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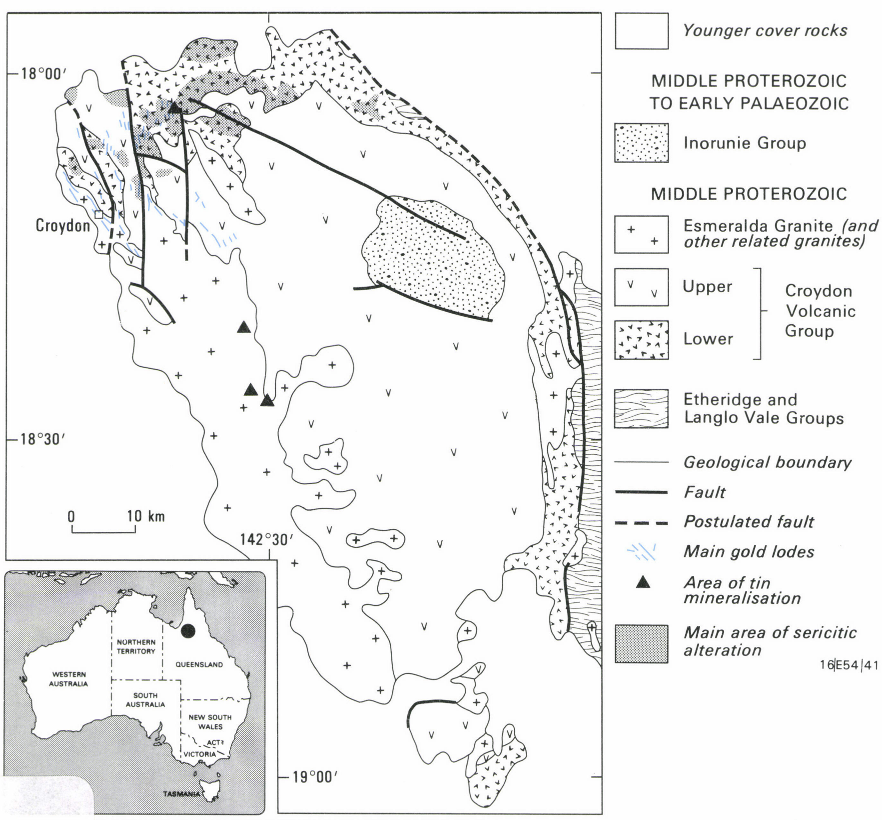
Graphite-bearing ignimbrites and granites at Croydon, Queensland, and their relationship to gold mineralisation

The Croydon Goldfield (Fig. 1) appears unusual, if not unique, in NE Queensland: it is the only known gold mineralisation with a probable genetic link to S-type (Sheraton & Labonne, 1978: *BMR Bulletin* 169; White & Chappell, 1983: *Geological Society of America Memoir* 159, 21–34) **felsic ignimbrites and comagmatic granite** (Branch, 1966: *BMR Bulletin* 66) **of Proterozoic age** (Richards & others, 1966: *BMR Bulletin* 88). **Many other gold deposits in NE Queensland have similar geological settings but are associated with Palaeozoic igneous rocks of demonstrated or probable I-type or A-type character** (e.g. *BMR Research Newsletter*, 2 (1985), 9–10; 6 (1987), 6–7). **The presence of widespread and abundant graphite and graphitic metasedimentary enclaves in the host rocks of the Croydon Goldfield (Esmeralda Granite and Croydon Volcanic Group) may be the key to understanding this unusual association.**

Graphite pellets and graphitic enclaves

The Croydon Volcanic Group consists dominantly of dacitic to rhyolitic ignimbrites. A conspicuous feature of these rocks is the ubiquitous presence of abundant graphite, mostly as rounded or ellipsoidal 'pellets' up to 1 cm long, amounting to about 1 percent of the rock. The volcanics are intruded by bodies of generally coarse-grained biotite granite which were probably emplaced to within 1–2 km of the surface. Recalculated Rb–Sr isotopic ages based on work by Black (1973: *BMR Record* 1973/50) are 1399 ± 75 Ma for the volcanics and ~1381 Ma for the granite.

The largest pluton (900 km^2) is the Esmeralda Granite, whose upper contact is broadly conformable with the gentle regional dips in the volcanics. Contact effects in the volcanics are generally limited to moderate to intense recrystallisation. Greisenisation and chlorite–tourmaline alteration are associated with minor tin mineralisation. Extensive zones of commonly intense, pervasive, mostly sericitic, alteration are present in the northwest, in the same general area as some of the gold mineralisation and several small granite apophyses, but the relationship between the granite and the alteration is uncertain. Parts of the granite are extremely rich in graphite: in the Croydon Goldfield, variably sheared, tabular zones up to 120 m thick and several km long, generally subparallel to the granite/volcanics contact, are packed with graphitic metasedimentary enclaves and masses of almost pure graphite set in a matrix of intensely hydrothermally altered granite. Some of these zones are at the granite/volcanics contact, others up to 150 m below it. Similar accumulations of graphitic metasedimentary enclaves occur in the roof zones of other granite plutons intruding the Croydon Volcanic Group.



Metasedimentary source

The volcanics and granites are peraluminous, and have high K/Na (about 2) and Rb/Sr (about 4) ratios, and other chemical characteristics of K-rich, S-type rocks. The graphite and graphitic enclaves in the granite roof zones and the graphite in the volcanics are direct evidence of a metasedimentary (S-type) source. Some of the enclaves appear not to have reacted with the granite, and are clearly derived from the low greenschist-grade Proterozoic metasediments that abut the Croydon igneous province to the east; these are probably accidental (stoped) xenoliths. However, other enclaves include variably reacted amphibolite-facies schist and gneiss, and almost pure (residual) graphite. These, and the disseminated and 'pelletised' graphite which is distributed throughout at least 1000 km^3 of volcanics, are probably of cognate, or restite, origin. The zones rich in graphitic enclaves and graphite, below the granite/volcanics contact, may have formed by accumulation of this low-density material at the roofs of sheet-like intrusions, or by differential flow in the magma.

Gold related to the graphite?

Gold mineralisation in the granite is contained in gently-dipping to vertical, commonly anastomosing, quartz veins striking subparallel to the gently to moderately dipping graphitic zones (e.g. Clappison & Dickinson, 1937: *AGGSNA Report* 25). Where the veins intersect the graphitic zones, they broaden, anastomose further, and increase in grade; the fineness of the gold decreases both below the graphite-rich zones and upward towards the granite/volcanics contact (Reid, 1935: *Queensland Government Mining Journal,* 36, 76–78, 125–131, 155–165). The gold is associated with arsenopyrite and minor pyrite, galena, and sphalerite; native silver is present in places near the granite/volcanics contact.

Gold-bearing quartz veins in the volcanics are narrower and more numerous than in the granite, and generally lack graphite, but sulphide minerals are similar to those in the granite lodes. Ore grades were lower than in the granite, but the fineness of the gold was generally higher.

Isotopic age data on the mineralisation are not available, but the foregoing observations and the lack of any known younger igneous rocks in or near the mineralised area are circumstantial evidence of a Proterozoic age.

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Bureau of Mineral Resources, Geology and Geophysics, Canberra

Department of Primary Industries and Energy

Carbon-isotopic analyses of graphite samples from the volcanics, granites, enclaves, and orebodies ($\delta^{14}C = -28.50 \pm 0.84$), and of carbonaceous and graphitic units in the basement rocks (Etheridge Group: $\delta^{14}C = -31.46 \pm 0.77$) show that all of the carbon is of biological origin, and is consistent with graphite in the igneous rocks having been derived from the Etheridge Group. There are no significant differences in $\delta^{14}C$ between graphite in unreacted enclaves, graphite masses associated with the ore deposits, and graphite pellets in the volcanics.

The graphite, whether of restite or xenolithic origin, may hold the key to the source of at least some of the gold in the Croydon goldfield. Withnall & Mackenzie (1979: *Geological Survey of Queensland, Record* 1979/37) showed that some carbonaceous horizons in low-grade metasediments near the eastern margin of the volcanics contain unusually high gold contents relative to average crust. Rocks similar to these, and to lithologies stratigraphically above and below them, are recognisable amongst the enclaves in the granites.

Presently available data suggest that deposition of gold in the Esmeralda Granite may have been controlled by the abundant graphite in the pyrite stability field (cf *BMR Research Newsletter*, 7 (1987), 12–13). The general depositional reaction may be written as:

$$Au(HS)_2^- + 0.5H_2O + 0.25C = Au + H_2S + HS^- + 0.25CO_2$$

There is probably also enough graphite present in the volcanic rocks to produce a similar chemical control on the volcanic-hosted deposits.

This work shows that, in northeast Queensland, neither S-type character nor Proterozoic age should be regarded as necessarily disqualifying an igneous rock as a potential host and/or source of gold deposits.

Further work on the Croydon goldfield is planned, including detailed geological, fluid-inclusion, and isotopic studies to determine (1) the relationship between the extensive alteration (especially in the volcanics) and the mineralisation, (2) the structural and chemical controls on, and age of, ore deposition, (3) the origin and isotopic evolution of the graphite in the granites and volcanics, and (4) the composition of the ore fluids.

For further information, contact Dr Doug Mackenzie at BMR (Division of Petrology & Geochemistry).

Extension tectonics extended: new results from the Mount Isa Inlier

Further results from the Mount Isa Inlier of northwest Queensland considerably enlarge the area of known extensional tectonics, and reinforce the importance of regional extension at a significant stage in the geological history of the Inlier: the extensional structures may have initiated the basins in which the Mount Isa type stratiform zinc–lead–silver orebodies were deposited, and could also have exerted an important control on the mineralisation.

Extensional origin of the Deighton Klippe

Since the current BMR work in the Mount Isa Inlier began in 1983, the importance of major low-angle extensional faulting accompanied by large-scale subhorizontal movement of rock masses has become increasingly recognised. Dunnet (1976: *Philosophical Transactions of the Royal Society of London, Series A*, 283, 333–344) first suggested the possibility of low-angle normal faulting when he proposed that the Hilton and Mount Isa orebodies were originally parts of a single mass, later separated by major low-angle extensional faulting. Passchier (1986: *Geology*, 14, 1008–1011) and BMR (1987: *Research Newsletter* 6, 10–11) respectively documented early low-angle normal faulting in the southern part of the Alligator Syncline and in the Bulonga Anticline (Fig. 2). Loosveld & Schreurs (1987: *Australian Journal of Earth Sciences*, 34, 387–402) described the West Leichhardt Klippe and Deighton Klippe east of Mount Isa as outliers of thrust nappes. We report further evidence of early low-angle normal faulting throughout the central Mount Isa Inlier, and reinterpret the Deighton Klippe in those terms.

Loosveld & Schreurs showed that the Deighton Quartzite forming the synformal Deighton Klippe (Fig. 3) is in tectonic contact with the underlying Corella Formation. They suggested that the Deighton was emplaced as a nappe on top of the Corella, and that the Deighton is stratigraphically equivalent to the Ballara Quartzite, which normally underlies the Corella. However, recent mapping of Deighton Quartzite outliers away from the Deighton Klippe has shown that over large areas it rests conformably on the Corella Formation. The evidence includes parallelism of strike and dip of the two formations, a passage-beds interval between the two formations, comprising alternating beds of Deighton Quartzite rock types (feldspathic metasandstone ± chlorite or biotite) and Corella rock types (scapolite–biotite granofels, calcareous granofels, metasiltstone, mica schist, and metabasalt), and pebbles of Corella rock types in the lowermost Deighton Quartzite (as earlier noted by Carter, Brooks, & Walker, 1961: *BMR Bulletin* 51). Hence, the Deighton Quartzite cannot have been thrust-faulted over the Corella Formation. Nevertheless, the mapping has confirmed that the two formations are in tectonic contact around the entire extent of the Deighton Klippe, and that restricted and minor thrust-faulting placed Deighton over Deighton on the western limb of the Deighton Klippe. Following the recognition of extensional faults predating the earliest compression (D1; 1610 Ma) in the Ballara Quartzite of the Alligator Syncline (Passchier, 1986) and in its correlative in the Bulonga Anticline (BMR, 1987), we suggest that the contact of the Deighton Quartzite and Corella Formation in and around the Deighton Klippe is a bedding-parallel fault along which the Deighton Quartzite slid during regional extension. The suggestion is based on the following evidence seen in the Deighton Klippe:

A New Mount Isa Bulletin

GEOLOGY OF THE MOUNT ISA INLIER AND ENVIRONS, QUEENSLAND AND NORTHERN TERRITORY, by D.H. Blake, 1987. *Bureau of Mineral Resources, Australia, Bulletin* 225, 83 pp, 17 tables, 58 figs., 1:500 000 scale geological map (coloured). Price: $27.95. Available from Publications Sales, BMR, GPO Box 378, Canberra, ACT 2601.

This Bulletin and accompanying 1:500 000 geological map, released in August 1987, summarises the results of the 1:100 000 geological survey of the Proterozoic Mount Isa Inlier and correlative outcrops to the northwest carried out between 1969 and 1980 by BMR and the Geological Survey of Queensland, and also incorporates some results of more recent research. Hence it provides an update on the pioneering *BMR Bulletin 51*, 'The Precambrian mineral belt of north-western Queensland' by E.K. Carter, J.H. Brooks, and K.R. Walker, published in 1961. Major sections in the new Bulletin deal with Proterozoic stratigraphy, Proterozoic intrusions, structure, metamorphism, igneous rock geochemistry, tectonic setting, and geological history and the mineral deposits of the region are briefly summarised. Also included is a glossary (Appendix 1) of all Proterozoic stratigraphic and intrusive rock units which have been used on published maps, with information on distribution, references to definition, dominant lithology, stratigraphic or intrusive association, isotopic age, and synonyms. Names of structural and tectonic features, with locations and brief descriptions, are listed in Appendix 2.

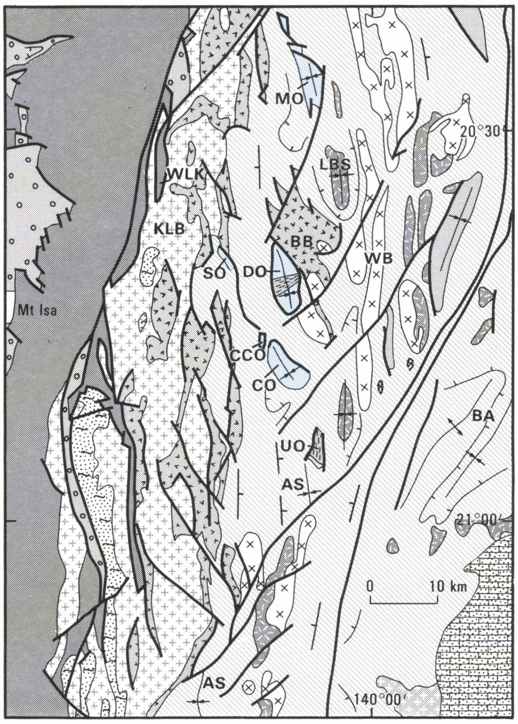
In Bulletin 225 the three broad tectonic divisions of the Mount Isa Inlier are termed the Western Fold Belt, Kalkadoon–Leichhardt Belt, and Eastern Fold Belt. Each is formed of Early and Middle Proterozoic sedimentary and volcanic rocks, which are assigned to four major sequences, and many igneous intrusions. Correlatives to the northwest are exposed within and around the younger Proterozoic South Nicholson Basin and along the Murphy Tectonic Ridge.

The oldest Proterozoic sequence comprises all rocks deformed and metamorphosed before about 1875 Ma, and is designated basement. The three younger sequences form the Proterozoic cover; the earliest, cover sequence 1, consists predominantly of subaerial felsic volcanics dated at 1850–1875 Ma (e.g., Leichhardt Volcanics). Cover sequence 2 (1760–1790 Ma; e.g., Haslingden and Mary Kathleen Groups) and cover sequence 3 (1670–1680 Ma; e.g., Mount Isa and McNamara Groups) are represented by mainly shallow-water sediments and both felsic and mafic volcanics. The sequences are intruded by voluminous I-type granites, emplaced between about 1860 Ma and 1500 Ma, and by innumerable mafic bodies, mainly dykes, ranging in age from pre-1860 Ma to post-1200 Ma. They were deformed and metamorphosed during major orogenesis between about 1620 and 1550 Ma.

The Mount Isa Inlier contains, in addition to the large Mount Isa orebodies (brecciated sediment-hosted copper and stratiform zinc–lead–silver), other substantial copper and zinc–lead–silver deposits and significant deposits of gold, uranium, and cobalt. There are also many small shear and fault-controlled vein copper deposits in the eastern part; most of the gold production has come as a by-product from these veins.

Geochemical and other evidence is considered to favour an intracratonic, rather than a continental-margin, tectonic setting for the region during the Early and Middle Proterozoic.

For further information contact Dr David Blake at BMR (Division of Petrology & Geochemistry)



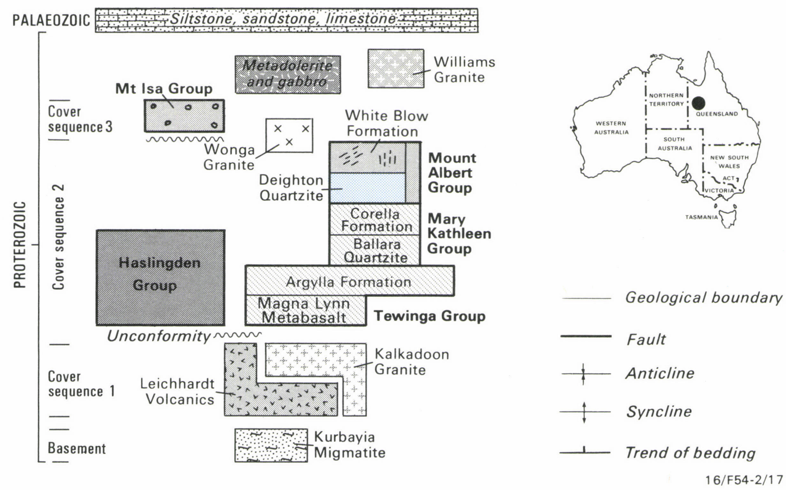


Fig. 2. Generalised geological map of central Mount Isa Inlier. AS Alligator Syncline, BA Bulonga Anticline, BB Blockade Block, CO Campbell Outlier, CCO Charley Creek Outlier, DK Deighton Klippe, LBS Little Beauty Syncline, MO Maylene Outlier, SO Scorpion Outlier, UO Unnamed outlier, WB Wonga Belt, WLK West Leichhardt Klippe.

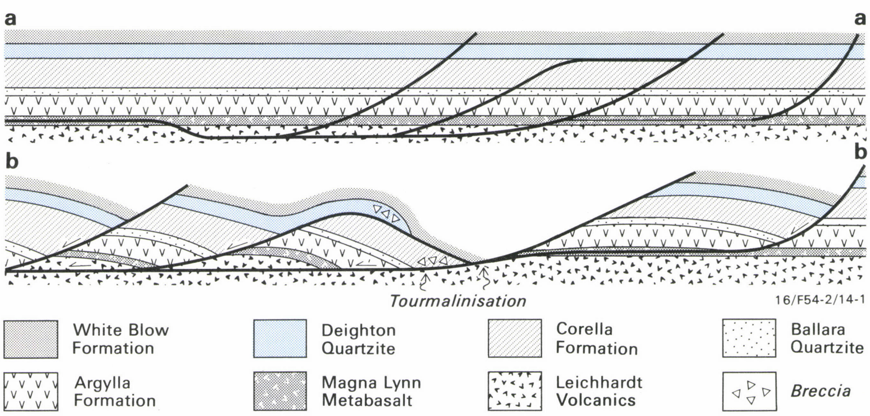


Fig. 4. System of hypothetical normal faults together with a bedding-parallel fault (a) before, and (b) after extension.

Fig. 5. Schematic cross-section through Fig. 3, showing normal faults folded by D2, Deighton Klippe, and Scorpion and Maylene outliers projected on to line of section.

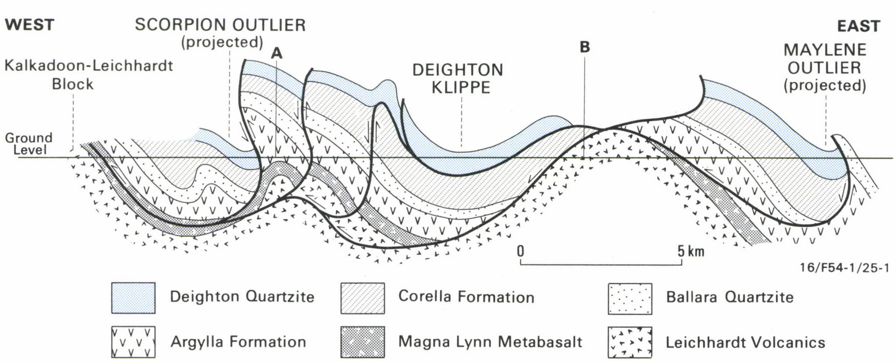
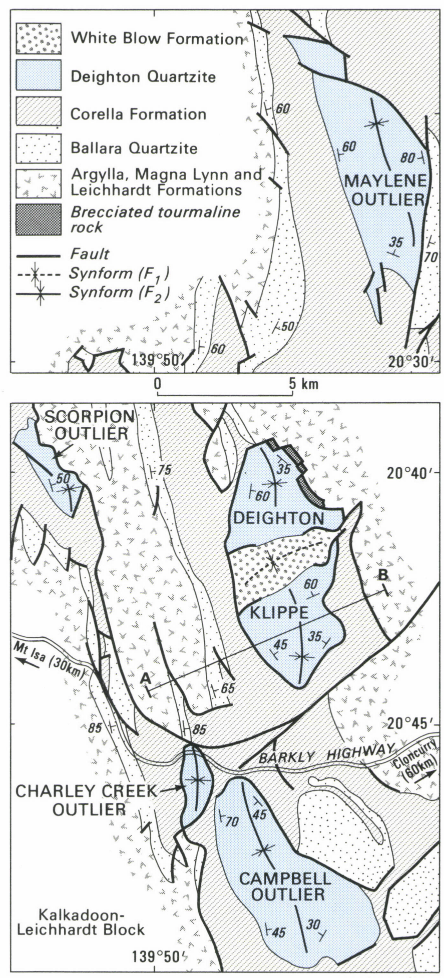


Fig. 3. Geological map of Deighton Quartzite outliers. A–B indicates position of section line in Fig. 5.



— Strong fracturing and extensive masses of fault breccia in the Deighton Quartzite; the brittle structures are strongest at the contact with the Corella Formation, weaken away from the contact, and in many places are deformed by a steep, northerly-striking foliation (S_2).

— Boudinage of a prominent white sandstone about 20 m thick at the base of the Deighton Quartzite, thereby bringing the overlying sandstone into contact with the Corella Formation.

— Metre-scale normal fault blocks cut by S_2 in the Deighton Quartzite; similar centimetre-scale normal fault blocks are cut by S_2 in the Scorpion outlier.

— Extensive masses of brecciated tourmaline rock along the northeastern limb of the Deighton Klippe (Fig. 3); the breccia is deformed by S_2.

— Thick extensive megabreccia in the Corella Formation below the Deighton Quartzite on the eastern limb; the breccia comprises rafts of schist and quartzite up to several hundred metres long enclosed in granofels and marble, and is deformed by S_2.

— The Corella Formation along the entire west-dipping eastern limb is in fault contact with the Leichhardt Volcanics; the Argylla Formation and Ballara Quartzite, which normally lie between the Leichhardt Volcanics and Corella Formations, are missing.

Younger rocks placed tectonically over older

The evidence indicates west-directed extensional faulting, brecciation, and tourmalinisation along a system of pre-D_2 west-dipping low-angle normal faults (Fig. 4a). The bedding-parallel fault beneath the Deighton Klippe was originally a flat that formed part of this system. The normal faults were probably pre-D_1 in origin, because high and low-angle normal faults filled with metadolerite containing S_1 foliation, stretching lineation, and metamorphic mineral assemblages occur in the Bulonga Anticline (BMR, 1987), the Little Beauty Syncline (P.R.Williams, unpublished results), and in the Wonga Belt (P.J.Pearson, personal communication). The extension (Fig. 4b) placed younger rocks over older, i.e., Deighton over Corella and Corella over Leichhardt. Extension was followed by north–south compression (D_1), which formed the F_1 synform in the White Blow Formation of the Deighton Klippe, and then by east–west D_2 compression (Fig. 5). This produced minor thrust-faulting and folding on the western side of the Deighton Klippe, and then the major northerly-trending upright folds (such as the synform forming the Deighton Klippe) and steep northerly-striking axial-plane foliation (S_2).

Of the other Deighton Quartzite outliers, the Charley Creek outlier has a fault right around it, and is identical to the Deighton Klippe. In contrast, the Campbell, Scorpion, and Maylene outliers are in conformable sequence with the underlying Corella Formation on their western sides (including the passage bed interval described above), and are in steep fault contact with older rocks (Leichhardt, Magna Lynn, or Ballara) on their eastern sides. At the Scorpion outlier, the fault is marked by prominent breccia which is cut by and therefore predates S_2 foliation. The eastern bounding faults at the Campbell and Maylene outliers are syn or post-S_2; Maylene has a steeply east-dipping thrust-fault combined with sinistral strike-slip, and Campbell has a vertical to steeply west-dipping normal fault. The structural setting of the Scorpion and Maylene outliers is shown in the appropriate parts of Fig. 5. The folding rotated the early normal faults, thereby reversing their dip and sense of throw and making them appear to be thrust faults. This removes the necessity for westerly-directed thrusting in the Deighton area, as suggested by BMR (1985: *Research Newsletter* 2, 11) and by Loosveld & Schreurs (1987). On the eastern side of the Campbell outlier, undeformed fault breccias cut S_2, separate different orientations of S_2 on each side of the fault, and in places contain flattened clasts of S_2-foliated rock in random orientations. This indicates post-D_2 reactivation of the early fault, and similarly for the combined thrust and strike-slip fault on the eastern side of the Maylene outlier.

The phenomena described here reinforce the importance of the regional extension that post-dated deposition of the Mary Kathleen and Mount Albert Groups. We suggest that it was this crustal extension that initiated the basins in which the Mount Isa Group and its related and correlated sequences were deposited. The extensional structures may have localised the Mount Isa-type zinc–lead–silver mineralisation, similarly to the syn-sedimentary normal faults which allowed metal-bearing fluid to enter the McArthur Basin to the north, to form the HYC zinc–lead–silver deposit.

For further information, contact Dr Alastair Stewart, Dr Peter Williams, or Dr Mike Etheridge at BMR (Division of Petrology & Geochemistry).

Collaborative regional geochemical survey in Kalimantan: results of gold analyses

Since 1978 BMR has been assisting the Indonesian Geological Research & Development Centre (GRDC, a directorate of the Ministry of Mines & Energy) by training staff in regional geological and geophysical mapping within the Indonesia Australia Geological Mapping Project, funded jointly by the Indonesian Government and the Australian International Development Assistance Bureau.

Between 1978 and 1982 the project completed geological and gravity mapping of the western half of Irian Jaya. Between 1983 and 1986 the project undertook coverage of the province of West Kalimantan and adjacent parts of East and Central Kalimantan, extending for 700 km from the west coast to within 100 km of the east coast of the island of Borneo and covering roughly 150 000 km^2, or twice the area of Tasmania.

All geologists were asked to collect stream-sediment and pan-concentrate samples when the opportunity occurred, at suitable locations on geological traverses, resulting in a complete, though uneven, coverage (Figure 6). The results represent a wide range in volume of sediment sampled at the various sites; at best they are only semi-quantitative. They also largely reflect the distribution of small alluvial or, rarely, lode gold mines operated by the local people. Figure 6, however, provides a broader picture of gold mineralisation than would be obtained simply by plotting known gold workings.

Most gold occurs in rocks ranging in age from Early Cretaceous to Early Miocene. A little subeconomic alluvial gold appears to originate from Plio–Pleistocene volcanics, and some good shows in the northwest may originate from pre-Cretaceous rocks.

Five main geological settings

Gold appears to occur in five principal geological associations (Fig. 7):

- Early to Middle Cretaceous plutonic and volcanic plugs,
- sheared sedimentary or low-grade metamorphic rocks of the Cretaceous to Middle Eocene orogenic complex,
- base of the Late Eocene sandstone unconformable on the orogenic complex,
- Late Eocene volcanic rocks,
- Late Oligocene to Early Miocene sub-volcanic plugs.

The greatest concentration of high gold values is in the centre of the area, northeast of Sintang in the western part of the Muller Range, principally in sheared Cretaceous sedimentary rocks, including melange containing large masses of ultramafic and other exotic rock. The overlying basal Late Eocene sandstone of the Muller Range also yields considerable quantities of gold, including small nuggets with complex shapes, suggesting a secondary origin.

Locally sheared sedimentary or metamorphic rocks of the orogenic complex also yield gold in both the upper Kapuas and Ogah rivers. In the Murung and Busang rivers alluvial gold is shed from complex source areas comprising schist, Permian granite, sedimentary rocks of the orogenic complex, Late Eocene sandstone, and Oligo–Miocene plugs. On the Kelian River in the southeast RTZ is developing a prospect in Late Eocene volcanics.

Moderate to high gold values in the Schwaner Range in the southwest are located in a huge tonalite batholith where the gold is mined from quartz veins or washed from weathered rock. Gold north of the Ketungau River appears to be confined to Early Tertiary volcanic plugs piercing Tertiary sedimentary rocks.

Associated diamonds in alluvials

North and northeast of Pontianak lie the 'Chinese districts' where large quantities of primary and alluvial gold were produced in the late 19th century. The eastern group of high gold values here represents alluvial deposits which also yield diamonds; the diamonds are probably derived from Early Tertiary sandstone at the head of the Landak River. Across the border in Sarawak gold is mined from Cretaceous limestone intruded by Tertiary granite.

Gold values extending south of the Sambas River, near the west coast, are associated with various Cretaceous or earlier, basic to acid igneous rocks. Between Sanggau and the Ketungau River, and in the subdued western end of the Schwaner Range, terrain with favourable geology has low relief and the absence of gold values indicates only that very few samples were taken here.

New tectonic map of the Tasman Fold Belt System

This project was begun in late 1982 when the Director, BMR, wrote to all State Government Geologists and Heads of university geology departments suggesting that a map at 1:2.5 million scale be compiled.

The map (to be derived from an initial 1:1 000 000 scale compilation) spans from the beginning of the Adelaidian to the Cretaceous and includes the eastern Australian orogenic belts and their covers and the Adelaide Fold Belt and Stuart Shelf. Its purpose is to depict successive assemblages of rock units, each corresponding to a major stage in the region's tectonic evolution.

For each 'stage assemblage' the map will show regional variations in tectonic environment (deep-marine, shallow-marine, and continental) by varying the intensity of the stage time-range colour — darkest for deep-marine, lightest for continental. The lithofacies will be subdivided into quartzose, quartzo-feldspathic, volcaniclastic, or volcanic; the last two are further broken down into felsic, mafic, etc. Igneous intrusives are divided into those which were, or were not, comagmatic with nearby volcanics, and extrusives into those that did or did not shed into adjacent penecontemporaneous sediments. Lithofacies will be indicated by pattern symbols overprinted on the stage time-range colours.

The map and accompanying text are due for publication in 1989.

For more information contact Mr David Palfreyman at BMR (Special Projects & Geoscience Services Branch).

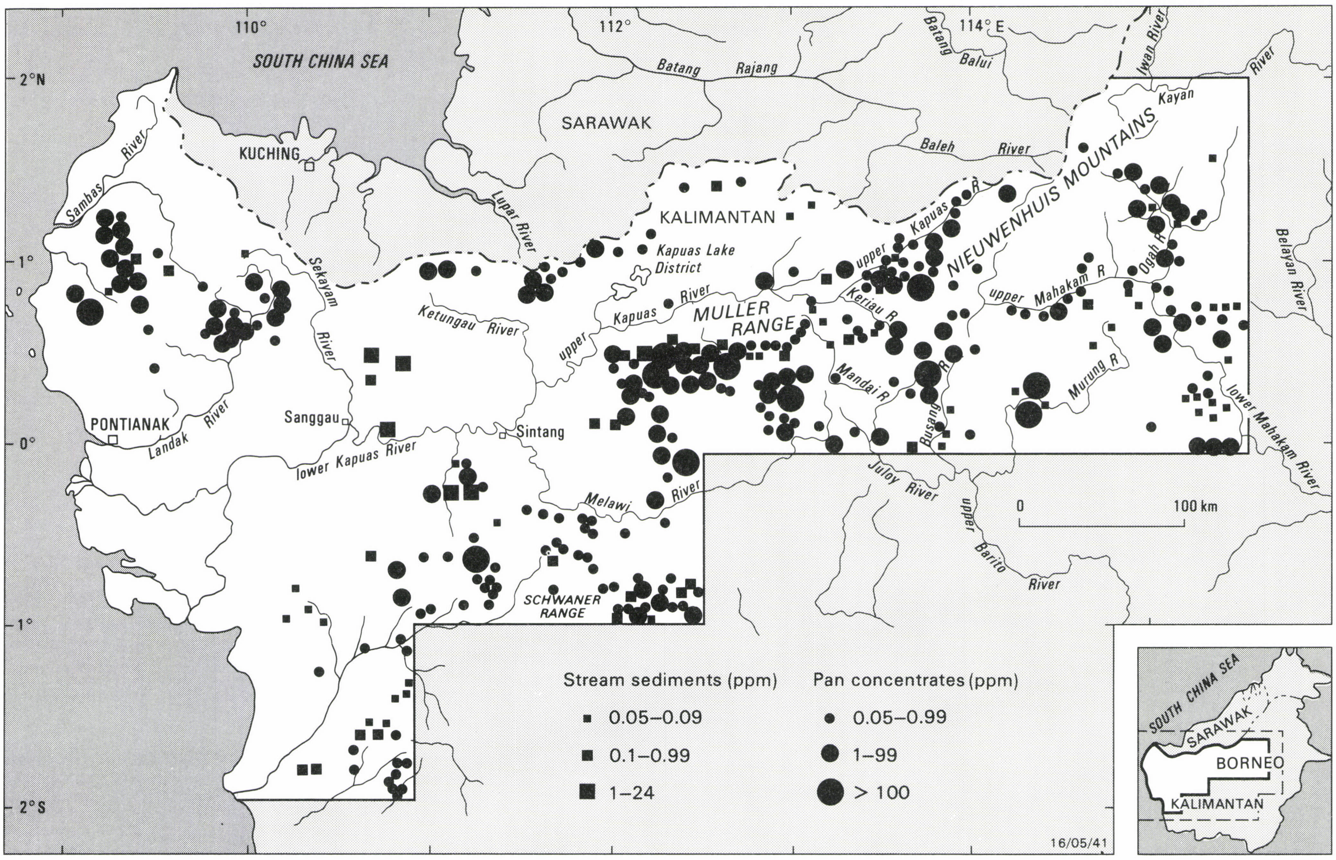


Fig. 6. Localities and gold values (ppm, semi-quantitative) for samples collected during the joint mapping project in Kalimantan.

Alluvial gold as very small particles

For sor. ɛ locations, useful gold values in stream-sediment samples are not reflected in pan-concentrate results, since much of the alluvial gold in Kalimantan occurs as very small particles that are difficult to recover. For the same reason, many pan-concentrate samples showing only one or two small colours of gold returned surprisingly high values on analysis.

The common occurrence of detrital gold in basal Late Eocene sandstone indicates that at least one episode of gold mineralisation was pre-Late Eocene. The association of gold with Late Eocene and Late Oligocene to Early Miocene volcanic and sub-volcanic rocks shows that gold continued to accompany the emplacement of igneous rocks in Kalimantan at least until Early Miocene times.

Associations of gold variously with mercury, antimony, or arsenic have been noted in the field and in plotting the geochemical results. Values of other metals are generally low throughout the area investigated, particularly silver, copper, lead, and

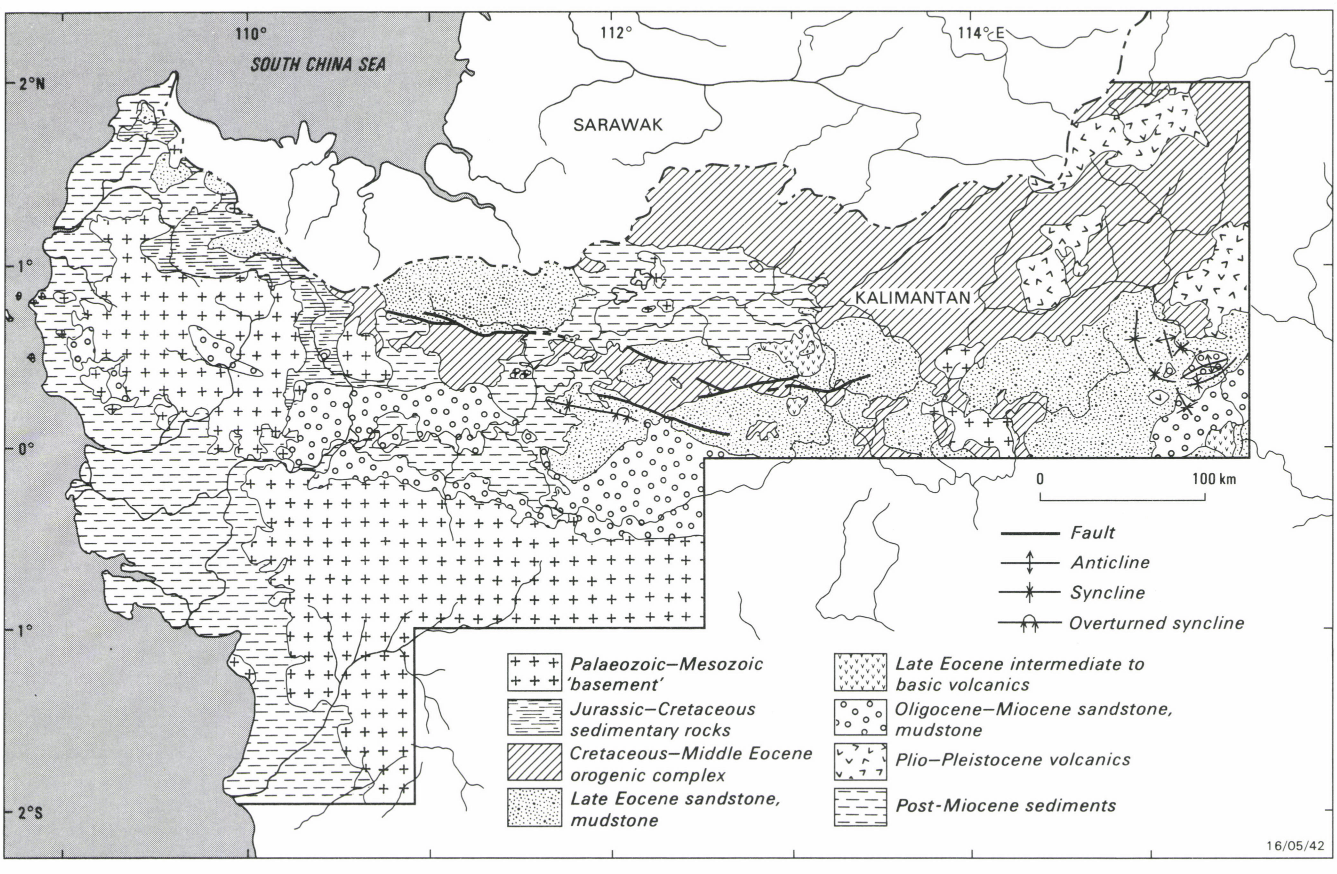


Fig. 7. Geology of area shown in Figure 6 (after Pieters, Trail, & Supriatna, 1987: *Proceedings, 16th Indonesian Petroleum Convention. Indonesian Petroleum Association,* 291–306).

zinc. Uranium, thorium, and cerium are significant in places, particularly in the more alkaline granitic rocks in the southwestern extension of the Schwaner Range.

The wide range of ages and rocks associated with the gold strongly suggests that the small-scale geological mapping has provided only the broad picture and that much more research must be done to determine more precisely the origins of the widespread gold in Kalimantan. In structural terms, for example, there are indications that gold may occur in both detachment horizons and normal faults. (Published with the permission of the Director, GRDC.)

Some results of the collaborative surveys in both Irian Jaya and Kalimantan are available in published form or as open-file reports at GRDC, Jalan Diponegoro, 57, Bandung, Indonesia; these may be discussed with Dr Rab Sukamto and Mr Sam Supriatna at GRDC, and Mr David Trail and Dr Peter Pieters (BMR) in Bandung at Jalan Cilaki, 49, phone (022) 72103. Information on the project can be obtained in Australia from Mr John Casey at BMR (Special Projects & Geoscience Services Branch).

Biomarker research and its application in petroleum exploration

Hydrocarbon biomarkers are being increasingly used to determine the geological history of a petroleum deposit and have application in the determination of thermal history, oil–oil and oil-source correlation and in recognition of altered oils. BMR is actively engaged in identification of new hydrocarbon biomarkers and their application in petroleum exploration.

What are biomarkers?

Sedimentary rocks record a wide variety of ancient environments and are hosts for the fossilised remains of the living creatures which populated those habitats. The bulk of biomass is, however, composed of microorganisms, comprising bacteria, algae and fungi. Most of these are without skeletal tissue and have little chance of preservation in a recognisable form, except in very favourable circumstances. Microbes may, however, leave a record of their presence through the modified but identifiable residues of the lipids which formed their cell membranes. Many higher plants also leave chemical residues which once constituted their cuticular waxes, resins, and essential oils. These molecules, which are mostly preserved in the form of hydrocarbons, are known as chemical fossils, or biomarkers.

Chemical fossils occur in all organic-rich rocks and petroleums. They do not represent the remains of an individual organism in the same way as a shell or a bone but rather a 'brew' comprising the residue of an entire community. Such a mixture will include the relics from the original primary producers or photosynthesisers, as well as the subsequent waves of grazing or heterotrophic organisms beginning with meiofauna, protozooans, fungi, and bacteria which use oxygen, followed by anaerobes such as sulphate-reducing bacteria and finally by methanogens. If sunlight persists to depths where the waters become anaerobic then the photosynthetic bacteria may be important community members.

The usefulness of biomarkers lies in the recognition of systematic chemical structure features which can be related to specific molecules in the precursor organism. Primitive as they are, microbes have continued to evolve from their earliest appearance about 3500 million years ago, giving rise to distinctive and recognisable chemical components analogous to the morphological features that allow us to distinguish shells from insects or fish, etc.

New techniques for biomarker detection

The complexity of the mixtures of naturally occurring hydrocarbons, and the low concentrations and structural specificity of the molecules of interest present formidable challenges to the analyst. Gas chromatography and mass spectrometry (GC/MS) continue to be the mainstay analytical methods in organic geochemistry. Newly available aluminium coated capillary columns extend the upper temperature limits and consequently the molecular size of analysable compounds. Tandem mass spectrometers for MS/MS and GC/MS/MS are being increasingly employed to refine the specificity of the measurements and this results in significantly lower detection limits and higher accuracy in quantitative measurement. A further major advance and to be generally available in the near future is the carbon isotope GC/MS which will facilitate determination of the $\delta^{13}C$ measurement for individual hydrocarbons in an oil or sediment extract, adding a complete new dimension to biomarker profiles. UV/VIS spectrophotometers continue to be the most sensitive detectors for high performance liquid chromatography (HPLC), restricting analyses to those compounds which absorb in these wavelengths but providing many new applications in the study of aromatic hydrocarbons and porphyrins.

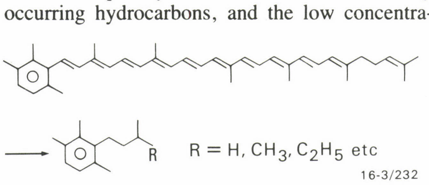


Fig. 8. Chlorobactene, a photosynthetic pigment from the green sulphur bacteria (*Chlorobium* sp.), and its fossil hydrocarbon derivatives from petroleum.

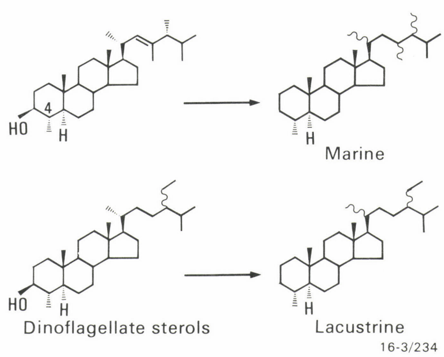


Fig. 9. Two distinctive 4-methyl sterols from the lipids of dinoflagellate algae and their fossil hydrocarbon derivatives.

Biomarkers as thermal indicators

Some of the most significant recent advances in biomarker chemistry are in the use of the ratios of key molecules to determine the thermal history of a sediment. Research into the formation and subsequent isomerisation of aromatic compound classes such as methylnaphthalenes, methylphenanthrenes, and alkylbiphenyls has identified changes which are effected more by time than by temperature and vice versa. This then opens the possibility of quantifying both upper temperature limits and heating rates, data which in turn can be applied in basin modelling studies. A new source rock maturity indicator for marine sediments based on an HPLC analysis of porphyrins has recently been identified, allowing unequivocal recognition of the generation status of a particular source interval.

Biomarkers as palaeoenvironmental and biostratigraphic indicators

Continuing improvements in understanding the chemical structures of new classes of biomarkers leads to new indicators for palaeoenvironmental reconstruction and oil–source correlation. A recent example arising from research by the BMR group is the tracing of the origins of a homologous series of trimethylalkylbenzenes (Fig. 8) found in certain oils and source rocks to their source organism, *Chlorobium* sp., by a combination of their chemical structures and carbon isotope signatures. *Chlorobium* sp., or green sulphur bacteria, require both low light and anoxic, sulphide-rich waters for growth, thus indicating a quiet, stratified marine water body for the depositional environment of the source rock. In another BMR study, the distributions of C_{30} 4-methyl sterane isomers, which are known to be produced by dinoflagellate algae, showed dramatic differences between marine oils/source rocks and those occurring in sediments deposited in deep eutrophic lakes (Fig. 9).

The C_{30} 4-methyl steranes described above appear to be largely confined to sediments of Mesozoic and Tertiary age. Continuing BMR research has shown that a previously unknown class of steroids with methyl substitution at positions 2- or 3- of ring-A predominates in sediments of Proterozoic and Palaeozoic age (Fig. 10). Research associated with BMR projects on potential Proterozoic source rocks has led to the recognition of distinctive patterns of bacterial triterpanes and branched alkanes. Carboniferous and younger rocks with input of terrestrial higher plants contain distinctive diterpenoid hydrocarbons. These are just a few examples of biomarkers which show restricted distribution in time and have the potential to confine the possible age of oils and indicate where the age of reservoir and source rock may be significantly different.

Biomarkers for oil–oil and oil–source correlations

The advent of GC/MS/MS has meant that we can visualise distribution patterns for specific classes of biomarkers unaffected by interference from other components in the oil and can detect

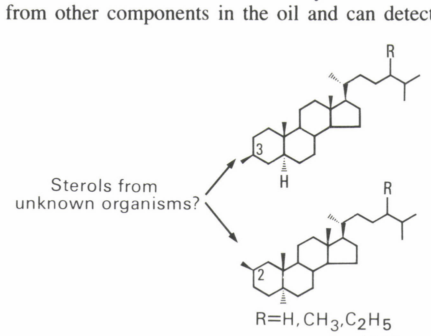


Fig. 10. Steranes with unprecedented methylation patterns and having no known sterol counterparts. They appear to be most abundant in rocks of Palaeozoic age and may be a useful biostratigraphic marker for rocks of this age.

compounds which up to now were screened by co-eluting components. The value of determining carbon isotope signatures of individual hydrocarbons has also been demonstrated for delineating their source organisms. Sophisticated methods exist to separately identify changes in hydrocarbon composition of oils arising from thermal effects and from biodegradation. A combination of all these advances is leading to widespread and confident use of biomarkers to relate oils to each other and to their original source rocks. Together with improved recognition of the factors affecting conversion of kerogen to petroleum and its primary and secondary migration, organic geochemistry and particularly biomarker studies are going to be increasingly useful tools for the explorationist.

BMR organic geochemistry research

The principal thrust of the BMR organic geochemistry research is a thorough characterisation of the petroleum source rocks of Australia. Projects in their concluding stages have concentrated on Proterozoic and early Palaeozoic basins, the Toolebuc Formation (Cretaceous), and a general study of coals and non-marine sediments to identify criteria for source rock quality and the timing of oil generation. The Canning Basin and a selection of potentially important Palaeozoic and Mesozoic sediments will be the focus of new studies together with continuing work on the chemical characterisation of new biomarkers and the biology of their source organisms. The longer-term aim of these individual projects is the marriage of biomarker and other source rock data to the sedimentological and palaeoenvironmental setting of the host rocks, leading to predictive models of source rock distribution and characteristics in Australia. Explorationists are invited to collaborate in organic geochemical studies related to particular regional problems or specific exploration objectives in Australia.

For further information contact Dr Roger Summons or Dr Trevor Powell, at BMR (Division of Continental Geology).

Petroleum potential of the Clarence–Moreton Basin upgraded

The Clarence–Moreton Basin in southeastern Queensland and northeastern NSW contains Mesozoic sediments in part equivalent to oil-producing sequences in the Surat and Eromanga Basins to the west. BMR, together with the Geological Surveys of NSW and Queensland, has been studying the basin for the past four years. This has included a source-rock investigation with CSIRO and the University of Melbourne School of Earth Sciences. Mature, high-quality oil-prone source rocks have been identified, enhancing the basin's petroleum potential.

Until this study, little was known of the basin's source-rock potential in comparison with the Mesozoic oil-producing basins in eastern Australia. Four hundred samples of carbonaceous mudrocks and coals were examined by Rock Eval pyrolysis. Some of these were further subjected to (1) extraction and analysis of hydrocarbons, (2) organic petrographic analysis, (3) vitrinite reflectance measurement, and (4) elemental analysis and pyrolysis gas chromatography of kerogen isolates. Sampling concentrated on the Walloon Coal Measures and underlying units because younger formations crop out extensively and are not considered to have hydrocarbon potential.

Source rock abundance

Figure 11 shows the revised stratigraphic column and histograms of the abundance of potential source rocks. The first set of histograms shows that the Walloon Coal Measures contain the largest proportion of fine-grained facies; the second set shows that the Walloon shales and coals are the richest in total-organic-carbon (TOC), followed by the Koukandowie Formation. Other units contain some mudrocks but are low in TOC. The histograms are only a broad guide to source-rock abundance because mudrock facies are very variable in these non-marine units and sampling was biased towards organic-rich lithologies. They indicate, however, that carbonaceous shales and coals are abundant not only in the Walloon Coal Measures but also in the Koukandowie Formation.

Source-rock quality

Rock Eval pyrolysis data show that the coals and carbonaceous shales are at least as rich in oil-prone terrestrial organic matter as their contemporaneous equivalents in the oil-producing Eromanga Basin, and in some cases richer. The Walloon coals are renowned for their high hydrogen content, and in petroleum source-rock terms are classified as Type II/III organic matter (Fig. 12). These hydrogen-rich coals are not confined to the Walloon Coal Measures but occur throughout the Clarence–Moreton sequence. The organic matter in the carbonaceous shales ranges from superior to inferior in source rock quality to that in the coals; it ranges from Type III to Type II, the better quality organic matter occurring as cannel coal.

Source rock maturity and burial history

Vitrinite reflectance and Tmax data (from Rock Eval) indicate a progressive eastward increase in source-rock maturity. The isoreflectance map for the Walloon Coal Measures (Fig. 13, overleaf) shows that they are immature in the western part of the basin but reach oil maturation levels in the south-central part. They are overmature along the eastern basin margin. The underlying Raceview Formation is in the oil generating zone where the Walloons are immature, and overmature where the Walloons are in the oil zone.

Fission track ages of apatites from surface samples analysed by the Fission Track Research

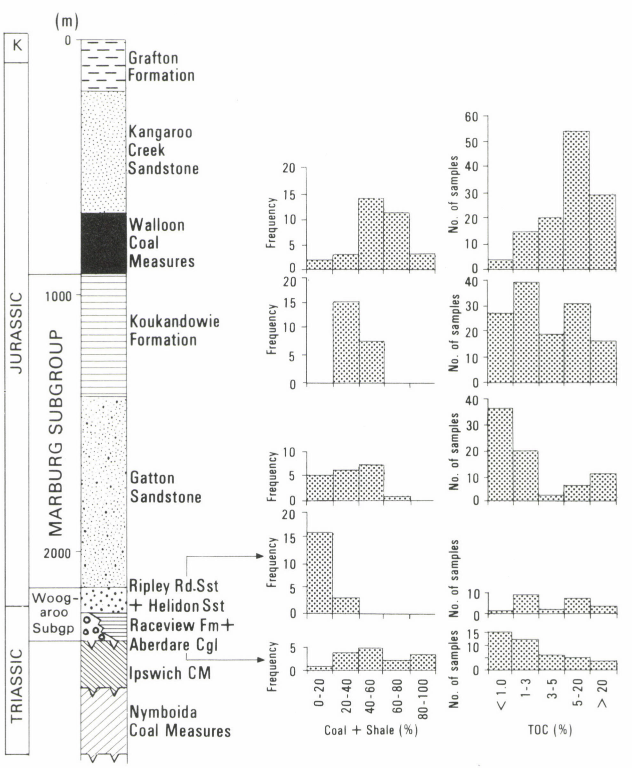


Fig. 11. Revised stratigraphy of the Clarence–Moreton Basin, and petroleum source rock abundance. The histograms show the percentage of shale + coal in each unit versus the number of subsurface sections, and total-organic-carbon versus the number of samples.

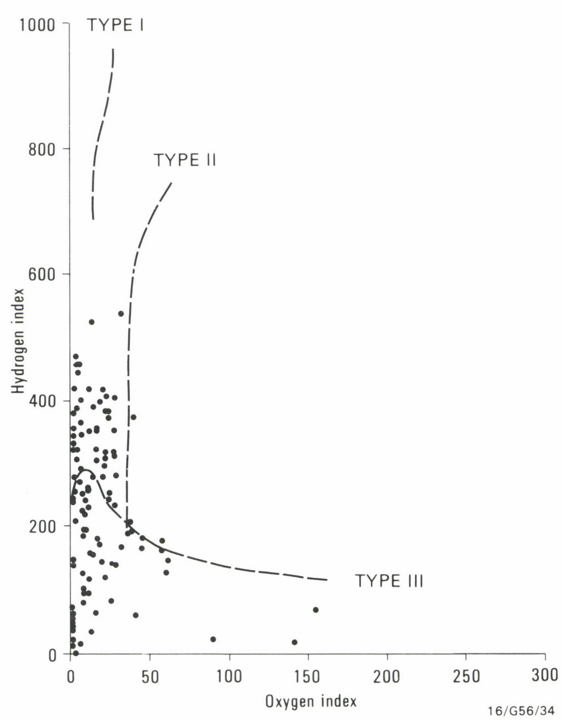


Fig. 12. Oxygen index versus hydrogen index from Rock Eval analysis of coals and shales from the Walloon Coal Measures. The kerogens are mostly Type II and III, i.e. oil-prone.

Unit of the University of Melbourne School of Earth Sciences show higher basin temperatures in the east: original rock ages in the west give way to progressively younger reset ages in the east. These reset ages, which are in the range of 50 to 100 Ma, suggest that maximum temperatures and burial depths were reached in the Late Cretaceous.

Subsidence curves show greater burial depths and more rapid uplift in the east than in the west. Mainly near the State border, the sequence is intruded by mid-Tertiary igneous rocks.

Conclusions

- Good quality, oil-prone source rocks are abundant, particularly in the Walloon Coal Measures and Koukandowie Formation.
- The western part of the basin has low potential: source rocks are less abundant in the units that are mature for hydrocarbon generation.
- The most prospective area for oil is the western and central part of the basin in NSW where the abundant Walloon and Koukandowie coals and shales are oil-mature. Pre-Koukandowie strata are overmature in this area.
- The eastern side of the basin in NSW is prospective for dry gas because the Walloon Coal Measures are overmature.
- Maximum hydrocarbon generation was in the Late Cretaceous.

For further information, contact Dr Trevor Powell, Mr Allan Wells, or Dr Phil O'Brien at BMR (Division of Continental Geology).

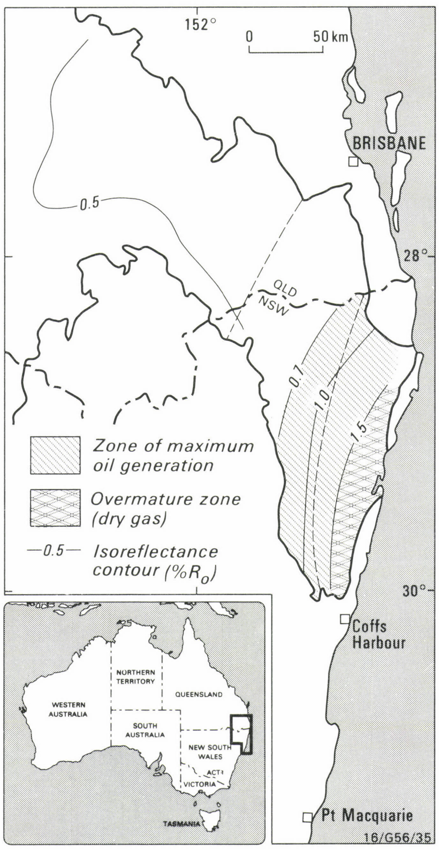


Fig. 13. Contour map of vitrinite reflectance for the Walloon Coal Measures showing zones of maximum oil generation and of overmature kerogen. The dashed lines delineate zones of fission track age resetting of apatites. East of the western line, apatite ages become younger than their depositional age; east of the eastern dashed line they are extensively reset.

Professor Rutland honoured

Emeritus Professor Roye Rutland (above), Director of BMR, was appointed an Officer of the Order of Australia (AO) in the 1988 Australia Day Honours List.

Professor Rutland has made numerous contributions to geoscience research, and to national and international geoscience organisations and programs.

Since taking up appointment as Director of BMR in 1980 Professor Rutland has restructured the organisation with its overall responsibilities for strategic geoscientific research, petroleum and mineral resource assessment, and the development of geoscience databases. This period has seen the introduction of a career structure based on merit promotion for research scientists, and the acquisition of new equipment and facilities.

Major initiatives which he has set in train have included a comprehensive study of Australia's Continental Margins, which has involved the chartering of a research vessel, the *Rig Seismic*, and the establishment of BMR's Australian Seismological Centre, with the dual role of monitoring nuclear explosions worldwide and monitoring and studying earthquakes in and around Australia.

At the national level, Professor Rutland's contributions have included membership of the Australian Research Grants Committee and the National Committee for Solid Earth Sciences, Australian Academy of Science. He was elected a Fellow of the Australian Academy of Technological Sciences in 1983, and is an Emeritus Professor of the University of Adelaide.

Internationally, his current or recent involvements include membership of the IUGS/UNESCO Scientific Committee of IGCP (Chairman 1984–85), the Circum-Pacific Council for Energy & Resources, the IUGS Research Advisory Board, the IUGS Commission for Tectonics, and serving as Vice-Chairman of Working Group 2 of the International Lithosphere Project.

Bass and Otway Basin Study Folios

The results of the Bass and Otway basins studies which have been carried out as part of the Continental Margins Program have been drawn together for public release in the form of a Bass Basin Study Folio and an Offshore Otway Basin Study Folio to be published later this year.

These large-format folios present regional results and data and include a text giving an overview of the study and results along with structural maps and structural and stratigraphic analyses, reduced multichannel seismic reflection sections, geohistory analyses, dredge, heatflow and geochemistry results and seismic inversions, depending on the project; and appendices detailing hydrocarbon discoveries within the basins and available well and seismic data. All BMR data — both digital and analogue record sections and maps — can also be obtained at full scale from BMR.

The Continental Margins Program, begun in 1984, aims to provide framework data and analyses relevant to hydrocarbon exploration of Australian offshore basins. The folio series is the intended medium for comprehensive overviews of the program. Folios will be obtainable through the BMR Copy Service.

For further information on the content and scope of the Study Folios, contact Dr David Falvey or Dr Paul Williamson at BMR (Division of Marine Geosciences & Petroleum Geology).

ISMI–cobalt: a new report on world cobalt resources

An international working group of Earth scientists has released a summary report on world resources of cobalt. The report, entitled 'International Strategic Minerals Inventory summary report — cobalt' ('ISMI–cobalt'), was prepared as a co-operative data collection effort by Earth-science and mineral resources agencies in Australia (BMR), Canada, West Germany, South Africa, UK, and USA.

ISMI reports are designed to be of benefit to policy analysts and geologists, making available non-proprietary data, including characteristics of major deposits of strategic mineral commodities, for policy considerations in relation to short-term, medium-term, and long-term world supply.

'ISMI–cobalt' provides an overview of the supply aspects of cobalt (Part 1) and a summary statement of the data compiled (Part 2). Part 1 discusses the geology of cobalt and the distribution of cobalt resource provinces and their geologic type; provides a breakdown of resources by geologic deposit type and economic classification of country (modified from the World Bank classification); and gives an analysis of world production by country, economic classification of country, and geologic deposit type. Part 1 concludes by outlining a cobalt supply scenario for the next few decades. Part 2 tabulates such data as deposit or district location, geology, mineral production, and resources.

'ISMI–cobalt' is the sixth, and most recent, in a series of reports having a similar format; reports already issued cover platinum-group metals, nickel, manganese, chromium, and phosphate. Work is proceeding on similar reports for graphite, tin, titanium, tungsten, vanadium, and zirconium. BMR's Resource Assessment Division has provided the data on Australian deposits and reviewed data for other countries for each of these reports. BMR's Mr Roy Towner is the chief compiler of 'ISMI–titanium' and 'ISMI–zirconium'.

For more information contact Mr Ian McLeod at BMR (Resource Assessment Division)

Landsat Thematic Mapper: a valuable geological tool, but . . .

In July 1982, ten years after the launch of the first Landsat satellite, NASA launched Landsat-4 which heralded a new phase of earth resources sensing. Besides the conventional 4-band multispectral scanner (MSS), Landsat-4 also incorporated the more advanced Thematic Mapper (TM) scanner. All seven sensing bands of the TM have more spectral, radiometric, and geometric sensitivity than its 4-band predecessors, and thus provide increased sensing capability. The aim of this article is to sound a note of caution with respect to the digital processing of TM data, particularly those techniques involving band-to-band manipulation of raw data.

TM was the first satellite system with a band incorporated for geological purposes. Band 7 (2.08–2.35 micrometres), is particularly sensitive to absorption of electromagnetic radiation by clay, carbonate, and some mica minerals. Based on studies conducted in the USA, the TM Band 7 wavelengths offered particular promise for locating areas of hydrothermal alteration. Since 1986 Landsat TM data have been recorded in Australia via the ALS/CSIRO/AMIRA Signal Processing Experiment.

Band to band manipulation of satellite scanner data such as 'ratioing' (i.e. dividing one band digital number by another band digital number) has become a common form of raw data enhancement and for processing to extract specific thematic information from Landsat MSS data. A more significant application is its potential as a processing method to identify specific geological materials based on their spectral properties. Several 'standard' ratio combinations have evolved as basic detection methods for particular minerals. However, the successful application of these approaches necessitates some form of preprocessing of the raw satellite data.

Table 1. Comparative spectral bands of the Landsat MSS and TM scanners (micrometres)

Landsat 1,2,3: MSS		*Landsat 4,5: TM*	
Band No.	*Wavelength*	*Band No.*	*Wavelength*
4	0.5–0.6	1	0.45–0.52
5	0.6–0.7	2	0.52–0.60
6	0.7–0.8	3	0.63–0.69
7	0.8–1.1	4	0.76–0.90
		5	1.55–1.75
		7	2.08–2.35
		6	10.4–12.5

Raw radiance data recorded by the satellite scanners comprise reflected radiation and additive and subtractive components representative of the atmosphere through which they pass. Thus the raw scanner signal, which is ultimately contaminated with various other electronic signals, does not represent a true spectral reflectance value. Combined effects of radiance, gain and offset settings, and different relative band sensitivities of the raw data can seriously affect digital manipulations such as ratioing.

Problems associated with attempted spectral interpretation of raw radiance data as recorded by Landsat scanners are not new and have been reported by Australian and overseas authors. Despite this, the raw radiance data are frequently regarded, in digital manipulation, as a form of spectral information. With Landsat MSS data this approach has resulted in some acceptable rock discrimination, but the more sensitive TM data need to be treated with caution.

The problem is illustrated in Figure 14 which shows 6-point extrapolated curves of the reflectivity of a volcanic rock type as measured on the ground (dashed line), and equivalent band radiance values from the raw TM data (solid line) as recorded by the satellite over the same rock type.

It is apparent that ratio manipulations on such raw data will produce erroneous results, the magnitude of the error being band-dependent. Thus before spectral signature processing can be reliably performed, the raw data (solid curve) must be corrected to the equivalent values of the dashed curve. Successful TM ratio results have been obtained by BMR (such as accurate discrimination of mafic and ultramafic rock types) after conversion of the raw radiance data to equivalent ground reflectance based on field spectral reflectance measurements at selected ground sites. Other preprocessing techniques can be applied to improve the raw data prior to band-to-band manipulation.

The differences between raw radiance values and spectral reflectance values appear more pronounced with TM data than has been previously experienced with MSS. One aspect of current BMR remote sensing research is the investigation of possible techniques for direct calibration (conversion of raw radiance data to reflectance) of TM data recorded over the Australian arid zone.

It is not the intention of this note to deter users, or potential users, from using TM data. Enough examples of different geological applications have been investigated by BMR to show that TM data can have significant cost-effective applications in a variety of field programs. From what we have seen it is the best geological remotely sensed spectral data yet recorded by any satellite system, but selectivity is required with the processing techniques employed, especially if band-to-band manipulations are being contemplated.

For further details contact Mr Colin Simpson, or Mr Taro Macias at BMR (Division of Petrology & Geochemistry).

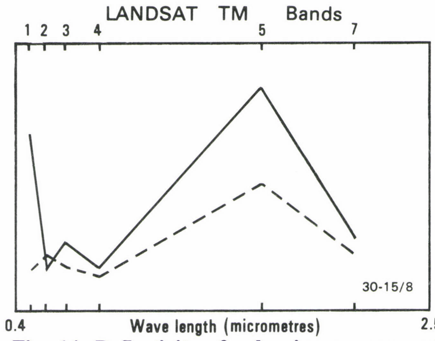


Fig. 14. Reflectivity of volcanics as measured on the ground (dashed line) and equivalent TM raw radiance values (solid line).

Brave new world in cartography

This month BMR is scheduled to let a contract for the first stage of a new, state-of-the-art, high-resolution, automated map production system. The conventional environment of ink pens, light tables, and opaquing brushes will be replaced by map publishing software, a laser photoplotter/scanner system and interactive graphics terminals, enabling BMR to retain its place as a world leader in geoscientific cartography.

BMR's vast collection of map separates at various scales and projections is becoming brittle with age, and keeping it up to date by hand-revision of boundaries, name changes, etc. on each map separate is become prohibitively time-consuming. The new system will combine laser scanning hardware and VAX*-based scanning software, to provide complete data capture, vectorisation, editing, and plotting capabilities. The development of a digital cartographic database will enable BMR's Cartography Section to meet specific customer requests by accessing any part of it and manipulating content, symbology, text fonts, scale, projection, or design without actually changing the master design file.

Capturing the data

The high-resolution scanner will convert hardcopy map data to digital format rapidly and accurately. It can handle media up to 1 metre x 1 metre and scan paper or stable-base materials at 12.5, 25, 50, 100, or 200 microns (2000, 1000, 500, 250, or 125 pixels) per inch, to a positional accuracy of less than 2.5 microns per inch. Once scanned, the data are converted to vectors or polygons for use as a digitising backdrop. Text and symbols are recognised, and specialised editing commands smooth the process of conversion. Using interactive graphics terminals and mapping software, cartographers will update existing map data, adding information as required.

* VAX is a trademark of Digital Equipment Corporation.

New tools

Traditional map printing may require up to 40 overlays, each containing a component of the final map; using positive artwork, the photographer makes masks and open-window negatives to hold out ink where only a single tint should print. In the final stages, separates are sandwiched with dot screens to create a set of four composite positives. The new customised software replaces this entire darkroom process. With perfect registration assured, the cartographer can concentrate on the creative aspects of map publishing by simply building a specification table to define the map, e.g. creating digital masks, text haloes, and banded area tints, reversing symbols or text (white text on a coloured area), customising colours, etc.

Using the laser photoplotter capability of the scanner, the cartographer displays the new map at the workstation before plotting any film positives. This eliminates costly trips to the darkroom for colour proofs to verify masking, registration, and content quality. Instead, softcopy proofing replicates the map on screen so that changes can be made before final plotting. For final editorial approval, the software includes the option to generate a hardcopy coloured map on an electrostatic plotter.

Print-ready output

After final clearance for publication, the scanner plots film positives for the standard four-colour printing process (cyan, magenta, yellow, and black). It can also produce negatives for other multicolor lithographic printing processes. Screens are automatically composited, to plot each positive in a single pass, producing a complete set of film positives ready for lithographic platemaking.

BMR's new system will be an end-to-end digital map production system consisting of integrated digitising, attribution, editing, design, symbolisation, and colour separation tools. It is a very exciting system, and new applications are being discovered every day.

For more information contact Mr John Hillier at BMR (Special Projects & Geoscience Services Branch).

Kimberlites and diamonds in China

Advances in diamond research in the past decade have had a major impact on diamond exploration concepts and strategies. Two of the most important have been the recognition that lamproite as well as kimberlite may host economic concentrations of diamond (see *BMR Research Newsletter* 1 (1984), 10), and the demonstration, on the basis of isotopic dating of inclusions in diamond, that diamonds are mantle xenocrysts merely transported in their volcanic host (see *BMR Research Newsletter* 6 (1987), 15–16).

It is against this background that the **International Seminar on Kimberlite,** organised and hosted by the Chinese Academy of Geological Sciences of the Ministry of Geology & Mineral Resources (CMGMR), was held in Beijing, China from 1–10 August 1987. Delegates included 12 invited speakers from Australia, South Africa, USA, West Germany, UK, and Canada, and some 90 geoscientists from the Institute of Mineral Deposits in Beijing and the geological teams of the provincial bureaux of the CMGMR. The seminar was followed by an excursion to the diamondiferous kimberlites in Fuxian County, Liaoning Province, and Mengyin County, Shandong Province. Dr Lynton Jaques of BMR attended at the invitation of the seminar convenors, under the scientific agreement between CMGMR and BMR.

Much of the program was devoted to the invited review papers covering most aspects of diamond research and exploration. Topics included: (1) exploration strategies and management, (2) exploration area selection, (3) modern exploration techniques with emphasis on the use of indicator mineral chemistry, mineralogy/petrology and geochemistry (including isotopes) of kimberlite/lamproite and mantle xenoliths, (4) volcanism and diatreme formation, and (5) the physical and chemical characteristics of diamond and its inclusions. A detailed review of the geology and evaluation of the Argyle and Ellendale diamond deposits, WA, was also presented. Chinese presentations included descriptions of new discoveries of kimberlite, lamproite, and lamprophyre (some diamondiferous) from Guizhou, Hubei, Hebei, Shanxi, and Sichuan Provinces, and results of diamond exploration in Anhui and Jiangsu Provinces. Panel discussions were held concerning future directions for diamond research and exploration in China. These and other informal discussions showed the continued importance of indicator minerals in reconnaissance exploration in most countries. The discussion also highlighted the greater emphasis placed in Western countries on (1) comprehensive databases using the mineral chemistry of indicator minerals obtained by electron microprobe to discriminate diamondiferous from non-diamondiferous sources, and (2) airborne and ground geophysical methods using modern highly sensitive instruments.

Both the seminar and the excursion were well organised and successful in enabling greater exchange of information between Chinese scientists and their foreign counterparts. It is hoped that the scientific interaction generated by this seminar will continue and will be followed by other meetings and increased participation by China in international meetings.

Chinese diamond deposits

A concerted exploration program by the Chinese Government since the early 1960s has resulted in the discovery of several diamond deposits and a large number of kimberlites and related intrusions (Fig. 15). There are at least six districts producing diamonds: four are alluvial and two contain primary sources hosted in kimberlite — Changma in Mengyin County (6, Fig. 15) and Toudaogou in Fuxian County (2, Fig. 15). The alluvial deposits are in the Tancheng and Linshu areas of Shandong Province (7,8, Fig. 15), Yuanshui River (Changde County) in Hunan Province (10, Fig. 15), and Jingshan in Hubei Province (9, Fig. 15). Alluvial diamonds are also known from the Bachu area in extreme northwestern China (Xinjiang Autonomous Region), and from Anhui Province.

China's diamond production is thought to be about 300 000–500,000 ct/yr, with 15–17% of the stones being of gem quality (Green, 1985: *China Business Review*, May–June 1985, 13–15). This falls well short of China's needs for both its cutting and polishing plants and for its industrial requirements and thus requires the importing of some 150 000–200 000 cts of gem-quality rough and 300 000–400 000 cts of industrial stones.

The Binhai mine in the Toudaogou field (Fuxian County: 2, Fig. 15), discovered in 1971, is the most important source of relatively large high-quality gem diamonds. Production is from a kimberlite pipe which averages some 2 cts/m^3 and from associated alluvial deposits which, although lower grade, produce very good quality stones. Most of the Toudaogou stones are colourless or only lightly coloured octahedra and more than 50% are of gem quality. The largest diamond produced to date is about 40 cts. In contrast, the Changma (Mengyin County: 6, Fig. 15) and Changde (10, Fig. 15) deposits produce mostly industrial stones. The Changma deposits were discovered in 1965 and diamonds (20% gem) are currently being mined from kimberlite pipes in a large open pit — Shengli (Victory) No. 1. The largest stone recovered from the Mengyin kimberlites is 119 cts. Larger stones (up to 159 cts) have been recovered from the nearby Chengjiafu alluvial deposits in Tancheng County.

Kimberlites and related rocks in China

According to Hu & others (1986: *4th International Kimberlite Conference, Extended Abstracts,* 121–123) and new information presented at the Seminar, kimberlites are now known from eight provinces in China. Most, including the three best known occurrences — Mengyin, Fuxian, and Hebi — are in the Precambrian Sino–Korean Craton (Platform) which comprises Archaean and Early Proterozoic crystalline basement overlain by mid–late Proterozoic, Cambro–Ordovician, Permo–Carboniferous, and Meso–Cenozoic platform-cover sediments.

The Fuxian kimberlites lie to the west of the Jinzhou fault separating upwarped Archaean granulites to the east (Xinjing upwarp) from Proterozoic and Cambro–Ordovician sediments (Fuzhou downwarp) to the west. The Toudaogou field includes more than 10 pipes and dykes strongly elongated NNE, where three faults intersect. The kimberlites are considered to be Early Devonian (about 400 Ma, based on K–Ar dating).

The Mengyin kimberlites (about 500 Ma, Ordovician, based on K–Ar dating) are on the Western Shandong anticline, in Precambrian basement overlain by Cambro–Ordovician limestone, in a zone that was uplifted and eroded in the Mesozoic and Quaternary. Of the three main fields — Changma, Xiyu, and Poli — only the Changma and Xiyu kimberlites contain economic diamond. The Changma field comprises two pipes and eight dykes in a belt some 14 x 2 km and the Xiyu kimberlites occur as eight pipes and 14 dykes; the distribution is controlled by NNW and NNE faults.

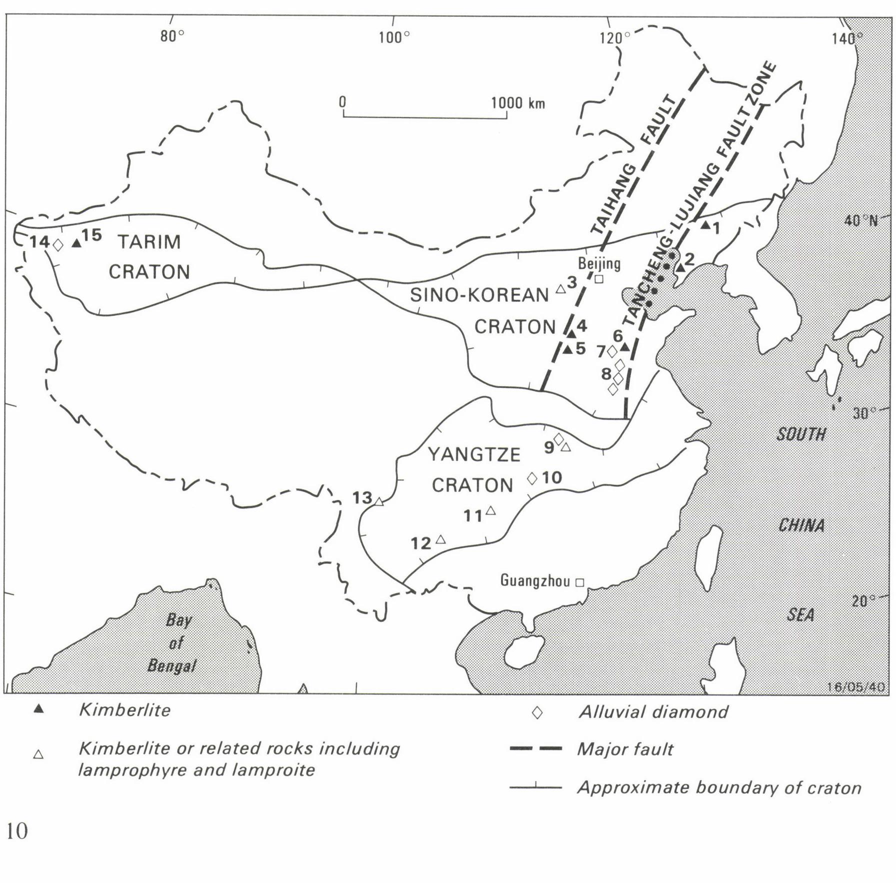


Fig. 15. Distribution of diamonds, kimberlites, and related rocks in China with respect to the Precambrian cratons (modified after Hu & others, 1986: *Fourth International Kimberlite Conference, Extended Abstracts,* 121–123, and using information presented at the International Seminar on Kimberlite, Beijing, 1987). Counties/areas: 1 Tonghua, 2 Fuxian, 3 Yinxian, 4 Shexian, 5 Hebi, 6 Mengyin, 7 Tancheng, 8 Linshu, 9 Jingshan, 10 Changde, 11 Zhenyuan, 12 SW Guizhou, 13 Panxi, 14 Hodian, 15 Bachu.

The Hebi kimberlites (5, Fig. 12), found in 1971 in the southern part of the Taihang uplift, comprise some 79 dykes and sills in a belt 20 km long and 6.5 km wide. They intrude Cambro–Ordovician platform carbonates but have not been dated.

Kimberlites (mostly dykes, some pipes) have since been found in Shexian County in SW Hebei Province (4, Fig. 15), in Yinxian County in Shanxi Province (3, Fig. 15), and at Tonghua in Jilin Province (1, Fig. 15). The Shexian and Yinxian kimberlites, which lack diamonds, lie at the margin of an upfaulted block. Diamonds and indicator minerals have been found in Sihong County (Jiangsu Province) and Sixian County (Anhui Province) near the Tancheng–Lujiang Fault Zone but their sources, believed to be local, have not been found.

Kimberlites and related alkaline ultrabasic rocks are also known from the Yangtze Craton, which comprises Archaean to Early Proterozoic basement rocks but is mostly covered by Sinian (Late Proterozoic) and younger (Paleozoic–Mesozoic) clastics and carbonates. The zone between the Yangtze and Sino–Korean cratons is occupied by the Qinling Fold Belt, a geosynclinal sequence deformed mostly during the Indosinian (Late Triassic–Early Jurassic) by collision of the two cratons. Devonian (~380 Ma) micaceous kimberlites and associated alkaline rocks including some resembling lamproites occur at the junction of the Jianhnan anteclise and upper Yangtze platformal folded zone in the Zhenyuan area of NE Guizhou Province (11, Fig. 15), and a much younger (80–90 Ma) suite of more than 80 intrusions (mostly dykes and sills with some pipes) of potassic low-TiO_2 lamprophyres occurs in SW Guizou (12, Fig. 15). In the Jingshan area of Hubei Province (9, Fig. 15) near the Qinling Fold Belt, potassic ultrabasic rocks occur as pipes, dykes, and sills, at least some of which are thought to be Ordovician (~450 Ma). To the southwest, in the Panxi area (13, Fig. 15), an Oligocene (~30 Ma) suite of more than 350 separate intrusions of potassic lamprophyre lies within the Cenozoic Panxi Rift Zone at the boundary between the E-W trending belt of Hercynian sediments of the Sankian Fold System and the western margin of the Yangtze Craton.

The Tarim Craton of Xinjiang Autonomous Region comprises Archaean and Early to Middle Proterozoic crystalline basement unconformably overlain by Sinian, Palaeozoic, and Mesozoic–Cenozoic platform cover. The kimberlite at Bachu (15, Fig. 15) contains low-grade, mostly small diamonds. Alluvial diamonds occur nearby at Hodian in glacial deposits; this may be the source of a hard mineral (diamond ?) reported in early (300 BC) records to cut the local jade.

These discoveries highlight China's potential for new diamond deposits, particularly in the Yangtze and Tarim Cratons. Further isotopic dating will lead to a clearer understanding of the relationship between craton formation and kimberlite emplacement, but the distribution of kimberlite and associated rocks appears directly related to basement structures. Many intrusions are in uplifted basement blocks, some in zones of crustal downwarping, and most are associated with ancient fundamental fractures such as the Tancheng–Lujiang (Tanlu) and Taihang Fault Zones. On a local scale, the distribution of kimberlites in individual fields is strongly controlled by smaller-scale structures (e.g. splay faults) associated with the deep lithospheric fractures.

For further information contact Dr Lynton Jaques at BMR (Division of Petrology & Geochemistry).

A possible joint Sino–Australian project in Xinjiang, China

From May–June 1987 an Australian team, with Chinese counterparts, carried out a feasibility study for a possible co-operative geological and geophysical project in the eastern Junggar region of Xinjiang Autonomous Region, northwest China, to provide a framework for mineral exploration. The Australian team — Dr D.H. Blake and Dr S-S Sun, BMR, and Mr R.J. Smith, Chief Geophysicist, CRA Exploration Pty Ltd — held discussions with officials and geoscientists of the Chinese Ministry of Geology & Mineral Resources (MGMR) in Beijing and the Xinjiang Bureau of Geology & Mineral Resources (BGMR) in Xinjiang, and took part in a 10-day field trip to the eastern Junggar region.

The feasibility study resulted from: (1) the Memorandum of Understanding (MOU) on geoscientific co-operation between Australia and China signed in Canberra in April 1983; (2) discussions between Ministers in Beijing in October 1984, aimed at expanding this co-operation; and (3) a four-member Australian Mission to China in August–September 1985, led by Professor Roye Rutland, Director, BMR, which recommended the eastern Junggar region of Xinjiang as an area which was prospective for non-ferrous metals and suitable for a joint comprehensive study. The cost of the comprehensive study, if it goes ahead, would be met by arrangements under the Australia/China Technical Co-operation for Development Program administered by the Australian International Development Assistance Bureau (AIDAB).

Tectonic framework

Xinjiang is a major producer of coal, petroleum, and gas, but has no large mines exploiting metallic minerals. It covers about 1 260 000 km², and consists of the following five major tectonic units (Fig. 16).

— *Altai Fold System* in the north: a belt of Ordovician to Carboniferous metasediments and metavolcanics intruded by Variscan (Late Palaeozoic) granites; several beryllium and rare-metal (tantalum, niobium, etc.) pegmatite deposits are associated with the granites.

— *Junggar Basin and Fold Belts:* a non-marine Mesozoic basin, containing major hydrocarbon and coal deposits, flanked in the east and west, respectively, by northwesterly and northeasterly trending fold belts formed of little-metamorphosed Palaeozoic sedimentary, volcanic, and intrusive rocks hosting copper, nickel, gold, chromite, molybdenum, tin, and graphite deposits.

— *Tien Shan Chain:* a series of east–west belts formed largely of early Palaeozoic rocks, but including some of Archaean and Proterozoic age and also numerous Variscan intrusions; Jurassic coal-bearing strata and Permian oil shale are present along the northern margin, and diamonds have been found in the southwest.

— *Tarim Basin:* a thick sequence of Cambrian to Recent sediments overlying Proterozoic basement; promising oil prospects have been found in the northwest.

— *Kunlun Belt:* an extensive mountain chain in the south formed mainly of early Palaeozoic sedimentary, volcanic, and intrusive rocks.

Eastern Junggar region selected

The area selected for a possible comprehensive study, the eastern Junggar region, covers about

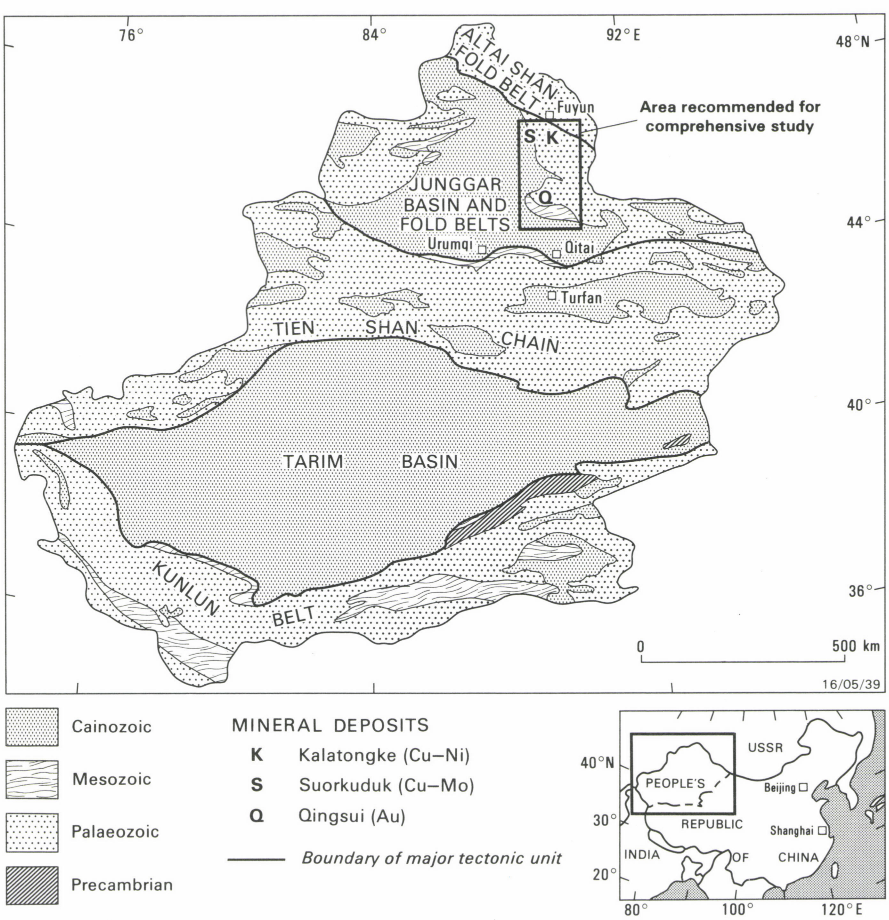


Fig. 16. Geological framework, Xinjiang Autonomous Region.

30 000 km² and includes parts of the Altai Fold System and the eastern Junggar Fold Belts. It consists of northwesterly trending ranges rising from about 1500 m a.s.l. in the south to about 3200 m a.s.l. in the north; local relief in the ranges is generally less than 500 m. The climate is temperate desert and semi-desert, with rainfall increasing northwards. The region is sparsely populated, especially in the south. Climatic factors restrict geological fieldwork to the May–September period.

Bedrock is well exposed in the ranges, where weathering is minimal and vegetation almost nonexistent. There are few roads, but most of the area is readily accessible to 4-wheel-drive vehicles.

Eastern Junggar was mapped by the Xinjiang BGMR in the 1960s and 1970s using contoured topographic maps and 1:60 000 black-and-white aerial photographs. This work resulted in the restricted publication of 1:200 000 geological maps accompanied by reports. An aeromagnetic survey covered the region in 1962. Subsequent work has included more detailed geological mapping and ground and airborne geophysics around some mineral prospects.

The rocks exposed range in age from Ordovician to Mesozoic. The Palaeozoic sequence, which includes abundant volcanics, especially andesitic rocks of apparently orogenic type and also some felsic ignimbrites, is intruded by Variscan granites, ultramafic bodies, and some differentiated mafic bodies. It was moderately to tightly folded during the Variscan orogeny, but only in the Altai Fold System is it highly metamorphosed.

Ultramafic intrusions are concentrated along three major fault zones (sutures?), and consist mainly of altered dunite and harzburgite; they commonly contain chromite deposits, but known occurrences are too small to be of economic importance.

Mineral potential

Although eastern Junggar has considerable potential for deposits of non-ferrous metals, few such deposits have so far been found, and there are no mines currently in production. Of the known mineral deposits, the most promising is the Kalatongke Cu–Ni deposit, which is being developed at present. Of the other mineral deposits visited by the Australian team, only the Qingsui No. 48 Au deposit and the Suorkuduk Cu–Mo deposit, both currently being evaluated, appear to be of potential economic significance.

The *Kalatongke Cu–Ni deposit* is in a differentiated mafic body intruded into Carboniferous sedimentary rocks. Mineralisation consists of pyrite, pyrrhotite, chalcopyrite, pentlandite, and complex sulphides. These are present throughout the intrusion, extending to a depth of at least 500 m, but are concentrated below 200 m. Proved reserves are 270 000 t Cu, average grade 1.17%, and 175 000 t Ni, average grade 0.74%. At the *Qingsui No. 48 deposit,* the gold occurs mainly in pyrite associated with calcite–quartz veins and shear zones near contacts between Carboniferous basalt and tuffaceous sandstone. Estimated reserves for the upper 70 m of the deposit are 417 kg Au at an average grade of 7.44 g/t; cut-off grade is 4.35 g/t. At Suorkuduk, chalcopyrite, pyrrhotite, and minor molybdenite occur in Devonian garnetiferous volcaniclastics.

Three-year study recommended

The Australian team has recommended in their report (*BMR Record* 1988/15) that the cooperative study, if undertaken, should be carried out over a period of three years, the aim being to provide a comprehensive geological and geophysical framework for eastern Junggar, gain a better understanding of the mineral potential, assist in the selection of areas for detailed mineral exploration, introduce integrated geological, geophysical and geochemical methods and techniques used in Australia in the search for metalliferous mineral deposits, and help train scientific and technical personnel. A low-level detailed airborne magnetic and radiometric survey of the whole region by the Aero Geophysical Survey, MGMR, Beijing, is a requisite. The recommended Australian contribution includes a project manager (full time), senior geologists, geophysicists, and geochemists with wide experience in the Australian mineral exploration industry (part time), and consultants to organise training courses.

It is hoped that Australian mining companies will seek to participate in the development of any significant mineral deposits found in eastern Junggar as a result of this project.

For further information contact Dr David Blake or Dr Shen-Su Sun at BMR (Division of Petrology & Geochemistry).

Probing the Canning's secrets: a new, five year study

BMR has begun a major study of the Canning Basin in northwestern Australia. The five-year study will cover this large basin's structural and tectonic evolution, sedimentary history, and petroleum geology, and also the chemical evolution and hydrodynamics of the basinal fluids in relation to the Mississippi Valley type (MVT) lead–zinc deposits.

The strata in the basin's several depocentres (Fig.17) range in age from Ordovician to Recent. The study will initially focus on the link between the Fitzroy Trough and the Willara Sub-basin, later extending east into the Gregory and Kidson Sub-basins and west into the offshore Fitzroy Trough and Bedout Sub-basin.

Studies of the basinal fluids have already begun, aimed at constraining the source regimes for brines, metals, sulphur, and hydrocarbons; they should also elucidate the timing of hydrocarbon migration and quantify the migration of fluid and heat flow and metal transport and deposition in the different structural units (*BMR Research Newsletter* 5, 15–16).

Are MVT basins good oil basins?

Brine-rich and hydrocarbon-rich fluid inclusions coexist in ores and gangues in the Lennard Shelf and southern Canning Basin. Studies of the time/space relations between oil and Pb–Zn mineralisation will test the hypothesis that oil basins are not good MVT basins, and vice versa.

The study of the structural evolution of the basin has also begun. A study of several thousand line-kilometres of industry seismic data so far has shown that the Fitzroy Trough is probably an asymmetric half-graben (Drummond & others., in press: APEA Journal), and this has significant implications for petroleum prospectiveness.

Most petroleum and Pb–Zn exploration has concentrated on Devonian and Carboniferous reef complexes along the margins of the Fitzroy Trough. In a symmetrical graben (i.e. as in most previous models of the trough) the reefs on both sides would have grown on a rapidly subsiding basement during rifting and would be stratigraphically similar. However, subsidence along the hinge margin of a half-graben would be much slower. Although, along the faulted margin, subsidence would dominate eustatic effects, along the hinged margin there would be a complex interplay.

Asymmetry has implications

Transfer faults have offset the bounding normal faults of the Fitzroy Trough (Begg, 1987: *APEA Journal,* 27(1), 137–151), and they also allowed the structural asymmetry to switch along the trough, so that the hinged margin is on different sides in different places.

The basin underwent a major inversion in the Mesozoic, when the transfer faults were reactivated as strike-slip systems. In many cases they compartmentalised the trough, allowing parts of it to invert separately. These faults also probably played a major role in fluid migration, determining where both petroleum accumulations and Pb–Zn deposits formed.

In 1988 BMR will test the asymmetric rifting model with a deep seismic reflection survey (Fig. 17). The longer of two lines will cross the Fitzroy Trough where the hinged margin seems to be in the north and the faulted margin in the south. By extending this line into the Willara Sub-basin, BMR hopes to test whether the faulting that formed the Willara Sub-basin is linked to that which formed the Fitzroy Trough. The second line is positioned where normal faults have been mapped on both sides of the trough and will test whether the faults on one side are just small-scale features.

The structural and basin fluid studies will continue until 1991. Detailed stratigraphic, sedimentological, and organic geochemical studies will start in early 1989, as will the offshore work. The contacts for the various aspects of the work and the BMR Divisions involved are: Project Co-odinator — *Dr Malcolm Walter (Continental Geology);* Regional Structure & Tectonics — *Dr Barry Drummond (Petrology & Geochemistry);* Sedimentology — *Mr Jim Jackson (Continental Geology);* Chronostratigraphy — *Dr John Shergold (Continental Geology);* Basinal Fluids & Mineralisation — *Dr Hashem Etminan (Petrology & Geochemistry);* Offshore — *Dr Paul Williamson, Dr Peter Davies (Marine Geosciences & Petroleum Geology).* These officers can all be contacted by telephoning BMR on (062) 499111.

Fig.17. Major structural elements of the Canning Basin and proposed seismic reflection profiles.

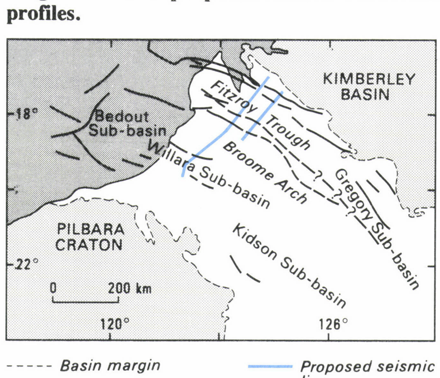
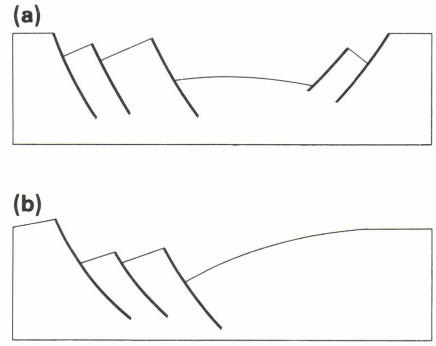


Fig.18. (a) Simplified structural model of the Fitzroy Trough as a graben. (b) Preferred asymmetric model; the asymmetry switches several times along strike.



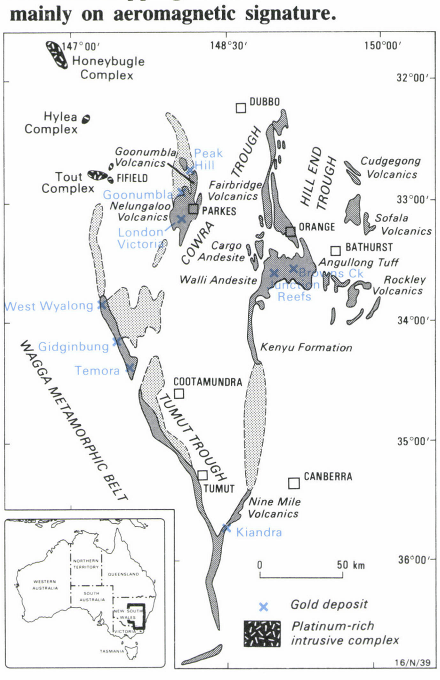
Ordovician magmatism, gold mineralisation, and an integrated tectonic model for the Ordovician and Silurian history of the Lachlan Fold Belt in NSW

In the Lachlan Fold Belt in NSW the remarkable contrast in geologic processes between the Ordovician and the Silurian has been an outstanding problem for the tectonicist. Superficially, the Lachlan Fold Belt in the Ordovician conforms to an oceanic island arc model lying offshore from a continent that was supplying large amounts of quartz-rich detritus. This oceanic regime contrasts with a Silurian history of multiple basin formation in a tensional, high-heat-flow environment, where widespread partial melting of lower to middle continental crust gave rise to great batholiths and eruption of large volumes of felsic ignimbrites on the regions between the basins. These contrasting regimes are not easily resolved with models involving continental collision and overthrusting that would imply a thickened crust, low geothermal gradients, and post-collision uplift. These effects are demonstrably absent.

Exploration has shown that the Ordovician volcanics and high-level intrusives in the Lachlan Fold Belt in NSW form a major gold province (Fig. 19). In 1979 Owen & Wyborn (*BMR Bulletin* 204) showed that much of the volcanism was of a particular basaltic type with high K, Sr, Ba, and P and low Ti, Zr, Y, and Nb (Fig. 20a), characteristic of the shoshonite association (Joplin, 1968: *Journal of the Geological Society of Australia,* 15, 275–294). With modern shoshonites a clear association with a contemporaneous subduction zone is mostly lacking, and in a recent paper on the shoshonite type area (Meen & Eggler, 1987: *Geological Society of America Bulletin,* 98, 238–247) isotopic evidence is provided to show that they are derived from melting of older subcontinental lithospheric mantle, rather than subducted oceanic crust. The depleted Ti, Zr and Nb in the magmas is inherited from the process that formed the subcontinental lithosphere, and the K, Sr, Ba, and P are introduced, possibly metasomatically, into the subcontinental lithosphere after its formation.

In this light a clearer relationship between the Ordovician and Silurian history of the Lachlan Fold Belt emerges. The suggested tectonic model outlined below also may explain why the area is a gold province and possibly also a potentially economic platinum province.

Fig.19. Distribution of Ordovician volcanics of the Lachlan Fold Belt in NSW and associated gold deposits. Dashed outlines indicate probable subcropping areas of volcanics based mainly on aeromagnetic signature.



Suggested tectonic model

At some time before the Ordovician the Lachlan Fold Belt consisted of new and possibly rather thin continental crust. Isotopic evidence from Silurian I-type granites derived from this crust indicates that it was formed in the Late Proterozoic to Cambrian. Underlying it was a subcontinental lithosphere depleted in basaltic components. Much of the primordial mantle sulphur (250 ppm) would have been removed during this depletion because sulphur is highly soluble in basaltic liquids (1000 ppm), so any sulphur left in the lithosphere (< about 50 ppm) would be in the form of sulphides enriched in Au and PGEs (Keays, 1982: Gold 82, *Geological Society of Zimbabwe, Special Publication* 1, 17–51).

Between the formation of the initial crust and the Ordovician the subcontinental lithosphere also became enriched in K, Ba, Sr, and P by hydrous metasomatism. A subduction origin for the metasomatism is normally assumed for such enrichment (Pearce, 1983, *in:* Continental Basalts and Mantle Xenoliths, *Shiva Publishing Ltd, UK,* 230–249), but the rather low Th, U, and light REEs in these rocks (Fig. 20) hints at some other process possibly operating.

In the Ordovician the continental crust must have been in a deep oceanic environment, suggesting downdrag of the lithospheric mantle, and certain conditions in the mantle must have triggered melting of the lithosphere to produce the shoshonites. A possible mechanism involves the delamination of a cold, dense subcontinental lithosphere (Molnar & Gray 1979: *Geology,* 7, 58–62) whose negative buoyancy, as a result of cooling, overcame the positive buoyancy of the overlying thin continental crust. As the subcontinental lithosphere foundered it partially melted. Magmas reached the surface in a broader distribution pattern than the curvilinear belts typical of island arcs (Fig. 19). This is even more apparent if the later E–W shortening of the intervening basins (Tumut, Cowra, Hill End troughs), estimated as about 50%, is taken into account.

Mineralisation

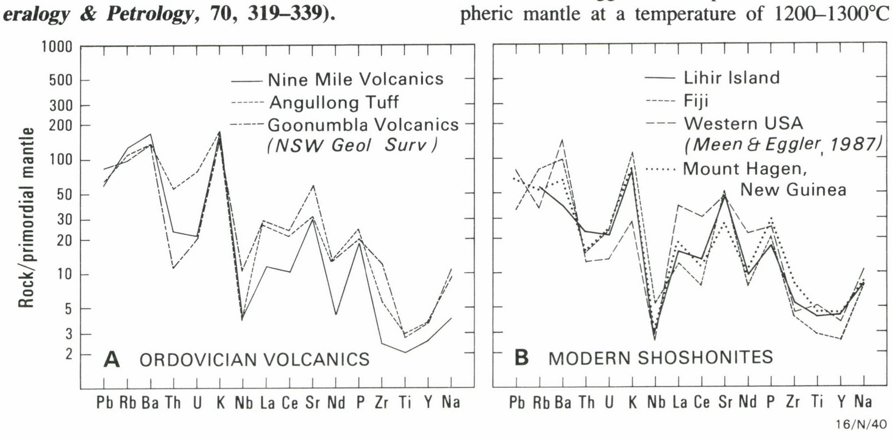
The Ordovician shoshonites resemble chemically volcanics on Lihir Island and Fiji (Fig. 20b) which also host major gold deposits. Clearly, then, such rocks are important hosts for gold mineralisation. As already suggested, the Ordovician shoshonites were derived from a lithosphere previously depleted in sulphur (< about 50 ppm) but with normal Au and PGE abundances (1 ppb Au, 5 ppb Pd, and 8 ppb Pt), so those sulphides present contained elevated abundances of Au and PGEs. The melting that produced the shoshonite magmas was able to remove virtually all of the remaining sulphur from the lithospheric source, and, since the residual silicate mineralogy (ol, opx, cpx...) had very low mineral/melt distribution coefficients for Au, Pd, and Pt, practically all the Au, Pd, and Pt was concentrated in the shoshonite melt (perhaps 4 ppb Au, 20 ppb Pd and 30 ppb Pt). When these magmas reached high levels in the crust they fractionated and crystallised. Provided sulphide saturation did not occur, the gold mineral/melt distribution coefficient for fractionating phases would be close to zero. A magma that had fractionated some 75–90% would contain 4 to 10 times the gold content of the primary magma, assuming Raleigh fractionation. Thus highly fractionated magmas would be ideal sources for low-sulphur porphyry style gold mineralisation such as at Goonumbla (Fig. 19) (Jones, 1985: *Economic Geology,* 80, 591–613), and at Cadia, 20 km south of Orange (Welsh, 1975: *in* Economic Geology of Australia and Papua New Guinea. *AusIMM Monograph 5,* 711–716). Other mineralisation styles, yet to be well documented (Gidginbung, London–Victoria, Junction Reefs, Browns Creek, Peak Hill) could also owe their formation to an initial high gold content in the upper crust as a result of Ordovician magmatism.

It is suggested that the ultramafic to intermediate intrusives in the Fifield area that contain thin bands of sulphide-poor clinopyroxenite cumulates averaging 13.2 g/t platinum (Suppel & Barron, 1986: *NSW Geological Survey Quarterly Notes,* 65, 1–8) are also part of this shoshonite province. These intrusives lie along strike from the Temora–Gidginbung–West Wyalong belt and have been termed shoshonites by Agnew & others (1987: *in* Platiniferous Horizons in Layered Intrusions: a symposium in conjunction with the J.J. Frankel Memorial Lecture. *Univ. of NSW*). Clinopyroxenite and olivine clinopyroxenite cumulates also occur in high-level sills in the Ordovician Nine Mile Volcanics southwest of Kiandra (Owen & Wyborn, 1979: *BMR Bulletin* 204). The Fifield complexes may have been deeper cumulate feeder zones to volcanics and high-level sills like those that occur further east and south.

Silurian tectonism

The foundering of subcontinental lithosphere in the Ordovician would have led to the upward flow of hot asthenospheric mantle to replace it. Initial breakage of the lithosphere probably took place beneath the Wagga Metamorphic Belt. Asthenospheric mantle at a temperature of 1200–1300°C

Fig.20. Comparative element content: (a) Ordovician volcanics of the Lachlan Fold Belt, NSW, and (b) modern shoshonites. The primordial mantle normalising values are from Wood & others (1979: *Contributions to Mineralogy & Petrology,* 70, 319–339).



was emplaced immediately beneath the thin continental crust. Not a great deal of asthenospheric melting took place, but that which did produced the tholeiitic gabbros, dolerite dyke swarms, and basalts of Silurian age in the Lachlan Fold Belt. Most of the subsequent crustal heating was by conduction. It took up to tens of millions of years for the resulting high geothermal gradient to be established, initially in the Wagga Metamorphic Belt in the Early Silurian. The high gradient spread eastwards at a rate of about 10 km/Ma (c.f. a suggested 20 km/Ma for the Basin-and-Range Province given by Humphreys, 1987: *EOS*, 68, 1450) in the same way as the asthenosphere spread eastwards as the lithosphere foundered in the Ordovician. Partial melting of all the lower to middle crust resulted from the high geothermal gradient. The crustal-derived magmas rose to form the great batholiths and ignimbrite sheets. All were derived from a pre-existing crust, so their upward migration was compensated by adjacent downward backflow of the crust. The Silurian basins formed above these adjacent areas. This process of internal crustal rearrangement associated with upward flow of granitic magmas has been termed granite tectonics (Chappell & others, 1987: *Journal of Petrology*, 28, 1111–1138).

Much of this hypothetical model is capable of being tested. Work is proceeding on the isotopic character of the Ordovician shoshonites to try to detect any signature of the proposed pre-existing subcontinental lithosphere. Ion microprobe dating of zircons from the Fifield complexes will soon be carried out at ANU, and analyses of gold and PGEs from the freshest samples of Ordovician basalts and clinopyroxenite cumulates are planned.

For further information contact Dr Doone Wyborn at BMR (Division of Petrology & Geochemistry).

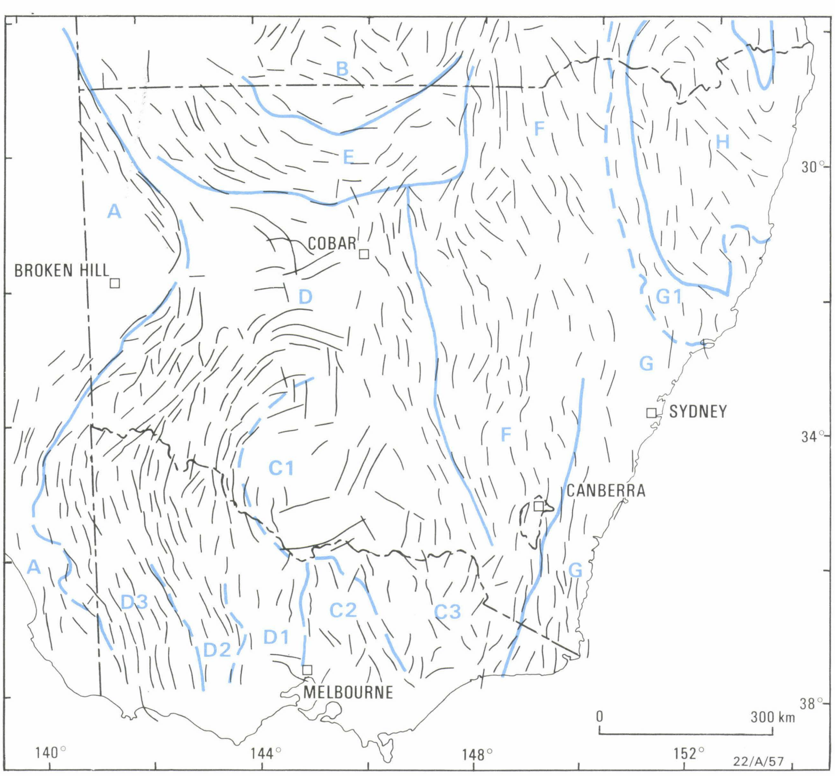
Growth of the Lachlan Orogen by eastwards accretion

The Lachlan Orogen is often considered a single entity, because all the outcropping rocks have a northerly trend, and the oldest outcropping rocks over the width of the orogen have a range of only Cambrian to Ordovician. This model has always had the difficulty that the orogen is too wide (1000 km) to have been formed in a single episode. Moreover, because the model is based on geological information only, it suffers from the additional problem that more than half the area is covered by post-orogenic sediments.

The Lachlan Orogen has been mapped over its total extent using gravity and magnetic anomalies. These give three independent data sets: (1) gravity anomaly gradients, thought to represent the boundaries between bodies of different density at mid upper-crustal levels; (2) short-wavelength (1–10 km) magnetic anomalies, indicating along-strike magnetic trends at the top of the Lachlan Orogen rocks (basement); and (3) intermediate-wavelength (10–50 km) magnetic anomalies indicating the extent of belts of anomalous apparent susceptibility near the top of the basement.

Figure 21 shows (in black) magnetic trends, and (in blue) areas inferred to be separate terranes on the basis of geology and the three geophysical data sets. The relative ages of cratonisation of the terranes have been inferred from the direction of the trends within: a younger terrane has trends parallel to its margin with an older one, whereas an older terrane has trends oblique to a younger one. The deformation of the younger terrane produces, in the older one, a band about 100 km wide along the margin, with trends parallel to the margin.

Fig. 21. Lachlan Orogen, showing trends of short-wavelength magnetic anomalies (thin lines), and boundaries between terranes (thick lines) inferred on the basis of geology and three geophysical data sets.



The subdivisions in Figure 21 are labelled in the order of their inferred cratonisation age. Terrane A is Proterozoic crust to the west. Its eastern margin at mid upper-crustal level is taken to be at an elongate gravity gradient that is low to the east. Terrane B is part of the Thompson Orogen. C may in part be the next-oldest terrane; C1 has trends that are generally not parallel to the adjacent margin, consistent with an allochthonous origin and cratonisation before accretion. D has trends parallel to the margins of both A and C1, so it is likely to have been cratonised later; it may consist of several separate, elongate terranes (D1, D2, D3). Terrane E has trends that cut those of B and have an indeterminable relationship with those of D. It may be an area of intracratonic deformation separating the Lachlan and Thompson orogens. Terrane F is younger than B, C, D, and possibly E. Its western margin is in part the Gilmore Suture. Terrane G truncates the gravity trends at the southern end of terrane F at an angle of about 40°. Its western margin is the boundary between the igneous and sedimentary granites (the S/I line). Terrane H is the New England Orogen of Silurian to Carboniferous accretion, with fore-arc deposits on older crust in G1.

The geophysical data appear to confirm the separation between the Thompson and Lachlan orogens, and the reality of the S/I line and Gilmore Suture as boundaries between major subdivisions in the Lachlan. They also provide a basis of subdivision of the western part of the Lachlan Orogen, which is largely covered by post-cratonic sediments.

Because of the truncations of trends described above, the terranes must each have been accreted to the Australian continent in the sequence of their age, and folded and cratonised before the next terrane was accreted, folded, and cratonised. Hence the continent in New South Wales and Victoria has predominantly accreted from the west to the east. The direction of transport is unknown. The geophysical data are consistent with the accretion being by either gradual formation of new crust in place, or the docking of pre-existing allochthonous terranes.

Two geological associations in places characterise the boundaries between the terranes. First, some of the boundaries contain ultramafic–mafic flows or intrusions. Secondly, the major terrane boundaries (C2/D1, C/F, and F/G) are the abrupt eastern margin of bands, 70 to 200 km wide, of low-pressure greenschist facies metamorphism. At boundaries C/F and F/G the metamorphism is in the older terrane, so it is likely that area D1 was cratonised before accretion of area C2.

This model describes the formation of the Lachlan Orogen by successive sequences, each involving accretion, folding, and cratonisation. It should be consistent with the rocks and structures in the upper part of the upper crust. Lower parts of the crust may be older or younger. For example, there is good chemical and isotopic evidence for Precambrian material under area F and the western margin of area G.

For further information contact Dr Peter Wellman at BMR (Division of Geophysics).

AMEC's Working Party on Gemstone Processing

Since the 1960s at least, studies have been made of the Australian gemstone industry in an endeavour to establish what proportion of Australian gemstones is processed locally and what proportion is exported unprocessed. In December 1987 the first formal meeting of the AMEC (Australian Minerals & Energy Council) 'Working Party on Gemstone Processing' was held at the South Australian Department of Mines & Energy, Adelaide. The Working Party is made up of representatives from State Mines Departments, jewellers' associations, gem cutters, gemstone miners' associations, and BMR.

The objectives of the Working Party are:

— to establish the proportion of gemstones processed in Australia compared with that exported unprocessed overseas.

— to identify the current level of technology employed by the local gem processing industry.
— to identify short and long term solutions that could improve the competitiveness of the Australian gemstone industry.
— to evaluate the benefits which could be expected to accrue from a higher percentage of local processing of Australian gemstones.

Six task groups were set up to study specific problems related to the review: statistics, technology, workforce, access, marketing, and finance. The BMR representative was elected to serve on the statistical group study but all members of the task groups are expected to contribute to studies made by other groups. The main objective of the statistical task group will be to investigate the means by which the accuracy of data on the mining, treatment, and processing of Australian gemstones can be improved. At present only the most general estimates of production and sales are available because most sales of unprocessed gemstones (other than diamonds) in Australia are private transactions between miners and buyers, the majority of whom represent Hong Kong dealers (opal) and Thai dealers (sapphires).

Australia is particularly well endowed with gemstones, producing each year about 30% of the world's natural diamonds, about 90% of the world's opals, including the only supply of the valuable black opal, and about 70% of the world's uncut natural sapphires. Australia also has the world's largest resource of nephrite jade and is almost the only source of black nephrite jade.

For further information, contact Dr Dick Dodson, at BMR (Resource Assessment Division).

Bicentennial earthquakes at Tennant Creek

The Australia Day holiday weekend of 1988 will be remembered by the residents of Tennant Creek, NT, for a series of strong earthquakes that began on Friday 22 January and continued through the weekend and beyond. Three main shocks, of surface-wave magnitudes 6.3, 6.4, and 6.8, occurred on Friday at 10.06 am, 1.27 pm, and 9.35 pm local time, and were followed by a strongly-felt aftershock of magnitude 5.3 at 6.24 am on Saturday morning.

The earthquakes were not the first felt by local residents but there is no historical record of activity before 1986, when two small earthquakes were followed by a swarm of over 150 events in January 1987, the largest four of which were all in the magnitude range 5–5.5 and caused minor damage in the town. Activity continued at a low level throughout 1987. The epicentres of the January 1987 events, located by a three-station BMR field array and ANU's fortuitously close Warramunga Seismic Array, were in the same area as the 1988 events, about 35 km southwest of the town.

Estimates of damage from the 1988 events currently run at around $1 million when lost production at Warrego and other nearby mines is included. Remarkably there was little structural damage in the township, but fault movement across the gas pipeline running to Darwin from the Mereenie and Palm Valley gas fields compressed it axially by an estimated 1.5–2 m and necessitated hasty replacement of a 93-m section.

North–south compression

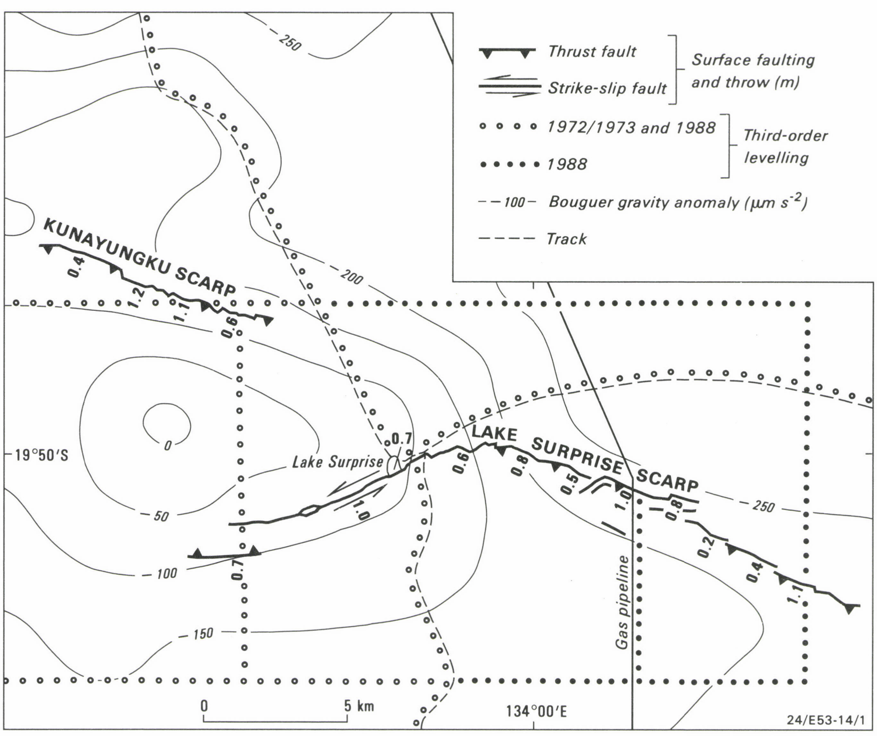
Surface faulting was evident on two main scarps totalling about 30 km in length, and generally trending east-southeast, except for an 8-km length trending east-northeast (Fig.22). From the surface faulting we interpret the earthquake mechanisms to be predominantly thrust in a direction approximately 15 degrees east of north. The southern block was thrust over the northern block, except in the area where the surface faulting was east-northeast; here the mechanism was reversed, that is, northern block over south. Uplifts of the order of 1 m were common.

Within 24 hours of the main shocks seismologists from BMR's Australian Seismological Centre and the Phillip Institute of Technology had begun to deploy a ten-station field network of seismographs and accelerographs, half of which were triaxial digital instruments, and during the ensuing days hundreds of aftershocks were recorded, making this the most comprehensively recorded Australian earthquake sequence. Surveyors from the Survey & Lands Information Group, Darwin, are mapping the scarps and associated structures using aerial photography, and relevelling along survey lines laid in the early 1970s for BMR gravity and magnetic traverses.

Those BMR surveys (Hone, 1974: *BMR Record* 1974/171; Bullock, 1977: *BMR Record* 1977/30) defined gravity and magnetic highs over the block between the two fault scarps, interpreted then as originating from a dense intrusive body with its top at about 1 km depth. Almost the entire epicentral area is covered by Quaternary alluvium but in general the east-southeast trend of the scarps parallels both the lineaments seen on aerial photographs and the strike of the Early Proterozoic Warramunga Group sedimentary rocks outcropping 20 km to the northeast.

For further information contact Mr Trevor Jones at BMR (Australian Seismological Centre).

Fig.22. Epicentral area.



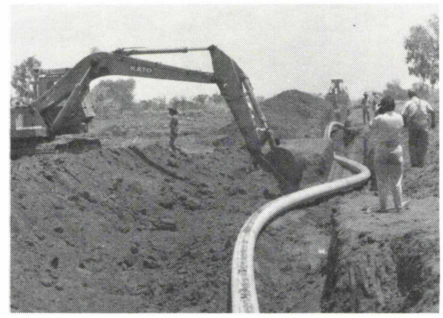


Fig.23. Excavation of Alice Springs–Darwin gas pipeline near Tennant Creek to replace earthquake-damaged section.

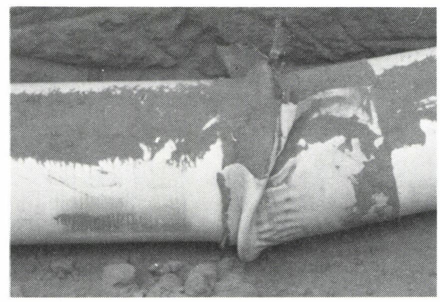


Fig.24. Compressive buckling failure at welded joint where the Tennant Creek earthquake fault plane intersected the Alice Springs–Darwin gas pipeline. The 6 mm-thick steel wall did not rupture.

Release of the Australian Geomagnetic Reference Field, 1985

The Australian Geomagnetic Reference Field, 1985 (AGRF1985) is now available from BMR as a software package. It is supplied as a mainframe version on 1/2-inch magnetic tape and also as an MS-DOS version on a 5 1/4-inch floppy disc for IBM PCs and compatibles.

The package comprises full documentation, a set of general-purpose subroutines, and a main program for generating AGRF1985 at either a single station or at a set of grid points within the Australian region. Options are included for computing values of IGRF1985 (the International Geomagnetic Reference Field), or IGRF1985 extrapolated using the AGRF1985 secular variation model, or differences between AGRF1985 and IGRF1985 (termed the 'regional residual field').

AGRF1985 is BMR's prospective model of Earth's magnetic field and its annual change (i.e. secular variation) over the Australian region for epoch 1985.0. It is a combination of Earth's main field originating within the core represented by IGRF1985 and the broad-scale crustal field represented by a rectangular harmonic analysis of observations at 86 repeat stations and magnetic observatories in the region (reduced to epoch

1985.0). The AGRF1985 model is expressed as a set of spherical harmonic coefficients of IGRF1985 (120 for the field and 80 for the secular variation) together with a set of rectangular harmonic coefficients of the regional residual field (71 for each of the field and the secular variation). The numbers of harmonics included in the analyses of the regional residual field and the secular variation were chosen objectively by a data-adaptive procedure. The resulting models contain information down to wavelengths of 1300 km in the north-south direction and 1200 km in the east-west direction at the centre of the modelled region. Charts and regional field models produced by BMR for earlier epochs were more highly smoothed than this.

AGRF1985 is recommended as the best available regional model for the secular variation within the time interval 1980.0 to 1990.0, and hence for reducing magnetic survey data to a common epoch. Altitude information is incorporated into the model, and the field can be upwards and downwards continued. AGRF1985 will eventually be replaced by a 'definitive' model (DAGRF1985) sometime after 1990.0. This will incorporate more accurate, retrospective secular variation data and a comprehensive set of observations of the field derived from all available sources.

A charge of $195.00 is made for the software package which is available from Geomagnetism Section, Division of Geophysics, Bureau of Mineral Resources, GPO Box 378, Canberra, ACT 2601. Tel. 062–499111, Fax. 062–488178 (this charge includes a set of isomagnetic charts of AGRF1985 when they become available).

For further information, contact Dr Charles Barton at BMR (Division of Geophysics).

New datafile on WA gold deposits

BMR has released data on 80 major gold deposits in its new *Resource Report 3 — Gold Deposits of Western Australia: BMR datafile (MINDEP)*. The report is the first part of a larger datafile that will include details of all Australian gold deposits with resources and/or production of more than 1 tonne Au.

Resource Report 3 is also the first stage of an extensive database, the Mineral Deposits Database (MINDEP), that will provide the same kind of information for a range of mineral commodities.

Items for which data have been compiled include: location, and regional setting of the deposits; development history, including operating status of individual mines; mineral resources and production; deposit geology including brief descriptions of host rocks and their structures, metamorphism, and alteration; genetic controls and proposed genetic models; ownership, geological setting, mineralogy, and dimensions of orebodies; and bibliography.

The 35-page Resource Report consists of a brief introduction (containing three text-figure maps showing deposit locations, goldfields, and tectonic settings) followed by tables listing deposits covered (including individual orebodies) and appendixes illustrating the MINDEP recording format and an example (Paddington) of the standard report format. The datafile itself (360 pages of printout) is supplied as microfiche in a pocket at the back. The complete report, as thus packaged, costs $24.95.

The datafile is also available in the following alternative forms:

- as either diskettes or magnetic tape in ASCII format, i.e. suitable for a wide range of customer usage (cost, including Resource Report, $150);
- as either diskettes or magnetic tape in ORACLE format with schema, i.e. database structure information (cost, including Resource Report, $200); or
- hard-copy (paper) computer printout (cost, including Resource Report, $75).

Purchasers of ASCII data will be able to enter it into established databases or view and/or print the information, either using DOS 3.1 or via a word-processing package. Customers with ORACLE database-management software can use the schema and ORACLE format to manipulate the data to suit their own needs.

BMR aims to revise both the data and the schema and to develop a wide range of standard reporting formats to meet users' needs. Updates will be made available to previous purchasers at a reduced price.

Similar data are being compiled for major gold deposits in the rest of Australia (some 100 deposits) for release in mid to late 1988. These data will be sold separately from the data for WA.

BMR plans to publish similar datafiles over the next two years for iron ore, manganese, tin, titanium, tungsten, and zirconium.

For further information, contact Mr Brian Elliott at BMR (Resource Assessment Division). The report may be obtained from: **BMR Publications Sales, GPO Box 378, Canberra, ACT 2601 (phone 062–499519).**

Recent publications and data releases

Over the period 1 September 1987 to 29 February 1988 BMR has released the following publications and data:

Publications

Bulletins
227 — Hydrogeology of Australia

Reports
263 — Hydrogeology of the ACT and environs (incl. coloured map)
265 — Physical property measurements on rock samples from the Mount Isa Inlier, northwest Queensland
274 — *Rig Seismic* research cruise 6: northern Australia heat flow — post-cruise report
277 — Seismic velocities in the crust and upper mantle of Australia
280 — Australian seismological report 1983
282 — Australian geoscience 1986–87

BMR Journal of Australian Geology & Geophysics (Vol. 10, No.3)
BMR Yearbook ('BMR 87'), covering year ended 30 June 1987

Resource Reports
3 — Gold deposits of Western Australia: BMR data file (MINDEP)

Australian Petroleum Accumulations Reports
3 — Gippsland Basin, Vic.
4 — Adavale Basin, Qld

Petroleum Exploration and Development Titles Map & Key: data to 1 July 1987

Australian Mineral Industry Quarterly (Vol. 39, Nos. 2, 3, and 4)

Australian Mineral Industry Annual Review for 1985

Australian Mineral Industry Annual Review for 1986 preprint chapters: Copper, Uranium, Petroleum; and Part 1: General Review (the other preprint chapters — Aluminium, Black Coal, Gold, Iron Ore, Lead, Nickel, Tin, Titanium, Zinc — were issued earlier in 1987)

Geoscience maps
1:100 000 geological map: Elkedra Region, NT
1:250 000 geophysical maps: Total magnetic intensity of the Georgetown Region, Qld; Bouguer gravity anomalies of the Georgetown Region
1:1 000 000 magnetic domains maps: Roper River, NT; Adelaide, SA

Records released on open file
1987/19(Groundwater 8) — Australian hydrogeological maps — a discussion paper
1987/23(Groundwater 1) — Hydrogeochemistry of the upper Hunter River valley, New South Wales
1987/24(Groundwater 2) — Reconnaissance palynology of selected boreholes in the central Murray Basin, New South Wales
1987/25(Groundwater 3) — Sedimentology and diagenesis of sediments encountered by Vic. D.M. Piangil West 1, Swan Hill area, Murray Basin, southeastern Australia
1987/26(Groundwater 4) — Hydrogeological mapping pilot study: Ballarat 1:250 000 Sheet area
1987/36 — CCOP/SOPAC *Moana Wave* Cruise 3 (MW 8702) to the territorial waters of Western Samoa, the Cook Islands and Kiribati — cruise report
1987/50 — Geology of the Stow Region, Northern Territory
1987/51 — Extended Abstracts — Applied Extension Tectonics, 16th BMR Research Symposium, Canberra 24–26 November 1987
1987/52 — A review of mineralisation in the South Alligator Conservation Zone
1987/53 — Mineral resources and prospectiveness of the proposed world heritage listing of wet tropical rainforest areas
1987/55(Groundwater 5) — Murray Basin hydrogeological project Report 17, for half year ending 31 March 1987
1987/62 — Tumut Trough seismic survey, NSW, 1987

Release of data

Airborne geophysical maps
1:250 000: 75 maps, showing either magnetic properties, magnetic contours or profiles, radiometric contours or profiles, or flight line systems (in all States)
1:100 000 and 1:50 000: Several maps (Northern Territory and Western Australia) showing either radiometric data or flight lines systems

Digital data
Digital point located airborne magnetic data from thirty-four 1:250 000 Sheet areas

Further details of these publications and data, and information on BMR'S activities in general, may be obtained by contacting BMR's Information Section, telephone: (062) 499620 or (062) 499623.

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This number of the *BMR Research Newsletter* was edited by A.G.L. Paine and word-processed by L. Dale; the figures were drawn by staff of the BMR Cartography Section.

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 to 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 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.