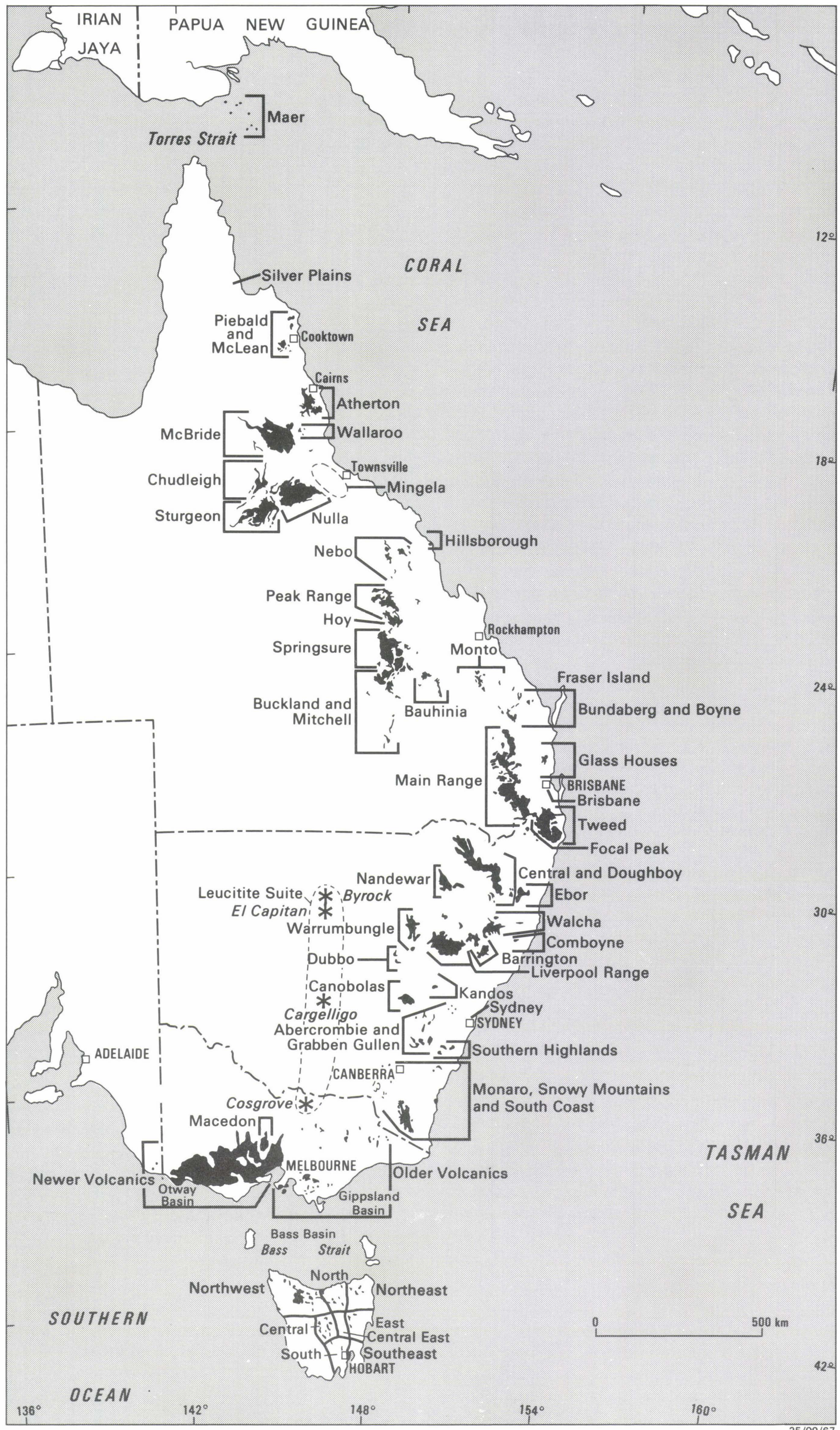



*For further information contact Dr Chris Heinrich or Dr Hashem Etminan at BMR (Minerals & Land Use Program), or Dr Subhash Jaireth (now at Geology Department, James Cook University, Townsville, Qld).*

# Major new publication on Australian and New Zealand intraplate volcanism

**INTRAPLATE VOLCANISM IN EASTERN AUSTRALIA & NEW ZEALAND,** edited by R.W. Johnson, J. Knutson, & S.R. Taylor, 1989. *Cambridge University Press,* 408 pp. Price $95.00. Available from: Cambridge University Press, PO Box 85, Oakleigh, Vic., 3166.

This important volume was officially launched by Professor D.H. Green, University of Tasmania, at the Academy of Science, Canberra on 5 December 1989. The volume was compiled over a period of six years under the auspices of the International Lithosphere Program and was published



in association with the Australian Academy of Science. The then BMR Division of Petrology & Geochemistry played a major coordinating role. Contributions from 59 authors have been combined into a single comprehensive account by the editors: R.W. Johnson, J. Knutson (both BMR), and S.R. Taylor (Research School of Earth Sciences, Australian National University, Canberra).

The volume brings together the vast amount of volcanological, petrological, geochemical, geochronological, geophysical, and tectonic data now available relating to east Australian and New Zealand intraplate volcanism. As such, it contributes substantially to the understanding of the geological evolution of eastern Australia and New Zealand in particular, and also of intraplate volcanism generally and its role in crustal and continental development.

### Quasi-continuous sampling of the mantle

Intermittent volcanism has taken place along the 4400 km-length of eastern Australia from about 70 Ma to 4000 B.P., and represents an exceptional example of long-term, widespread volcanic activity (Fig. 15). The abundance of mantle xenoliths and megacrysts in the basaltic rocks is also unusual, and represents one of the largest and most widespread quasi-continuous samplings of the mantle section on the Earth's surface, both in space and time.

The Cainozoic volcanic rocks of eastern Australia are characterised by: (1) a dominance of mafic magmas of diverse compositions, (2) the importance of fractional crystallisation in the development of the magmas, and (3) relatively diverse geochemical and isotopic compositions throughout the range of magma types, suggesting possible differences in magma source and evolution.

The distribution of the east-Australian volcanic provinces on the uplifted flank of a rifted continental margin strongly suggests control relating to the tectonics of the continental margin.

Two models are suggested in the volume for the origin of the east-Australian volcanism. In the first, uplift of the eastern highlands is attributed to a combination of the thermal anomaly generated during continental extension and the underplating of mantle-derived igneous rocks during lithospheric extension. This model predicts a regional thermal peak between 80 and 50 Ma that has been decaying ever since, except where locally perturbed by hotspots that have triggered relatively local volcanic and subvolcanic activity. A second interpretation is that the volcanism has been controlled largely by intraplate stresses in the Indo-Australian plate, caused by its interaction with surrounding plates. Much of the volcanism has taken place along the relatively young Tasman Fold Belt System, which, being adjacent to a mantle anomaly that produced late Mesozoic and early Tertiary seafloor spreading, is underlain by hotter mantle than in cratonic areas.

Sapphire, corundum, zircon, and pleonaste are present in alluvial and weathered deposits in many of the volcanic fields in eastern Australia, and are becoming of increasing economic importance. Diamond has also been reported in alluvial settings at numerous localities. Early work has indicated that the high geothermal gradient in eastern Australia makes any direct association between Cainozoic volcanism and diamond unlikely, and a derivation from Mesozoic pipes has been suggested from nitrogen-aggregation studies of Copeton diamonds (p.12, this issue).

*For further information contact Dr Wally Johnson or Dr Jan Knutson at BMR (Minerals & Land Use Program).*

**Fig. 15 (opposite). Intraplate volcanic provinces of eastern Australia (adapted in part from O'Reilly & Griffin, *in* Nixon, P.H. (Editor), 1987: MANTLE XENOLITHS. *Wiley, Chichester*).**

# Do lamprophyres have high precious-metal contents?

**A number of gold deposits are spatially and, in some cases, genetically associated with alkaline rocks, especially felsic stocks and porphyries of calc-alkaline to alkaline composition (e.g. Mutschler & others, 1985: *Transactions of the Geological Society of South Africa*, 88, 355–377). This association has been highlighted by a recent proposal that lamprophyres in general have inherently high levels of Au (Rock & Groves, 1988: *Nature*, 332, 253–255) and platinum-group elements (Rock & others, 1988: in *Geology Department & University Extension, University of Western Australia, Publication* 12, 295–308). As part of its program on alkaline igneous rocks and related mineralisation, BMR has obtained precious-metal abundances on a range of alkaline rocks with a view to establishing their background precious-metal inventory.**

New data on the Ellendale and Argyle lamproites, several Australian carbonatites, kimberlites from South Africa and India, picritic monchiquites from the Carnarvon Basin, and alkaline volcanics from the Stuart Shelf indicate much lower levels of Pd, Pt, and Au ($<$ 10 ppb, commonly $\leq$ 5 ppb each) than has been attributed previously to such rocks. Post-mineralisation lamprophyres from Tennant Creek have low to moderate contents of Au and PGE. Altered K-rich volcanic rocks from the Redbank area, NT, and metamorphosed lamprophyres from the Leonora area of the Yilgarn Block generally have low abundances of PGE and Au although a number have anomalously high PGE (Redbank) and Au (Yilgarn) abundances. The wide range in abundances and the distinctly non-chondritic abundance ratios observed in these anomalous samples are believed to result from mobilisation, particularly of Au, during low-temperature metamorphism and/or hydrothermal alteration.

### Modern analytical techniques

Published precious-metal values in alkaline rocks show a very wide range and are confused by the inclusion of mineralised samples and analyses by inferior techniques. Modern analytical techniques such as neutron activation and inductively coupled plasma mass spectrometry (ICPMS) with low limits of detection (e.g. $\leq$ 0.5 ppb) have overcome many of the problems in assessing the intrinsic or background precious-metal contents in unmineralised rocks, which requires accurate determination at the $<$ 5 ppb level. Problems remain, however, in terms of heterogeneous dispersion of metals and contamination, as well as the geological problems such as non-representative sampling and the effects of low-temperature alteration on primary values. The Pd, Pt, and Au analyses reported here were performed using ICPMS on the least-altered material available, following Pb collection by fire assay. Full PGE analyses were obtained by NiS collection and ICPMS for a limited number of samples.

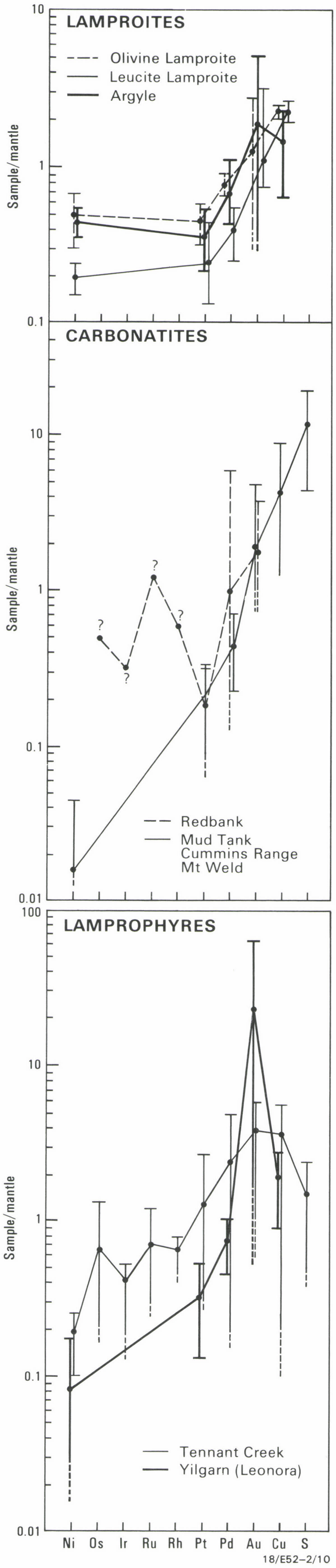



**Fig. 16. Plots showing mean and 1-sigma variation (bars) of metal and sulphur abundances in a range of alkaline rocks normalised to the mantle values suggested by Barnes & others (1988: in *Geo-Platinum*, 87, 113–143).**

### Kimberlites and lamproites

Previous analyses of Au and PGE in South African and Indian kimberlites by modern methods indicate a wide range of abundances: 1-19 ppb Pd (average 8 ppb), 0.5-6 ppb Ir (average 3 ppb) and 0.1-43 ppb Au (average 12 ppb: Paul & others, 1979: *in* KIMBERLITES, DIATREMES, & DIAMONDS: THEIR GEOLOGY, PETROLOGY, & GEOCHEMISTRY. *Blackwells Scientific Publications, Melbourne*, 272-279).

Rock & others (1988) suggested that lamproites may also have high intrinsic Au and PGE levels. However, new data obtained for Argyle and West Kimberley lamproites and several kimberlites from India and southern Africa do not support this contention. Low values of PGE and Au were obtained for both the kimberlites and the West Kimberley leucite lamproites: ~2 ppb Pd, ~2 ppb Pt, and 1-2 ppb Au, and only slightly higher values were obtained for olivine lamproites (> 20% MgO) from Ellendale: ~3 ppb Pd, 4 ppb Pt, and ~2 ppb Au (Fig. 16a). These values cannot be taken to indicate a mantle source enriched in PGE and Au. From a study of the PGE content of mafic- ultramafic rocks in the Kimberley and Pilbara regions, Sun & others (*Precambrian Research*, submitted) concluded that fertile mafic-ultramafic magmas commonly have ~15 ppb Pd and Pt, and that the convecting mantle has had fairly homogeneous PGE abundances (~4 ppb Pd, ~6 ppb Pt, ~1 ppb Au) throughout geological time.

### Lamprophyres

Higher precious-metal contents — 7 ppb Pd, 6 ppb Pt, and 4 ppb Au — were found in Jurassic lamprophyres (picritic monchiquites) from the Carnarvon Basin which have also been prospected for diamonds (Jaques & others, 1986: *GSWA Bulletin* **132**). These values are considerably higher than those reported by Mitchell & Keays (1981: *Geochimica et Cosmochimica Acta*, **45**, 2425-2442) for Victorian basanites (0.7-1.7 ppb Pd, ~0.3 ppb Au).

Lamprophyres — mostly minettes — are common in the Tennant Creek area and many have high MgO (10-20%), Ni and Cr (> 300 ppm Ni, > 400 ppm Cr), implying a mantle origin. The lamprophyres have a wide range in Au and PGE contents and include some with up to ~30 ppb Pd, 30 ppb Pt, and 10 ppb Au (Fig. 16c). PGE patterns are broadly chondritic in form, suggesting that the PGE and Au abundances are primary, though it is possible that the precious metals have been enriched because the lamprophyres intrude mineralised rocks (Black, 1977: *BMR Journal of Australian Geology & Geophysics*, **2**, 111-122) that have high PGE contents as well as Au.

Lamprophyres are also widespread in the goldfields region of the Yilgarn, and their spatial association with some Au deposits has led to speculation (Rock & Groves, 1987: *Geology*, **16**, 538-541) that fluid-rich lamprophyres may be the source of Au in Archaean mesothermal gold deposits. New data obtained by BMR during 1:100 000 scale regional mapping in the Leonora region indicate that many of the lamprophyres do not have high Au (or PGE) contents. Samples that do have anomalously high Au have PGE abundances which depart markedly from chondritic abundance (Fig. 16), suggesting that the Au is introduced rather than primary. The Au may have been introduced by metamorphic fluids because many of the lamprophyres have been metasomatised and/or metamorphosed. The low MgO, Ni, and Cr contents of most of the lamprophyres are inconsistent with mantle derivation, and high Au or PGE levels in these rocks cannot be taken to indicate Au- and/or PGE-rich mantle sources. Lamprophyres spatially associated with gold mineralisation in the Superior Province of Canada have also been shown to have low Au contents except where mineralised (Wyman & Kerrich, 1988: *Economic Geology*, **83**, 454-461).

Platinum-group metals are recovered from mining of the Precambrian porphyry-style copper deposit hosted by the Phalaborwa carbonatite complex in South Africa. However, data obtained on the Mount Weld, Mud Tank, and Cummins Range carbonatites in Australia indicate comparatively low levels of precious metals, averaging 2 ppb Pd, 2 ppb Pt, and 2-3 ppb Au with individual samples up to 3 ppb Pd and Pt, and 7 ppb Au (Fig. 16b). The high abundances of PGE and Au in the Phalaborwa Complex, therefore, do not appear typical of carbonatites. Samples from the Cu-bearing breccia pipes at Redbank, which are believed to have affinities with carbonatites (Knutson & others, 1979: *Economic Geology*, **74**, 814-826), commonly show higher values ranging up 30 ppb Pt: a carbonate-rich mineralised (pyrite-bearing) breccia gave 330 ppb Pd, 22 ppb Pt, and 120 ppb Au.

### Exploration models

The new data call into question previous speculation concerning intrinsic Au and PGE levels in lamproites, kimberlites, and a wide range of lamprophyres, and their possible role in the formation of Au and PGE deposits. Reliable published Au and PGE data on these rocks are scant and the new data highlight a need for better characterisation of background levels of precious metals in alkaline rocks generally, using modern precise analytical methods. Precious-metal enrichment in Australian alkaline rocks documented here is accompanied by pervasive alteration, notably K-metasomatism, oxidation, and carbonation ($CO_2$). These alteration facies, together with phyllic alteration, are characteristic of precious-metal deposits associated with alkaline and calc-alkaline rocks in general rather than a particular rock type. Nevertheless, certain calc-alkaline to alkaline suites, such as high-K calc-alkaline rocks and shoshonites (Wyborn & Cameron, 1990: *Australian Geological Convention, Hobart, Abstracts*), appear to have inherent high background values of PGE and Au which make them potentially attractive exploration targets.

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# The Giles Complex, central Australia

## New insights into tectonics and metamorphism

**The western Musgrave Block (where Western Australia meets the border between South Australia and the Northern Territory) contains the largest exposures of deep-seated basic-ultrabasic intrusions in Australia, and thus has special significance for the understanding of crustal structure and of potential mineralisation in central Australia. Recent investigations of the layered basic-ultrabasic Giles Complex (Proterozoic) in the Tomkinson, Blackstone, Murray, Cavanagh, and Jameson Ranges in Western Australia by BMR during 1987 and 1988, in collaboration with the University of Tasmania, the University of Melbourne, and the Geological Survey of Western Australia, have resulted in new interpretations of the structural and metamorphic evolution of this high-grade metamorphic terrane.**

The layered intrusions of the Giles Complex occur mainly as faulted segments in granulite-facies terrane. This terrane is located to the south (and constitutes the hanging wall) of the Woodroffe Thrust, a major east-west lineament where northward thrusting of granulite-facies rocks over amphibolite-facies rocks south of the Amadeus Basin (Collerson & others, 1972: *Journal of the Geological Society of Australia*, **18**, 379-394) mirrors the southward thrusting along the Redbank lineament north of the Amadeus Basin (Glikson, 1986: *Transactions of the Geological Society of South Africa*, **89**, 263-283; Glikson, 1987: *BMR Journal*, **10**, 89-107). The outcropping of the deep crustal layered intrusions of the Giles Complex and of equivalents at Mount Hay, north of the Redbank lineament, is significant for understanding the deep crustal structure in central Australia as interpreted following BMR's recent seismic reflection transects in the region (Goleby & others, *BMR Research Newsletter*, **7**, 8-9; Goleby & others, 1988: *Nature*, **337**, 325-330).

The Giles Complex is well exposed in the Tomkinson Ranges, SA and WA (Fig.17), where earlier studies by Thomson (1975: *Australasian Institute of Mining & Metallurgy, Monograph* **5**, 451-460) and Daniels (1974: *Geological Survey of Western Australia, Bulletin* **123**) outlined the regional framework and where detailed field and petrological studies have been conducted on some of the layered intrusions, including Kalka, Ewarara, and Gosse Pile (Nesbitt & others, 1970: *Geological Society of South Africa, Special Publication* **1**, 547-564). These studies and recent BMR work in Western Australia (*BMR Research Newsletter*, **10**, 3-4; Ballhaus & Glikson, in press, *Journal of Petrology*) have allowed the major structural elements of the western Musgrave Block to be identified.

### Structural and stratigraphic outline

The layered basic-ultrabasic units occur as slices separated and cut by mylonitic shear zones and intruded by mostly porphyritic (rapakivi) granites.

Aeromagnetic maps produced by BMR allow delineation of major structural discontinuities in the Musgrave Block. The Woodroffe Thrust stands out as a boundary between a magnetically disturbed terrane to the south (granulite and amphibolite facies rocks) and a magnetically quiet terrane to the north (amphibolite facies rocks). Major faults, such as the Mann, Davenport, and Hinckley Faults, are marked in part by linear anomalies. Tectonic slices of the Giles Complex in the Tomkinson Ranges are distinct from intervening granites and felsic granulities, while the recrystallised basic granulites of the Hinckley intrusion (Fig. 17) are expressed as a magnetically quiet zone compared to the gabbro. The Bell Rock intrusion is bounded on the west by a northwest-trending lineament interpreted as a major fault. This fault separates the more strongly deformed sector of the Giles Complex (including the Bell Rock, Hinckley, Michael Hills, Mount Davies, and Kalka layered bodies) from the shallow-dipping, least deformed sector (including the Blackstone, Cavanagh, and Jameson layered bodies).

Earlier work and the present study allow definition of several principal geological units, with the following time sequence:

1 **Banded felsic gneisses**, showing composite mineralogical banding (S1) and early intrafolial folds that deform an early fabric and lineation, are of probable volcanic origin (Gray,

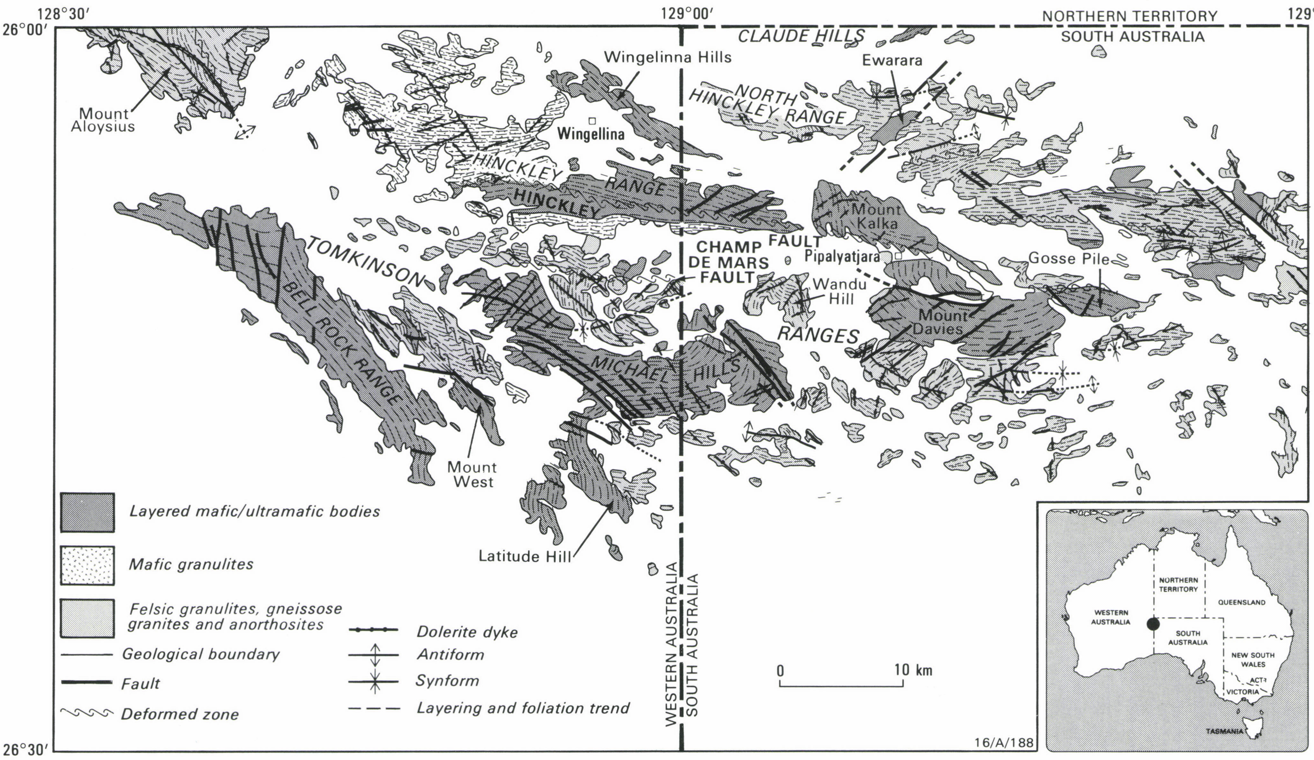


**Fig.17. Giles Complex and environs, Tomkinson Ranges, central Australia.**

1977: *Contributions to Mineralogy & Petrology*, **65,** 79–89; Gray, 1978: *Journal of the Geological Society of Australia,* **25,** 403–414). The intrafolial folds are cut by thin gneissose sheets of granitic composition coplanar with the axial surfaces of the intrafolial folds and by a younger generation of thicker, less deformed, granitic veins. Bands of basic granulite within the gneiss are probably derived from mafic volcanic protoliths.

2 **Homogeneous felsic granulite** with relict igneous features including xenoliths and porphyritic textures showing intrusive relationships with the banded gneisses.

3 **Layered basic and ultrabasic units of the Giles Complex,** mostly faulted against units 1 and 2, but in some places (at Ewarara and south of Mount Davies, Nesbitt & others, cited above, and north of Mount West) showing evidence of intrusive relationship with these units. At the latter locality the marginal basic rocks show hybridisation features consisting of quartz-feldspar intergrowths suggestive of intrusion by basic magma, as contrasted to the felsic veining expected from intrusion of granitic magma.

4 Extensive development of **basic granulite** formed by recrystallisation of gabbro (relicts of which are seen within the basic granulite) occurs along the margins of the basic-ultrabasic bodies and the granites, the granulites being extensively invaded by hosts of aplitic and granitic veins. This facies is spectacularly developed in the western part of the Hinckley Range. Pending isotopic studies, it is not clear whether the basic granulites developed due to (a) recrystallisation associated with remelting and back-intrusion of felsic wall materials at late stages of emplacement of the basic magmas, or (b) intrusion of post-Giles Complex felsic magmas and associated metamorphism of the gabbro.

5 **Post-Giles Complex rapakivi granites** (too small to map at the scale of Figure 17) showing only weak gneissosity and containing rafts of banded gneiss. These granites are believed to postdate the layered basic-ultrabasic bodies and are considered generally responsible for their deformation and metamorphism.

6 **Several dyke swarms,** mostly postdating the major deformation events but in places affected by shearing.

Although the age of these units is poorly defined at present, the possibly analogous gabbro of the Fraser Range, WA, about 800 km to the southwest, has yielded a Sm-Nd isochron age of 1291±21 Ma and a Rb-Sr whole-rock-biotite age of 1295±45 Ma (I. Fletcher & J.S. Myers, personal communication, 1988). A range of Rb-Sr and K-Ar ages from the felsic granulites and gneisses spans the period 1600–1000 Ma and is interpreted in terms of repeated thermal events whose geological significance is open to interpretation pending U-Pb zircon age studies.

## Tectonic sequence

The structural history of the Giles Complex and associated units can be summarised as follows (D — deformation event; F — fold element; S — foliation):

1 $D_1$ deformation, producing composite gneissosity/banding ($S_1$, possibly superposed on primary banding $S_0$), accompanied by development of intrafolial folds $F_1$.

2 Granulite-facies metamorphism (possibly contemporaneous with $D_1$).

3 Development of blastomylonitic gneiss belts.

4 $D_2$ development of appressed-to-isoclinal folds $F_2$ on steeply dipping axial planes which deform banding $S_1$.

5 $D_3$ deformation associated with the emplacement of the Giles basic-ultrabasic complex. Although the basic-ultrabasic intrusions are mainly concordant with banding/gneissosity in surrounding granulites and gneisses, the discordant contacts between the Ewarara intrusion (Fig. 3) (Goode & Krieg, 1967: *Journal of the Geological Society of Australia,* **14,** 185–194) and felsic granulites affected by $D_2$ folding enable the timing of the emplacement of the Giles Complex to be identified (some of the layered basic-ultrabasic bodies however may predate $D_2$).

As the layered intrusions are mostly faulted against the felsic country rocks, $D_3$ elements include shear zones bordering, and formed contemporaneously with emplacement of, the Giles Complex. As indicated below, the emplacement of the Giles Complex took place under granulite-facies conditions.

6 $D_4$ deformation associated with the emplacement of rapakivi granites, involving open folding of Giles Complex intrusions ($F_4$), such as the northward concave flexure of the Michael Hills intrusion which is flanked by granites to the north and southwest.

7 Extensional faulting associated with emplacement of intersecting dolerite dyke suites.

8 $D_5$ development of major subconcordant to low-angle-discordant mylonitic shear zones, such as the Hinckley Fault system, which in part border Giles Complex intrusions and in part transect the layered intrusions, older felsic granulites, and younger granites.

9 $D_6$ development of a system of pseudotachylite breccia-vein networks in brittle zones and of pseudotachylites associated with ductile mylonitic shear zones, reflecting earthquake-related seismic faulting (Glikson & Mernagh, *BMR Journal of Australian Geology & Geophysics,* in press).

## Pressure and temperature estimates

The Giles Complex has been regarded by Goode & Moore (1975: *Contributions to Mineralogy & Petrology,* **51,** 77–97) as a rare example of primary magmatic high-pressure fractionation, as evidenced by (1) reaction relations between olivine and plagioclase to form spinel-orthopyroxene-clinopyroxene symplectic intergrowths, (2) high Al, Ti, and Cr in pyroxenes, and (3) crystallisation of orthopyroxene at chilled margins. These authors estimated crystallisation pressures in excess of 10 kilobars on the basis of comparisons with high-pressure experimental data (Green & Ringwood, 1967: *Geochimica et Cosmochimica Acta,* **31,** 767–833). Since no corresponding metamorphic overprint has been observed in the basic and ultrabasic igneous rocks except where they have been recrystallised to basic granulites in conjunction with granite intrusion, the high-pressure conditions could be regarded as contemporaneous with magmatic emplacement and crystallisation.

A recent electron-probe study of spinel-bearing symplectite coronas in gabbro of the Wingellina Hills intrusion (Ballhaus & Berry, *Journal of Petrology*, in press), has defined the pressure and temperature conditions of magmatic crystallisation and of the metamorphism of this intrusion. Olivine- and chromite-bearing cumulates contain a variety of spinel-bearing clinopyroxene-orthopyroxene symplectites that formed as a result of olivine-plagioclase and oxide-plagioclase reactions during cooling. The symplectites formed by alumina transfer from plagioclase toward spinel when conditions of cystallisation reached the spinel stability field. Magmatic temperature estimates based on the two-pyroxene solvus (Wells, 1977: *Contributions to Mineralogy & Petrology*, **62,** 129–139) indicate temperatures around 1100–1160°, with pressures near 7 kilobars from the reaction: olivine + plagioclase = enstatite + diopside + spinel. Metamorphic temperature and pressure are estimated at 700-825°C and 6 kilobars (Fig.19). The results suggest near-isobaric cooling for the Giles Complex at about 6.5 kilobars, i.e. intrusion and cooling of the basic magmas at or below 20 km depth during high-grade metamorphic conditions.

These results answer a long-standing question about the origin of the Giles Complex — whether the intrusions formed at upper crustal levels and were subsequently metamorphosed at elevated temperatures and pressures, or, alternatively, were originally emplaced into lower crustal levels. The confirmation of the model of Goode & Moore (op. cit.), albeit at lower pressure levels than originally estimated, emphasises the significance of the Giles Complex in connection with studies of the deep continental crust. The outcrop of deep-seated layered intrusions in the hanging walls of major thrust faults in central Australia, coupled with evidence for an increase in crustal density with depth as based on modelling of gravity data (Mathur, 1976: *BMR Journal*, **1,** 177–186) and seismic velocity/depth models (Drummond, 1988: *Precambrian Research*, **40/41,** 101–116), indicates the existence of extensive basic zones and lenses at deep levels (velocities over 7.0 km $s^{-1}$below 25 km depth) of the central and northern Australian Precambrian shields. The emplacement of the basic magmas and magmatic underplating of the deep crust are considered to have provided the thermal source for major anatectic granite-forming events and related deformation in central Australia.

*For further information contact Dr Andrew Glikson (Minerals & Land Use Program) at BMR, Dr Christian Ballhaus at the Department of Geology, University of Tasmania, or Dr Tim Pharaoh at the British Geological Survey, Keyworth, Nottingham, UK.*

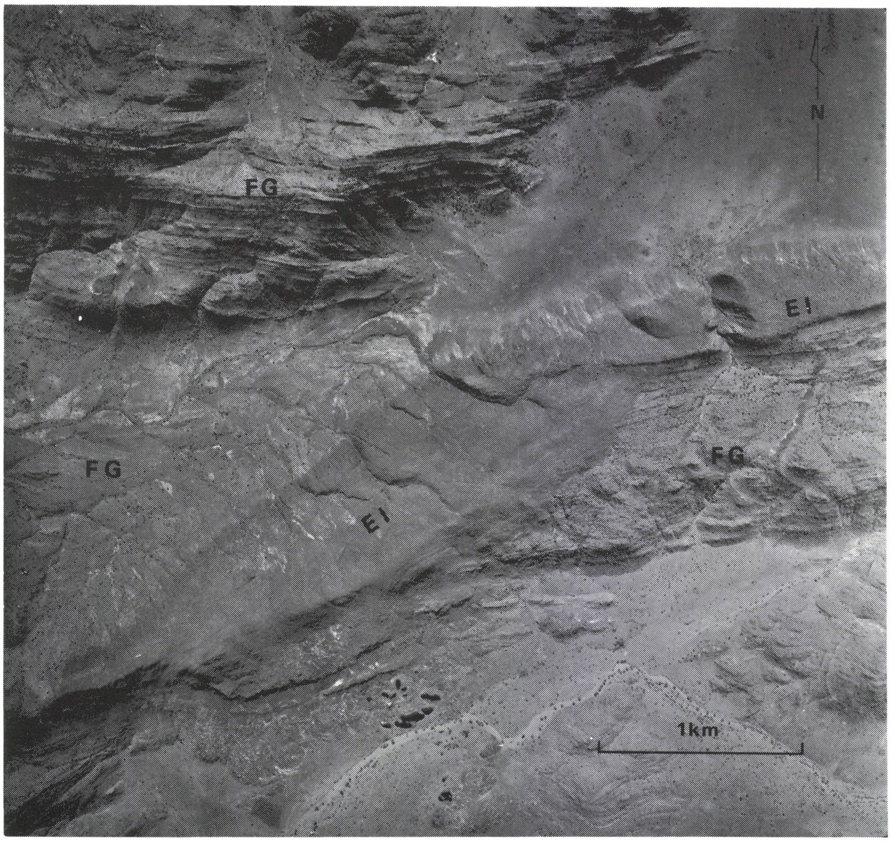


**Fig.18. Vertical air-photograph showing the Ewarara intrusion (E1), SA, emplaced into banded felsic granulites.**

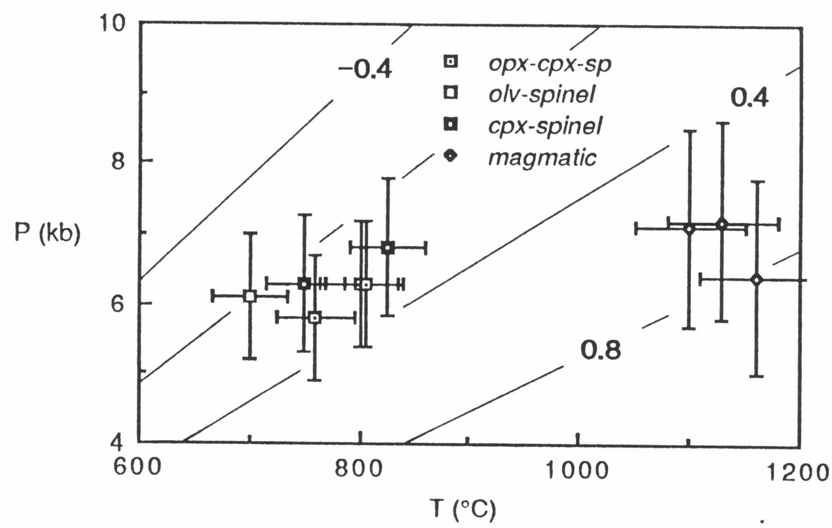


**Fig. 19. Pressure-temperature plot for the assemblages orthopyroxene-clinopyroxene-spinel, olivine-spinel, and clinopyroxene-spinel, based on the reaction: olivine = plagioclase + spinel + clinopyroxene + orthopyroxene (from Ballhaus & Berry, *Journal of Petrology*, in press).**

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The purpose of the *BMR Research Newsletter* is to provide the exploration industry with early information on the progress of BMR research and on the availability of new data relevant to exploration and resource assessment; to provide commentaries on relevant research developments worldwide; and to encourage close liaison between the exploration industry and BMR. Readers' comments and suggestions — addressed to the Executive Director — are welcome. Requests to be placed on the mailing list should be addressed to: Information Section, Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601.

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## Supplement

# Kalimantan Geoscientific Data Package released

**Fig. 20. Senator The Hon. Peter Cook (Australia's Minister for Resources) and Ir Ginandjar Kartasasmita (Indonesia's Minister of Mines & Energy) — flanked by Senator The Hon. Gareth Evans, QC (Australia's Minister for Foreign Affairs & Trade) and Dr Ali Alatas (Indonesia's Minister of Foreign Affairs) — pose with parts of the first two copies of the Kalimantan Geoscientific Data Package which they received in Bali on 11 December 1989 at the ceremony marking its official release. (Photograph kindly provided by the Australian Overseas Information Service; registered number KN19/12/89/97.)**

**In December 1989, BMR, in conjunction with the Indonesian Geological Research & Development Centre (GRDC), issued the Kalimantan Geoscientific Data Package. This package incorporates the results — almost entirely in preliminary form —of regional geological and gravity mapping and an integrated stream-sediment geochemical survey in western and central Kalimantan (Fig 21), by the Indonesia-Australia Geological Mapping Project (IAGMP). The survey was staffed by geoscientists provided by BMR and GRDC and was funded by the Australian International Development Assistance Bureau and the Indonesian Department of Mines & Energy.**

These results are in the form of maps, reports, and contributions to geoscientific journals and the proceedings of conferences. The data package — comprising five volumes — is the product of fieldwork over four field seasons (1983-86), and subsequent part-time follow-up investigations, interpretation, map compilation, and report writing. For much of the time since the first field season in Kalimantan and up to November 1988, the small team of geoscientists was completing its commitments to an earlier phase of the project —in western Irian Jaya — which culminated in the release of the Irian Jaya Geoscientific Data Package (see *BMR Research Newsletter* **10,** 11); consequently, most of the report writing and map compilation for the Kalimantan Geoscientific Data Package was accomplished in the twelve months preceding its issue.

*Volume 1* contains: an introduction to the data package; a 1:1 000 000 three-colour, combined geological/Bouguer anomaly outline map ('Preliminary geological map of the West, Central & East Kalimantan area'), which covers the area mapped by IAGMP (Fig. 21) plus adjoining parts of Kalimantan farther east and southeast that were mapped by GRDC both before 1983 and since 1986; an explanatory text on the 1:1 000 000 preliminary map; a bibliography of the IAGMP mapping area; a catalogue of isotopic ages that IAGMP commissioned for selected igneous and metamorphic rocks in Kalimantan; and a bound collection of photocopied papers and contributions to the proceedings of geoscientific conferences.

*Volume 2* comprises 12 two-colour outline (preliminary-edition) 1:250 000 geological maps of the quadrangles mapped by IAGMP (Fig. 21): SAMBAS-SILUAS, NANGAOBAT, PENGUNUNGAN KAPUAS, LONG NAWAN, SINGKAWANG, SANGGAU, SINTANG, PUTUSSIBAU, LONG PAHANGAI, PONTIANAK-NANGATAMAN, NANGAPINOH, and KETAPANG.

*Volume 3* comprises 11 two-colour outline Bouguer anomaly maps of the 1:250 000 quadrangles in which IAGMP acquired land-based gravity data. With only two exceptions, these maps have the same coverage as the preliminary-edition geological maps in Volume 2: the Bouguer anomaly contours cover only the northern one-third and eastern one-sixth of PONTIANAK-NANGATAMAN, where the IAGMP gravity coverage is incomplete; and the gravity data that IAGMP collected are too sparse in KETAPANG, for which no Bouguer anomaly map could be compiled. A catalogue of the gravity data in this volume complements the gravity maps.

*Volumes 4 and 5* incorporate in report form the data derived from the 1:250 000 geological mapping, integrated geochemical survey, and follow-up studies. Volume 4 contains Data Records of the combined SAMBAS-SILUAS, SINGKAWANG, SANGGAU, combined NANGATAMAN and PONTIANAK, and KETAPANG quadrangles. Volume 5 contains Data Records of the LONG NAWAN, SINTANG, LONG PAHANGAI, NANGAPINOH, and combined PUTUSSIBAU, PEGUNUNGAN KAPUAS, and NANGAOBAT quadrangles.

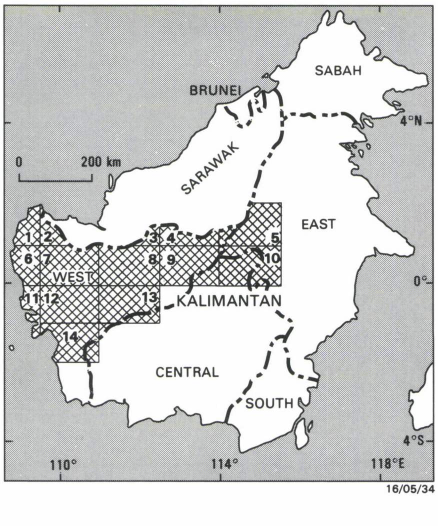
The availability of the Kalimantan Geoscientific Data Package should facilitate exploration by an increasing number of private companies — many of them Australian-based — searching for minerals in Kalimantan, particularly gold (*BMR Research Newsletter,* **8,** 4-6; **9,** 4-5) and to a lesser extent petroleum, in the northwestern part of Kalimantan in which the IAGMP has provided the first systematic dual coverage of 1:250 000 geological and gravity maps.

The Kalimantan Geoscientific Data Package was released in Bali on 11 December 1989 at a special ceremony attended by representatives of the Australian and Indonesian Governments. Indonesia's Director General of Geology & Mineral Resources, Dr Adjat Sudradjat, presented copies of the data package to Australia's Minister for Resources, Senator the Hon. Peter Cook, and to Indonesia's Minister of Mines & Energy, Ir Ginandjar Kartasasmita. In his presentation speech Dr Sudradjat praised the success of the IAGMP in its contribution — through the documentation of a wealth of systematic data — to establishing the geoscientific framework of western and central Kalimantan and western Irian Jaya; he expressed hope that Australian geoscientists would be invited to return to Irian Jaya in the near future to contribute to a similar venture whose primary objective would be the completion of systematic mapping in the eastern half of the province.

Copies of the Kalimantan Geoscientific Data Package are available for reference at the BMR Library, Canberra, and the Data Records are available on open file for consultation at the GRDC Library, Bandung. Copies of the data package may be bought for US$3300 from BMR (attention: Copy Service) or for US$3000 from GRDC via Dr Rab Sukamto, Director, Geological Research & Development Centre, Jalan Diponegoro 57, Bandung, Indonesia. The 1:250 000 Bouguer anomaly and preliminary geological maps may be purchased individually from GRDC for US$3.00 each.

*For more details, contact Messrs David Trail, Peter Pieters, Geoff Bladon, or John Casey at BMR.*

**Fig. 21. 1:2500 000 quadrangles in Kalimantan mapped by IAGMP: 1 — Sambas; 2 — Siluas; 3 — Nangaobat; 4 — Pegunungan Kapuas; 5 — Long Nawan; 6 — Singkawang; 7 — Sanggau; 8 — Sintang; 9 — Putussibau; 10 — Long Pahangai; 11 — Pontianak; 12 — Nangataman; 13 — Nangapinoh; 14 — Ketapang.**



# Epithermal sinters: a low-cost exploration tool

**Ancient sinters have been widely encountered in the northern Drummond Basin, Qld: their recognition provides tangible evidence of a palaeosurface associated with extinct geothermal systems and indicates the potential for significant mineralised epithermal systems beneath and possibly adjacent to the sinters. In *BMR Research Newsletter* 11 (October 1989), preliminary stable-isotope results in the northern Drummond Basin were reported as indicating the potential to characterise siliceous sinters in epithermal gold deposits on the basis of their oxygen-isotope signatures. Recent further isotopic data on known sinters has supported these earlier observations and confirmed the value of sinters as a low-cost exploration tool.**

Data for the Wobegong sinters (Conway prospect) and related, high-temperature vein quartz indicate that the sinters (+11.5±0.7 per mil) are consistently and significantly more $\delta^{18}O$ SMOW-enriched than nearby vein quartz (+6.3±1.9 per mil). These sinters conform with deposition at 90-100°C from a fluid having a value of around -9 to -8 per mil. Sinter at Durah Creek (White & others, 1989: *Geology,* **17,** 718-722), and a suspected sinter at the Hill 273 prospect *(BMR Research Newsletter,* **11,** 5) also have high $\delta^{18}O$ values (+14.4 and +13.6 per mil respectively). If the $\delta^{18}O$ value of meteoric water in the area at that time is assumed to have been between -10 and -8 per mil (based on data from Pajingo and Conway), then the temperature of formation for the Durah Creek and Hill 273 sinters would have been about 65-80°C and 70-85°C respectively, confirming their low-temperature hydrothermal origin. On the basis of this regional meteoric water $\delta^{18}O$ value, a suspected sinter with $\delta^{18}O$ value of say +7 per mil should be regarded with suspicion, i.e. fractionation in the quartz-water system (Kawabe, 1979: *Geochemical Journal,* **13,** 57-67) would require deposition at between 120 and 135°C, a temperature inconsistent with deposition of silica from hydrothermal fluids discharged at the surface.

If travertine sinters are preserved, they will also be isotopically heavy relative to higher-temperature calcite: $\delta^{18}O$ fractionation in the calcite-water system is in the same sense as the quartz-water fractionation (Friedman & O'Neil, 1977: *USGS Professional Paper* **440-KK).**

This work is part of joint research involving BMR and BHP-Utah Minerals International, and is currently being prepared for publication.

*For further information, contact Dr Greg Ewers at BMR (Minerals & Land Use Program).*

# Successful BMR workshop on application of fluid inclusions in exploration

On 20 & 30 March 1990 Mr T. James Reynolds from FLUID INC. of Denver, USA, conducted a workshop at BMR on the application of fluid inclusions to exploration for petroleum and minerals. Participants included BMR, industry, and university scientists working on ore deposits and petroleum geology. The workshop included intensive lectures, group discussions, and a microscope session. Throughout the workshop the limitations of the technique were stressed: as with any technique, once the limitations are understood the technique can become a powerful tool.

The workshop first reviewed the fundamentals of fluid inclusion research. The principles of how fluid inclusions provide information about temperature, pressure, composition, and density of fluids present throughout a crystal's history are relatively straightforward. But the basic requirements for obtaining valid information (i.e. that inclusion volumes never change, that the inclusions must never leak, and that the inclusions must have trapped a homogeneous fluid) are commonly violated in many geologic environments. Such violations occur when inclusions are trapped from immiscible or boiling fluids, when inclusions are healed after entrapment, and when inclusions are either significantly buried or uplifted after entrapment. The literature is fraught with studies conducted by persons either unaware that these requirements often are not met, or naively assume that they are. The participants of this workshop learned that the requirements are satisfied only when the data from a single healed plane (microfracture) of inclusions, or from a restricted area of a growth zone where the inclusions vary in size and shape, yield consistent results.

Fluid-inclusion study design and study philosophy were thoroughly reviewed. An important aspect of conducting a fluid inclusion study is that one must think in terms of time, for spatial variations cannot be assessed before temporal variations are first understood. Also, the most important part of any inclusion study is to first assess the time-significance of dozens of samples and, of course, their relevance to the problem at hand before any microthermometric data are collected. Mr Reynolds was adamant that a study of fluid inclusions should not be viewed like a geochemical survey: one must be more focused in one's approach in order to get the required information from the study within the time normally budgeted.

The fluid-inclusion characteristics of various ore-forming and basinal environments were reviewed, as well as the problems of working with inclusions in each environment. Of utmost importance to explorationists is that the fluid-inclusion petrography often defines an environment: all that is required is a petrographic microscope! In short, visually apparent $CO_2$-bearing inclusions are diagnostic of mesothermal environments deeper than porphyry systems, porphyry systems are characterised by NaCl-bearing inclusions, and epithermal environments commonly have abundant primary inclusions defining growth zones in crystals, and have low NaCl and $CO_2$ contents. Mr Reynolds pointed out, however, that once a broad environment is defined, the use of inclusions to locate a precise position or level within the environment is usually not possible.

Finally, the participants learned how to overcome various procedural problems involved in fluid-inclusion microscopy. Aspiring research students and company geologists also discussed their own prospective projects with Mr Reynolds.

*For further information contact Dr Hashem Etminan (Minerals & Land Use Program) at BMR.*

# BMR publications, maps, and data releases, and how to obtain them

## Forthcoming titles

**Bulletin 231: Permian coals of eastern Australia; by H.J. Harrington and others**

The Permian coals of eastern Australia are one of the country's greatest natural resources, extending from Cape York to Tasmania and from the Pacific coast to inland Queensland.

This Bulletin presents a definitive scientific assessment of the resource and will be used as a standard reference for the coal industry, and probably the petroleum industry, for many years to come.

A cooperative project of BMR and CSIRO, the project collected, analysed and consolidated a vast amount of data from a wide range of sources, including relevant State Government agencies and the coal industry itself. The Bulletin details information on individual coal measures in terms of surface and underground geology, stratigraphy, sedimentology and structure, and chemical and physical properties.

**BMR Journal of Australian Geology and Geophysics, Volume 11, Nos 2 & 3.**

This special double issue contains 21 papers from the conference 'Murray Basin 88 — Geology, groundwater and salinity management', held in Canberra in May 1988. The papers include overviews of the geology, groundwater systems, land degradation, irrigation recharge, options for the disposal of saline water, broadscale revegetation for salinity management, case histories, and techniques which have contributed to the understanding of the groundwater in the basin. This special issue is of interest to agriculturalists, soil scientists, engineers, environmentalists, managers and others concerned with salinisation in the Murray Basin.

**BMR 89, Yearbook of the Bureau of Mineral Resources, Geology and Geophysics.**

BMR 89, covering the 12 months to 30 June 1989, summarises the progress of all projects and lists all papers (including external) and monographs published in the period.

## Publications and data released during the period

## 1 September 1989 — 1 March 1990

**Publications**

*Bulletins*

**181** Guide to the geology of Australia (reprint)

**221** Hydrogeochemistry of the upper Hunter River Valley, New South Wales

*Reports*

**285** Australian Seismological Report, 1985

**290** Australian Geoscience 1988. Annual report of the Australian Geoscience Council Inc.

**6** Gold deposits of New South Wales: *BMR datafile (MINDEP)*

*BMR Journal of Australian Geology & Geophysics* **(Vol.11, No.1)**

*BMR Research Newsletter,* **11**

*Petroleum Exploration & Development Titles Map & Key,* **July, 1989**

*BMR Work Program* **1989—90**

*Papers from the 1989 BMR Research Symposium 'Geoscience mapping towards the 21st century'*

*Symbols Used on Geological Maps*

*BMR Earth Science Atlas of Australia, Map and Commentary:* **Main Rock Types**

*Geoscience maps*

1:250 000 geological: **Manokwari,** Irian Jaya

1:250 000 geological: **Waghete,** Irian Jaya

1:250 000 geological: **Taminabuan,** Irian Jaya

1:100 000 preliminary geological: **Jervois Range,** NT

1:1 000 000 total-magnetic-intensity, pixels: **Kalgoorlie,** WA, **Cape York,** Qld

*Records released on open file*

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| **1988/52** | An assessment of the mineral potential of the Helsham Inquiry areas containing the 'Hole in the Doughnut' area, Central Plateau Conservation area and Walls of Jerusalem National Park |
| **1989/16** | Magnetic modelling of two and three-dimensional bodies: test programs and subroutines in FORTRAN 77 |
| **1989/23** | Hydrocarbon prospectivity of the offshore Perth Basin |
| **1989/28** | (Volumes 1 & 2) — Government petroleum databases workshop, Adelaide 11—12 October 1988 —Edited transcript of proceedings and papers |
| **1989/30** | A review of gold mineralisation in eastern Australia, May 1988 |
| **1989/31** | Australian Phanerozoic timescales 1. Cambrian. Biostratigraphic chart and explanatory notes |
| **1989/32** | Australian Phanerozoic timescales 2. Ordovician |
| **1989/33** | Australian Phanerozoic timescales 3. Silurian |
| **1989/34** | Australian Phanerozoic timescales 4. Devonian. Biostratigraphic chart and explanatory notes |
| **1989/43** | Computer-generated crustal models for the southwest seismic zone, western Australia |
| **1989/44** | The BMR MAGSAT and 3rd-order geomagnetic ORACLE databases |
| **1989/45** | Gippsland Basin exploration wells stratigraphic data and seismic ties |
| **1989/46** | Notes on Croydon, north Queensland, fieldwork July/August 1988 and results of K/Ar dating of sericitic alteration |
| **1989/48** | An integral equation for the conduction of heat in a heterogenous layered structure and its solution for a three-dimensional hetero-geneity |
| **1989/51** | Proposals for the re-use of invalid and superseded stratigraphic names in Australia |
| **1989/52** | Central Victoria Seismic Test Survey, 1989. Operational report |
| **1989/54** | Geochemical sampling in the Arunta Block, 1980–81 |
| **1990/4** | Deep structure of the Gippsland and Bass Basins: onshore seismic recording operational report |
| **1990/6** | Leg 133 — Northeast Australia Safety Package |
| **1990/9** | Arafura Sea — Seismic Reconnaissance with Geochemistry — Research Cruise Proposal |
| **1990/12** | BMR Marine Survey 76 — Townsville Trough, Queensland — explanatory notes to accompany release of non-seismic data |

**Release of data**

*Airborne geophysical maps*

1:250 000 — 150 maps, showing either magnetic properties, magnetic contours or profiles, radiometric contours or profiles, or flight-line systems (all States)

1:1 000 000 — 29 magnetic pixel maps for two sheet areas

*Digital data*

Digital-point-located airborne magnetic or radiometric data from twenty three 1:250 000 Sheet areas

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BMR Publications and maps are listed in *Publications of the Bureau of Mineral Resources, Geology & Geophysics (Part 1: Publications other than maps; Part II: Maps),* which is available free of charge from: **BMR Publication Sales, GPO Box 378, Canberra, ACT 2601 (phone [06] 249 9519).** A *Quarterly List of Publications* showing current releases of all publications and other data is also available free of charge from BMR Publication Sales, together with detailed information on prices and postage costs. **All publications can be bought at the Publication Sales counter, BMR building, cnr Constitution Avenue and Anzac Parade, Parkes, ACT (open 9.00-4.30, Mon.-Fri.). Further information on the availability of preliminary data may be obtained from the Information Section, phone [06] 249 9620 or 249 9623.** Please note that orders for publications must be accompanied by payment in advance. Cheques, postal orders, etc., should be made payable to: Collector of Public Moneys (BMR). Payment from overseas should be made by bank draft or international money order in Australian currency.

The full results of many surveys and other research projects are published in two monograph series: *Bulletins* and *Reports.* Another major publication outlet for BMR's research results is the quarterly *BMR Journal of Australian Geology & Geophysics.*

The *BMR Yearbook,* covering the 12 months to 30 June, summarises the progress of all projects and lists all papers (incl. external) and monographs published in the period. Covered so far in the *Resource Reports* series: uranium resources of Australia; coal in Antarctica; gold databases for WA, Qld, and NSW; and the geology and economics of platinum-group metals in Australia. *Australian Petroleum Accumulations Reports* so far cover the Amadeus, Bass, Adavale, Gippsland, and Bonaparte Basins.

The results of BMR's offshore surveys using RV *Rig Seismic* are being progressively released in a new *Continental Margins Program Folio* series, so far covering the Bass, Otway, and North Perth Basins.

The large-format looseleaf *BMR Earth Science Atlas of Australia* by now contains 17 maps of Australia, mainly at 1:10 000 000 scale, on various earth-science themes. In similar large format, the first volume (Cambrian) of a major new publication series, the *Palaeogeographic Atlas of Australia,* is now available.

Preliminary results, results of limited interest, and some other manuscripts are published in the *Record* series. Records are produced in limited numbers; photocopies can be bought through the BMR Copy Service. Those available for reference at Open File Centres are listed in the *Quarterly List of Publications.*

BMR has published a large number of 1:250 000 scale geological maps, with Explanatory Notes booklets, covering quadrangles mainly in northern Australia. More detailed 1:100 000 scale geological maps and accompanying commentary booklets are also available for certain areas. Many smaller-scale geological maps covering various regions have also been published, often in conjunction with geological Bulletins. BMR also publishes stream-sediment geochemistry, radiometric, gravity (new series), total-magnetic-field (TMF), and TMF pixel maps at various scales. The results of most regional geophysical and marine surveys are made available as preliminary maps and sections. **A brochure illustrating the extent of coverage of Australia by surveys by BMR and the State mines departments can be obtained from: Information Section, Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601, phone (06) 249 9620.**

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