BMR Research Newsletter

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Complex hydrocarbons in fluid inclusions in gold and tin deposits

A new frontier for mineral exploration

Traces of complex hydrocarbons in fluid inclusions are beginning to provide for mineral exploration important clues about palaeotemperatures and source rocks deep within ancient hydrothermal systems. These compounds provide a basis on which exploration can focus on both the regional and deposit scales.

Hydrothermal gold and other mineral deposits result from the large-scale interaction of fluids with deep crustal rocks; therefore success in exploration ultimately depends on recognition of the regional-scale thermal and structural evolution of the crust. Recognition of temperatures deep in the hydrothermal system, below surface-exposed deposits, then becomes important in determining prospectiveness. One way of looking deep into the roots of a hydrothermal system is by examining some of the more stable temperature-sensitive components which may be trapped in fluid inclusions. A number of such chemical geothermometers have been developed over the years for use in the exploration of geothermal systems — many of which are now known to be actively depositing epithermal silver and gold (Henley, 1985: *Reviews in Economic Geology*, 2, 1–24). It is these developments which have prompted us to examine some of the trace constituents in fluid inclusions from hydrothermal mineral deposits, paying particular attention to hydrocarbons. As a result, using analytical techniques more commonly used in petroleum exploration, we have now detected trace quantities of hydrocarbons in fluid inclusions in quartz veins from the Aberfoyle tin–tungsten deposit, the active gold-depositing geothermal system at Broadlands (NZ), the Pine Creek gold deposit (NT), and the Archaean Southern Cross gold deposit (WA).

Although methane has frequently been recognised in fluid inclusions from a variety of settings, hydrocarbons identified in inclusion fluids have to date been confined to simple alkanes and occasionally rare aromatics, usually in low-temperature sediment-hosted deposits (Mississippi Valley type). In these environments, complex hydrocarbons may be generated from buried biological material, but in higher-temperature settings a range of relatively simple hydrocarbons, including benzenes, may be generated from abiogenic reactions involving carbon dioxide, hydrogen, and other precursors.

Analytical techniques and results

Initially, working with Dr Roger Summons, we used **thermal decrepitation–mass spectrometry** (TD–MS) to identify hydrocarbons in the samples. Milligram-size samples were introduced into a mass spectrometer, and the fluid inclusions decrepitated under vacuum by gradually increasing the temperature (from 50–550°C) at which the sample was maintained. This technique, apart from providing semi-quantitative data on the relative amounts of water and gases (e.g., carbon dioxide and methane) in the inclusions also showed that hydrocarbons were present (Fig. 1). These compounds were chiefly evolved at temperatures above 250°C, and show good correlation with carbon dioxide and water. This observation is important since it provides evidence that they are actually present in the inclusions and are not simply the result of surface contamination.

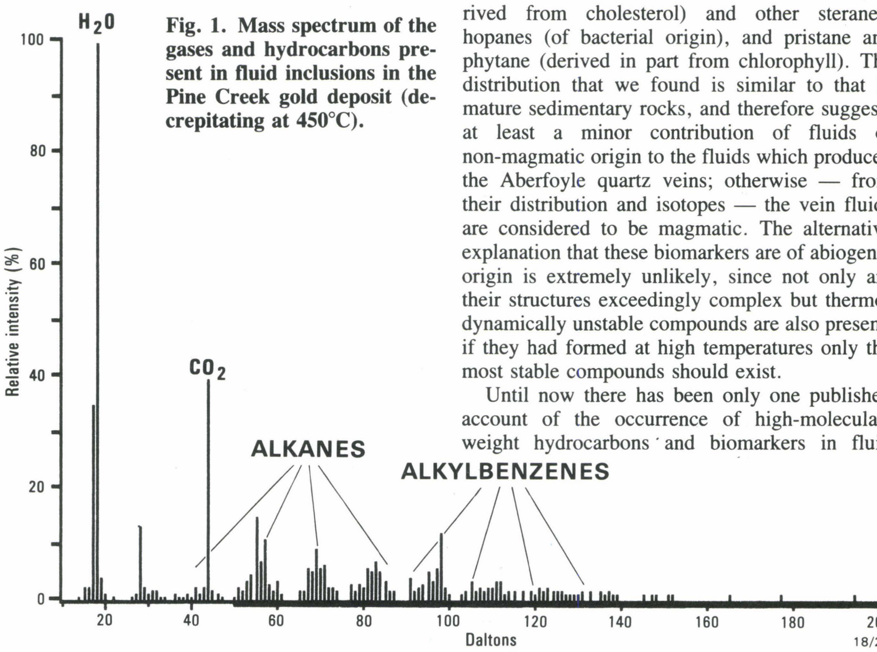

Fig. 1. Mass spectrum of the gases and hydrocarbons present in fluid inclusions in the Pine Creek gold deposit (decrepitating at 450°C).

Figure 2 shows the distribution of products arising from the decrepitation of fluid inclusions in quartz from the Pine Creek gold deposit. The major gases detected in the Archaean Southern Cross gold sample were carbon dioxide, minor amounts (ca. 5%) of methane, and traces of saturated hydrocarbons up to C7.

To examine the distribution of hydrocarbons more fully, the technique of **gas chromatography–mass spectrometry** (GC–MS) was used. In practice the extractable organic matter from the sample is injected into a gas chromatograph where, ideally, the mixture is separated into its component molecules. Individual molecules are ionised by an electron beam as they emerge from the gas chromatograph into the source of the mass spectrometer. The ionised species then fragment in the MS to yield a particular distribution of fragment masses — a mass spectrum. This can then be used to identify the original molecule.

A large sample of quartz from Aberfoyle, extracted with organic solvents, gave a small quantity of organic matter. Analysis by GC–MS showed that the major hydrocarbons in this organic matter were n-alkanes ranging in carbon number up to C30 (Fig. 1). In addition, numerous biomarkers or 'chemical fossils' were also identified; these are compounds of biogenic origin whose chemical structures can be directly related to their biological precursors. This sample has two populations of inclusions, which were formed at 290 ± 0°C and from 150 to 450°C.

We identified the biomarkers cholestane (derived from cholesterol) and other steranes, hopanes (of bacterial origin), and pristane and phytane (derived in part from chlorophyll). The distribution that we found is similar to that in mature sedimentary rocks, and therefore suggests at least a minor contribution of fluids of non-magmatic origin to the fluids which produced the Aberfoyle quartz veins; otherwise — from their distribution and isotopes — the vein fluids are considered to be magmatic. The alternative explanation that these biomarkers are of abiogenic origin is extremely unlikely, since not only are their structures exceedingly complex but thermodynamically unstable compounds are also present; if they had formed at high temperatures only the most stable compounds should exist.

Until now there has been only one published account of the occurrence of high-molecular-weight hydrocarbons and biomarkers in fluid

Gold database

The Divisions of Petrology & Geochemistry and Resource Assessment are to jointly compile published data on Australian gold deposits. The work is a continuation of a project begun last year, and the data eventually will form part of BMR's *MiNeral DEPosits* (MNDEP) database.

Some items for which data are to be compiled are:

- regional setting, locality, and geology of the deposits;
- characteristics of the deposits and their host rocks, and a brief summary of proposed genetic models;
- resources, production, and mine capacity;
- development history of individual mines, including discovery and mining methods; and
- bibliographic information based on over 1300 references.

BMR expects considerable interest in the data from industry, particularly those engaged in mineral exploration and geoscientific research. The data will be arranged State-by-State, and presented in a BMR publication and, for manipulation by users, on 5¼'' diskette (IBM PC/ASCII/DOS 3.1 format). The data for about 150 deposits will be available at the BMR Research Symposium in November 1987, and are expected to be updated and expanded annually.

For further information, contact Mrs Colleen Mock, Dr Greg Ewers, or Mr Brian Elliott at BMR.

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inclusions — from a relatively low-temperature Precambrian quartz vein in southwest Africa (Kvenvolden & Roedder, 1971: *Geochimica et Cosmochimica Acta*; 35, 1209–1229). Our data, therefore, are the first presented for such compounds in high-temperature environments.

The (epithermal) quartz sample from Broadlands contained fluid inclusions which also possessed a range of n-alkanes; however, their distribution was quite different, and maximised at C17 rather than C21. The distribution of biomarkers in this sample also contrasted with that in the Aberfoyle deposit. The inclusions were consumed at 260°C from fluids whose gas chemistry (based on sampling of geothermal wells) suggests higher temperatures of origin, so that the hydrocarbon mixture probably reflects thermal maturation at depths of over 2 km and temperatures of about 320–350°C.

dynamics of hydrothermal systems, we are working towards the development of the necessary framework.

In the Aberfoyle deposit, differences in the distribution and abundance of hydrocarbons in mineralised and non-mineralised samples are evident from preliminary TD–MS results. Further GC–MS work aimed at determining the detailed composition of these hydrocarbons, as well as the composition of the hydrocarbons in the surrounding country rocks (for purposes of correlation), is currently in progress.

The major work in this research project in the coming year will be to refine the analytical techniques; to investigate other possible methods (such as pyrolysis–gas chromatography) which may provide quantitative determinations of gases and hydrocarbons in fluid inclusions; and to develop the theoretical and experimental base for

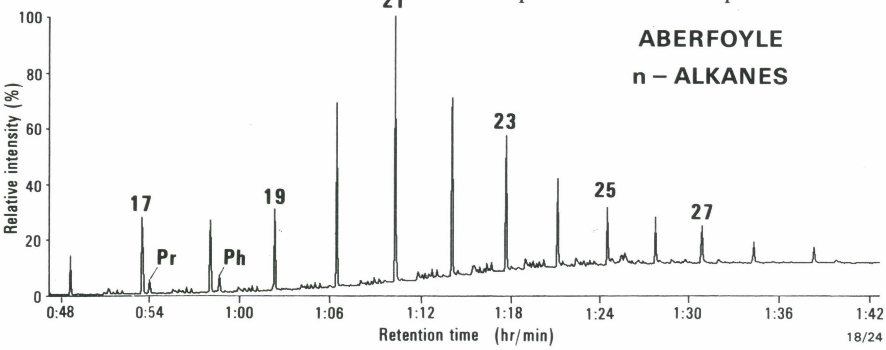

Fig. 2. Gas chromatogram showing the distribution of n–alkanes in fluid inclusions in the Aberfoyle tin–tungsten deposit.

Implications

Use of the techniques developed in petroleum geochemistry for correlating oils with their source rocks may permit the correlation of hydrocarbons in fluids trapped in inclusions in mineral deposits with their source rocks, and thus provide information about fluid pathways. Once the chemical controls on the origin and transport of hydrocarbons in hydrothermal fluids are known, we potentially have a powerful method of discriminating between terrains with respect to their prospectiveness. By combining thermodynamic and kinetic data with present-day understanding of the data interpretation.

Fluid inclusion studies have already provided a wealth of information on the physical and chemical processes involved in the genesis of ore deposits, and thus have aided mineral exploration. The hydrocarbon signatures of fluid inclusions may eventually provide valuable guides for the exploration industry through relating the deposits themselves to regional-scale parameters of the crust.

For further information, contact Dr Dick Henley or Dr Chris Hoffmann (Division of Petrology & Geochemistry) at BMR.

Detailed gravity traverse aids Murray Basin water resources research

The Murray Basin is a large nearly circular zone of relatively minor subsidence in which a thin blanket of Tertiary sediments 100–600 m thick covers much older Palaeozoic basement. The sediments are mostly saturated with water, and represent a vast water resource in an area where extensive agriculture is worth several billion dollars annually. While much of the water is fresh, problems arise where the highly saline water of the upper aquifer comes close to the ground surface. Water enters basin aquifers in the high ground on three sides of the basin, and travels towards the central-western and coastal parts. On the way, groundwater flow patterns are influenced by undulations in the basement, which in places force it to the surface where it causes salinity problems.

BMR and the New South Wales Water Resources Commission (WRC) made detailed gravity and magnetic measurements respectively along a traverse 20 km long in the central Murray Basin, near Balranald. A detailed seismic refraction survey along the traverse previously carried out by WRC had revealed a narrow ridge in Palaeozoic basement protruding into the overlying Tertiary Murray Basin sediments (Fig. 3; Odins & others, 1985: *Exploration Geophysics*, 16(2/3), 256–258). The ridge, which is next to a narrow depression, is 100 m below the ground surface, and can influence water flow. Mapping such ridges is therefore an important part of groundwater research.

The gravity and magnetic readings were made at 100–200-m intervals along the traverse, and the data were analysed using the refraction basement profile. The gravity data agree exceptionally well with the results interpreted from the refraction data, but the magnetic data were not useful. For both sets of data, a second model was produced to determine the effect of lowering the basement profile an extra 100 m.

The gravity data are consistent with both the interpreted structure as a whole, and with most of the small undulations that were determined from the refraction data in the shallow part of the basement. The small features could also be identified in the gravity computed from the lowered model, indicating very good resolving power. The success of the gravity method stems from the high density contrast between Tertiary sediments and Palaeozoic basement of 0.7 t m^{-3}. Unfortunately, structures of this type are too narrow to be detected by reconnaissance gravity surveys, where samples are taken on an 11-km grid. In the case of magnetics, airborne magnetic surveys are sufficiently detailed to detect such structures, if they produce a magnetic response. However, the Murray Basin survey has shown that a magnetic anomaly attributable to the ridge or depression is lacking. This is consistent with magnetic maps of the area, which show very little magnetic disturbance.

The co-operative project with WRC has shown that both gravity and refraction data are capable of accurately mapping basement topography, and detecting the important basement ridges. As the gravity method is much cheaper, future work is likely to concentrate on applying it in the Murray Basin. It is envisaged that an extensive network of gravity traverses will accurately delineate ridges and depressions in the basement surface, making it possible to map the passage of groundwater across the basin and predict areas with a potential salinity problem that could be activated by a general rise in the water-table.

For more information, contact Mr Vadim Anfiloff (Division of Geophysics) at BMR.

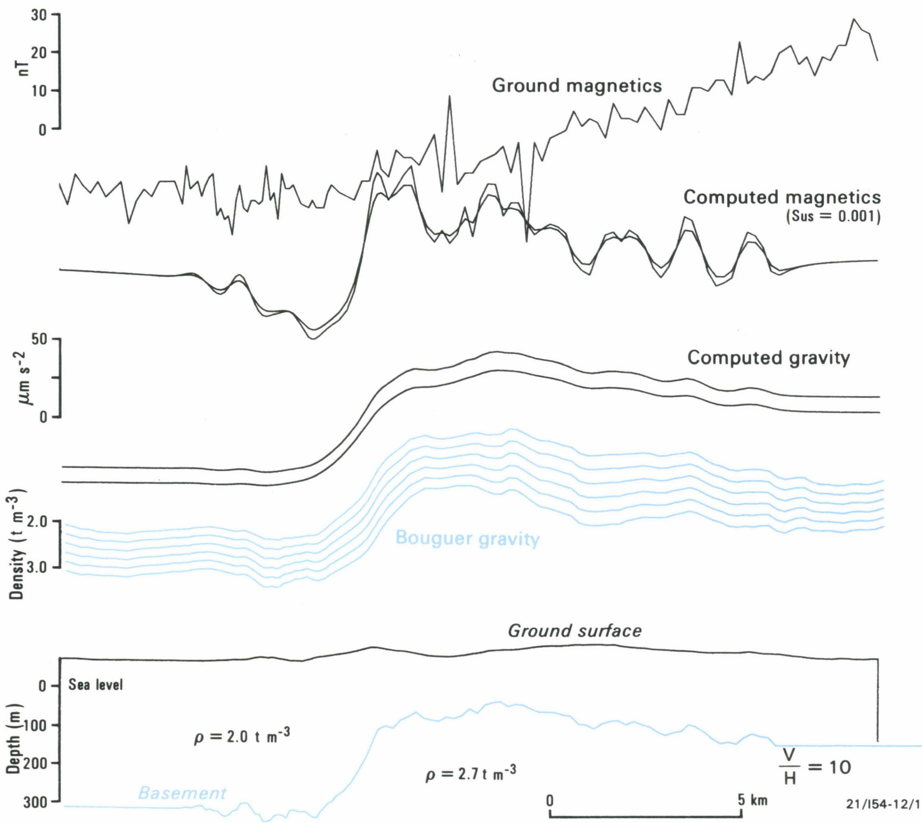

Fig. 3. Gravity, magnetic, and interpreted basement profiles along a short traverse 50 km north of Balranald in the Murray Basin; basement profile is after Odin & others (1985).

Changes in Proterozoic granitoid compositions with time

Igneous activity apparently prevailed continent-wide within restricted time intervals during the Proterozoic (Page & others, 1984: *Proceedings of the 27th International Geological Congress, Moscow*, 5, 25–72; Etheridge & others, in press: *AGU Geodynamics Series*, 16). Felsic igneous rocks are rare in the earliest and latest Proterozoic sequences, but dominate in sequences 1880–1400 Ma old; the time intervals of the major suites are 1870–1840 Ma, 1800–1780 Ma, 1740–1720 Ma, 1670–1640 Ma, and 1600–1500 Ma.

Collaborating with the South Australian Department of Mines & Energy, BMR has been comparing the compositions of felsic igneous rocks with time during the Proterozoic. Some 2000 whole-rock chemical analyses have been compared. The suites are mainly infracrustal rocks (I-types), and are derived from Proterozoic rather than Archaean precursors; rare supracrustal suites (S-types) also appear to have Proterozoic precursors. The economic implications of this study should enable us to confirm or refute the validity of applying Cainozoic subduction models to Proterozoic petrogenetic and metallogenic processes.

Compositions of the main time-interval suites

Most of the felsic volcanic and granitic rocks from the period 1840–1870 Ma, as well as some minor volcanic suites from the period 2000–1870 Ma, are I-type and have a distinctive chemical composition. The members of this suite rarely show any signs of fractional crystallisation — their compositional diversity is thought to have formed by restite unmixing. Their silica composi-

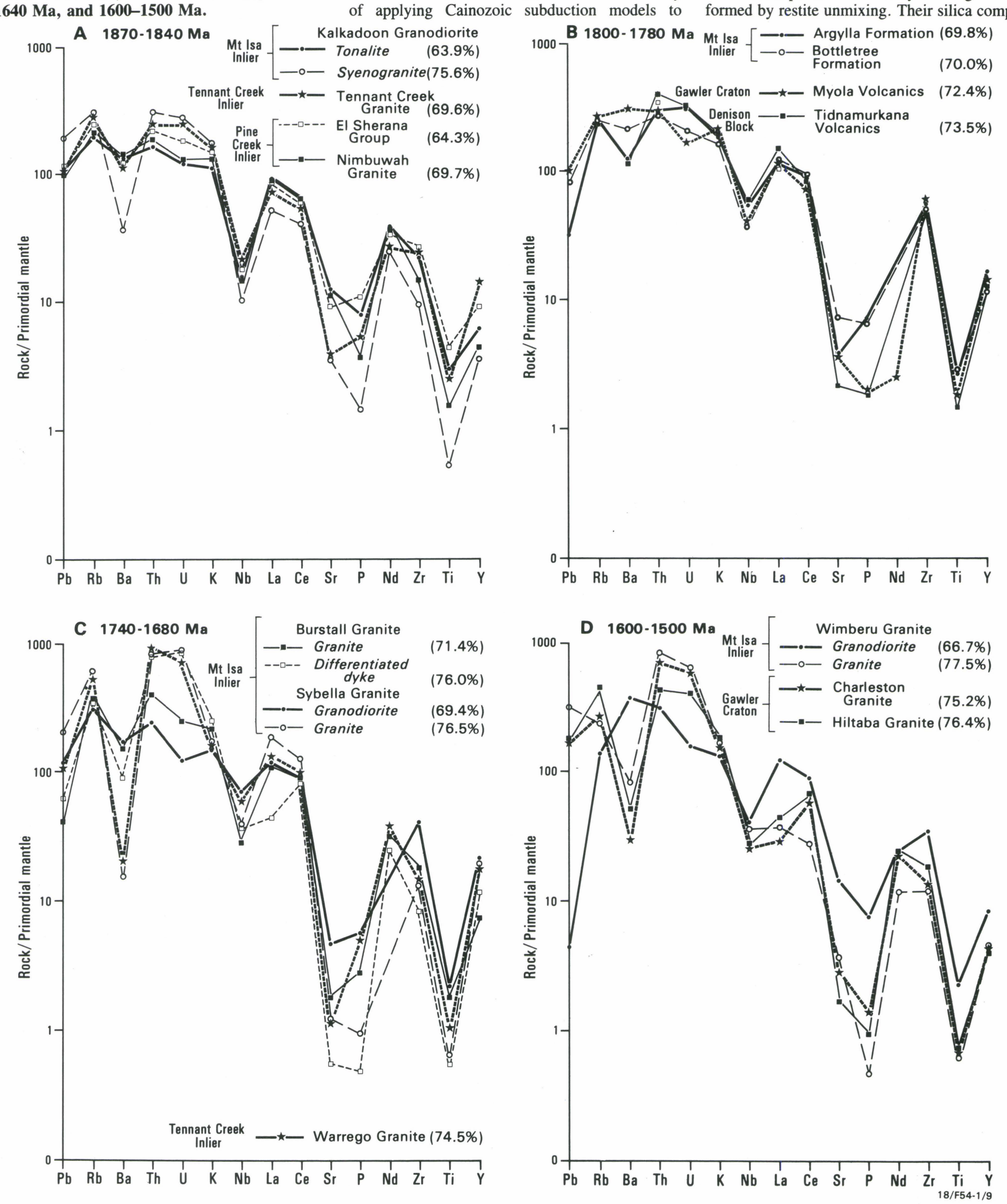

Fig. 4. Primordial-mantle-normalised geochemical patterns (after Wood & others, 1979: *Contributions to Mineralogy and Petrology*, 70, 319–339) of representative analyses for the various groups of granite compositions; the values in brackets are the SiO_2 values of each sample. Data sources: Wyborn & Page (1983: *BMR Journal of Australian Geology & Geophysics*, 8, 53–69); Ferguson & others (1980: *in* Uranium in the Pine Creek Geosyncline, *IAEA, Vienna*, 73–90); Bultitude & Wyborn (1982: *BMR Journal of Australian Geology & Geophysics*, 7, 99–112); and unpublished BMR and SADME data.

tion is from 60 to 78 wt %, but mainly within the range 68–75 wt %. Compared with Archaean and Phanerozoic I-type tonalites, they are high in K_2O, Rb, La, Ce, Th, and U, and depleted in MgO, CaO, Ni, and Cr. In the Litchfield province of the western Pine Creek Inlier a suite of peraluminous S-type granites has an isotopic signature indicating derivation from Proterozoic rather than Archaean sediments.

Compared with the pre-1840 Ma volcanic rocks and granites, the 1800–1780 Ma volcanic rocks, as well as the 1740 Ma Moonta Porphyry from the Gawler Craton, have very high Zr (up to 800 ppm), Nb (up to 60 ppm), Y (up to 120 ppm), and even higher K_2O, Th, and U contents (Fig. 4). This group of rocks is highly magnetic, and their compositions compare well with A-types.

Granites from the periods 1740–1720 Ma and 1670–1640 Ma are similar to one another, and are also mainly A-types. They are often associated with large gabbros and net-veined complexes, commonly contain fluorite, and have a characteristic rapakivi texture in which K-feldspars are rimmed by albite. The compositions of the granites and felsic volcanics in these two periods are also enriched in incompatible elements, and have even higher levels of Rb, Th, U, La, Ce, Nd, and Y than those in the 1800–1780 Ma rocks, whereas Sr and P tend to be more depleted (Fig. 4).

The last major period of felsic igneous activity was 1600–1500 Ma. I-type igneous rocks of this age are very extensive in the Gawler Craton and Stuart Shelf, and prominent in the eastern Mount Isa Inlier. The granites have fractionated to highly evolved compositions, and they have much higher values of Na_2O than the older Proterozoic felsic igneous rocks. Th, U, La, and Ce also tend to be high and similar to those for the A-type suites from the interval 1800–1640 Ma (Fig. 4). U concentrations are very high, ranging between 7 and 30 ppm over large areas in the three provinces. In the western Georgetown Inlier, one rare but major suite of S-type volcanics and granites occurs — the Croydon Volcanics and Esmeralda Granite, a series of reduced graphite-bearing S-types.

Compositional variation with time

The felsic volcanics and granites of the Proterozoic are different from those of the Archaean, Palaeozoic, Mesozoic, and Cainozoic. Pre-1840 Ma Proterozoic I-types are similar to early Palaeozoic I-type granites, and both have noted depletions in Sr, and enrichment in Y, although the levels of incompatible elements such as K_2O, Th, and U tend to be higher in the Proterozoic. Archaean tonalites and trondhjemites, and Cainozoic igneous rocks from subduction-related environments, are enriched in Sr and depleted in Y, and are nowhere near as enriched in Th, U, and Rb as Proterozoic tonalites. A-type granites throughout time have certain similar characteristics, although the Archaean examples are still enriched in Sr, and the Proterozoic examples have more Th and U than their Phanerozoic counterparts.

With his considerable database on Cainozoic and Archaean granites, Professor John Tarney from the University of Leicester spent several weeks at BMR as a visiting fellow helping to quantify these changes with time.

Metallogenic implications of compositional changes

Preliminary results to date suggest that owing to the rarity of peraluminous S-types in the Proterozoic, Sn deposits are not common, except in the Georgetown area and the Litchfield area. Likewise, porphyry systems such as those found in Cainozoic granite belts are also likely to be rare because igneous fractionation processes, which are fundamental to the evolution of a porphyry system, have not affected the majority of Proterozoic felsic igneous rocks. An exception to this is the magnetite-rich 1600–1500-Ma I-type magmas, which — although they probably did not develop in a subduction environment — do show similar fractionation processes to those found in Cainozoic I-type granite belts.

Another important metallogenic aspect of the Proterozoic granites and felsic volcanics is their enrichment in U. In the Pine Creek Inlier, some granites of Proterozoic age contain on average more U than those of Archaean age. Although no significant U deposits have been formed by primary igneous processes, the Proterozoic granites and volcanics may have brought a large amount of U into the upper crust, where it has been subsequently reworked into deposits by other processes such as metamorphism and hydrothermal remobilisation.

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

Alteration styles in the Eastern Creek Volcanics

Significance for Cu and U mineralisation

The Eastern Creek Volcanics are a major mafic volcanic unit in the western Mount Isa Inlier, and host numerous small Cu and U deposits (Fig. 5). The mafic volcanics are believed by some to be the source of the Cu in the main Mount Isa deposit (e.g., Smith & Walker, 1971: *BMR Bulletin* 131), although the deposit itself is located in a siliceous, dolomitic pseudobreccia (termed silica–dolomite) within the Urquhart Shale of the Mount Isa Group. Recent structural data have suggested that the Cu deposit was formed 200 Ma years after the deposition of the Mount Isa Group, during the third major deformational event to have affected the western Mount Isa Inlier (Perkins, 1984: *Economic Geology*, 79, 601–637; Swager, 1985: *Economic Geology*, 80, 107–125). The western Mount Isa U deposits, like the Mount Isa Cu deposit, are also epigenetic and structurally controlled (Carter, 1955: *BMR Record* 1955/26; Brooks, 1960: *GSQ Publication* 197).

As part of the Mount Isa project, a study was initiated to see whether (1) the Eastern Creek Volcanics are likely source rocks for the copper deposit, and (2) the enrichment and depletion of copper and other elements can be related to documented deformational events in the region. All geochemical data available for the Eastern Creek Volcanics have been reviewed, and all surface sample sites have been examined to assess the degree of deformation and the nature of the alteration at each location. The data were from three main sources: Smith & Walker (1971), Glikson & Derrick (1978: *BMR Record* 1978/48), and Wilson & others (1985: *BMR Journal of Australian Geology & Geophysics*, 9, 317–328). Geochemical samples have also been collected from the U deposits in the western Mount Isa Inlier, and the metabasalt samples of Smith & Walker were reanalysed for all major and some trace elements. As well, two metabasalt samples and 13 uranium deposits were analysed for Au, Pt, and Pd.

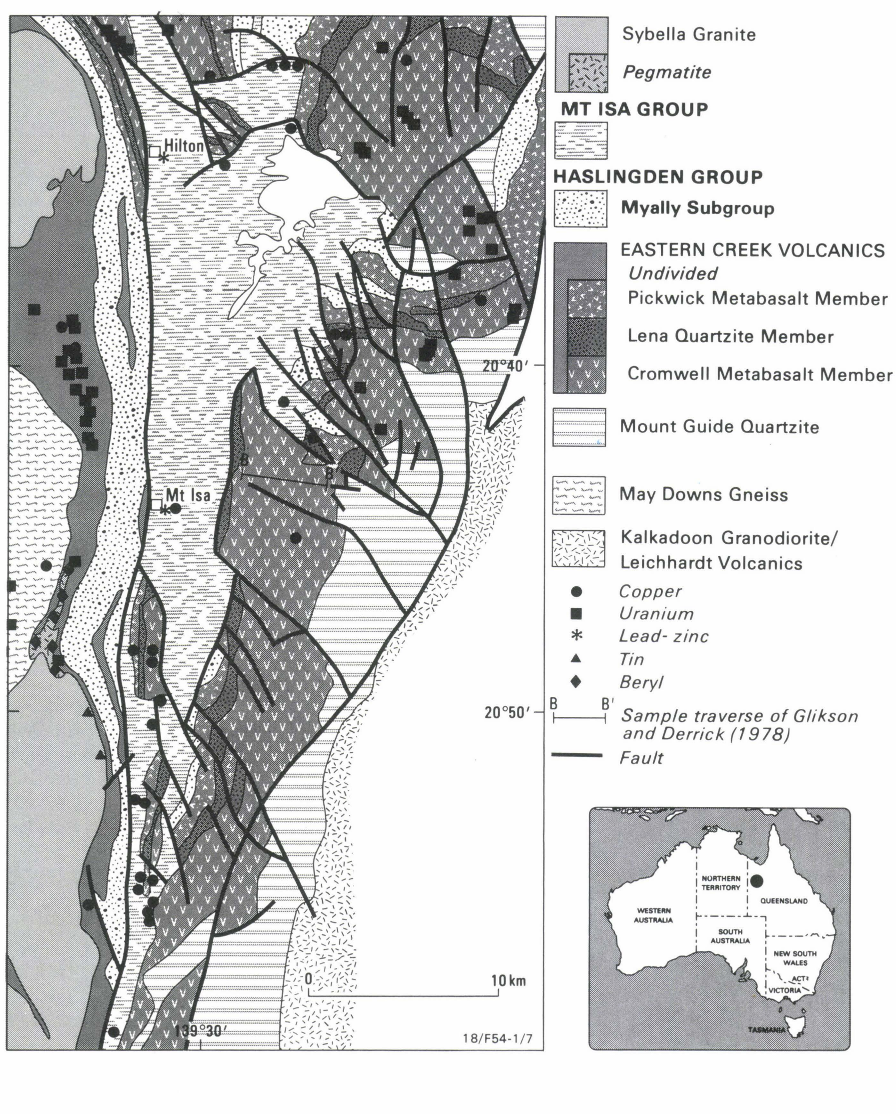

Fig. 5. Geology and mineral deposits of the area around Mount Isa mine.

Alteration styles

Results show that the metabasalts of the Eastern Creek Volcanics are affected by at least four major types of alteration, which can be distinguished mineralogically and by trace-element geochemistry. The earliest alteration (type 1), mainly of massive metabasalts, was more common in the area 8–10 km southeast of Mammoth Mines than around Mount Isa. Basalts affected by type 1 alteration consist of albite + actinolite with lesser chlorite + epidote + sulphides + magnetite. The sulphides are more abundant near the tops of the lava flows, particularly near impermeable sedimentary layers. Chemically these basalts are similar to modern continental tholeiites, and they have Fe_2O_3/FeO similar to that in fresh recent basalts. However, they are enriched in K_2O and S, and Cu has been locally redistributed within the lava flows; anomalously high values of Cu ranging up to 400 ppm have been recorded (Fig. 6).

The remaining three alteration types are evident only in deformed rocks. Two are closely related and are associated with the major regional metamorphism and deformation, which generally produced a dominant north–south cleavage. These two types are by far the most widespread and occur adjacent to the Mount Isa mine, particularly along the Barkly Highway, and in the metamorphics to the west. The altered basalts are dominated by either epidote + sphene (type 2) or calcite + magnetite (type 3), and their mineralogy is controlled by the concentration of CO_2 in the fluid phase during metamorphism. Despite differences in mineralogy, both types are very similar chemically, and, relative to type 1, are depleted in S, K_2O, Cu, Rb, Ba, and Sr, and enriched in Zr, V, Y, and Cr. These samples also have the highest ratios of Fe_2O_3/FeO. Their Cu values, which are less than in type 1 basalts, average from 50–100 ppm in the most altered types (Fig. 6).

The fourth alteration type was the most intense. It is evident only in drillcore from beneath the Cu orebodies at Mount Isa mine and in some late retrograde shear zones in amphibolite-grade metabasalts to the west. Rocks affected by type 4 alteration are dominated by albite + chlorite + rutile. They are intensely depleted in CaO, MnO, Fe_2O_3, Cu, Sr, Ba, Co, and Ni, and enriched in MgO and SiO_2 (Fig. 6). The altered rocks are also very reduced, and have very low Fe_2O_3/FeO. Because these metabasalts have virtually no Cu, Ni, Co, or other trace elements that occur in the Mount Isa copper orebody, type 4 alteration may be linked to the formation of this copper ore.

U deposit trace elements

The uranium deposits of the western Mount Isa Inlier are hosted by reduced rock types — e.g., metabasalts and graphite-bearing metasediments — of a variety of metamorphic facies ranging from upper amphibolite to lower greenschist. The main uranium-bearing phases are uraninite, brannerite, magnetite, and zircon (Carter, 1955: *BMR Record* 1955/26; Brooks, 1960: *GSQ Publication* 197). The uranium deposits have unusual trace-element concentrations, which vary with the metamorphic grade. Apart from U, most deposits are enriched in Fe_2O_3, Zr (up to 14 wt %), Y (up to 1500 ppm), and V (up to 2500 ppm), and contain little FeO or Th. The enrichment of these elements (the same trace elements which the altered epidote + sphene and calcite + magnetite metabasalts are enriched in) suggests that they have equilibrated with the same regional metamorphic fluid that was contemporaneous with types 2 and 3 alteration.

Precious-metal analyses

Limited precious-metal analyses from the U deposits and adjacent metabasalts were carried out by Analytical Services Pty Ltd (Western Australia). Values of around 10 ppb for Au and Pt, and up to 17 ppb Pd, have been recorded for the S-rich undeformed metabasalts of type 1. For the U deposits in the western Mount Isa Inlier, values average 46 ppb Au (range 4–400 ppb), 3.2 ppb Pt (range 0.5–19 ppb), and 3 ppb Pd (range 0.5–11 ppb). In contrast, Au values are very low (<.03 ppb) for the deformed calcite + magnetite and epidote + sphene metabasalts east of the mine (Peter McGoldrick, University of Tasmania, personal communication 1987), and the Mount Isa Cu deposit has virtually no detectable Au. This deposit may have been derived by type 4 alteration acting on the calcite + magnetite or even the epidote + sphene metabasalts that were already depleted in Au but still retained up to 100 ppm Cu.

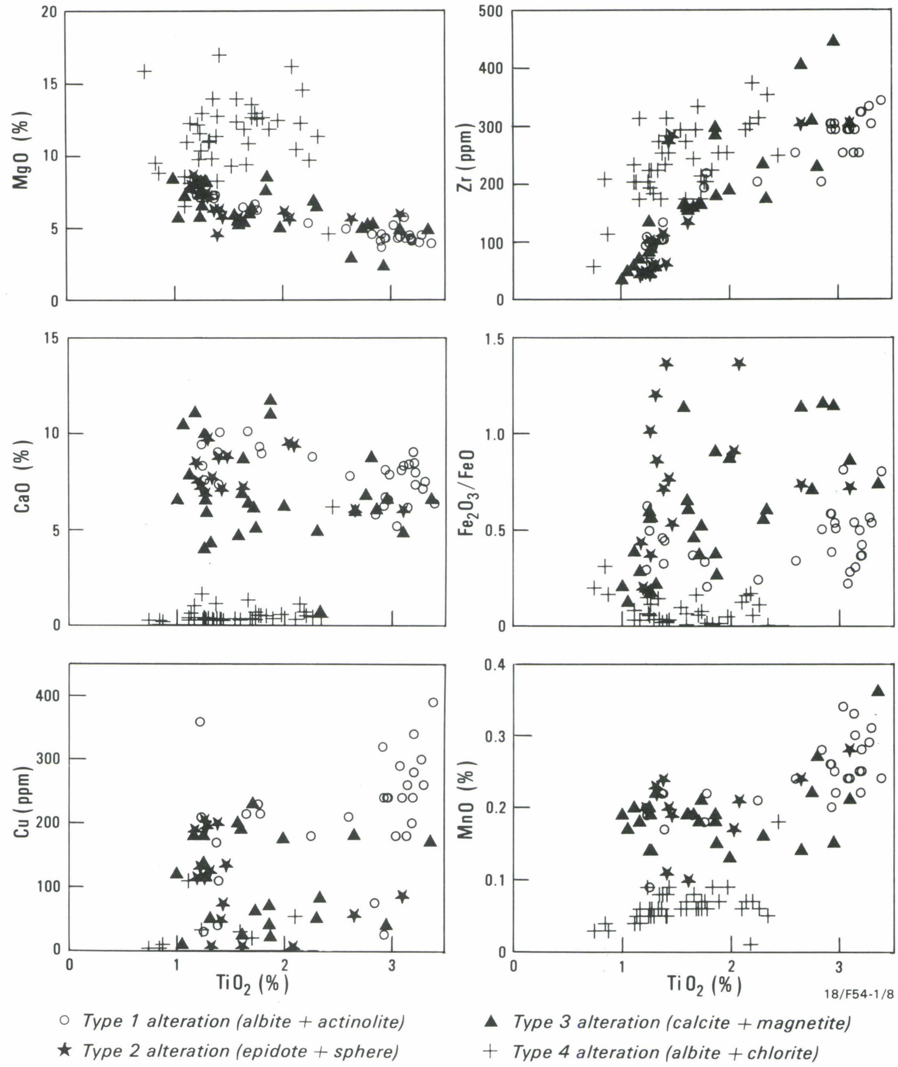

Fig. 6. Variation diagrams for the four alteration types.

Interpreted formation of Cu and U deposits

1) Basalt lava flows of the Eastern Creek Volcanics were extruded at around 1760 Ma. Subsequently, but before the main regional metamorphism and deformation, they were mildly altered (alteration type 1), resulting in the redistribution of Cu within the flows and the introduction of some S. Cu tended to be concentrated at the flow tops beneath impermeable sediment layers. It is important to note that the undeformed metabasalts do not appear to have lost any Cu.

2) During the major deformation and metamorphism at around 1600 Ma, oxidising fluid flushed S and probably most of the Au and Pt from the metabasalts; some Cu also moved at this time. The end-product included highly oxidised metabasalts, which were dominated by calcite + magnetite or epidote + sphene and still retained up to 100 ppm Cu but no S, Pt, or Au (alteration types 2 and 3). Most of the U deposits were formed at this time, and so were some of the spatially associated small Cu deposits. These deposits also tend to have anomously high Au and Pt values for the western Mount Isa Inlier, although these values in themselves are not remarkable.

3) During the third deformation at around 1500 Ma, a more reduced fluid (type 4 alteration) interacted with the previously oxidised metabasalts; it leached the remaining Cu from them, concentrating it in sites such as the Mount Isa Cu body. As Au had already been removed from the oxidised metabasalts, the Cu ores formed at this time are essentially Au free.

Remote-sensing studies are in progress to see if the various alteration types can be defined by multispectral image-processing.

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

ASEG/SEG Conference

The Australian Society of Exploration Geophysicists and the Society of Exploration Geophysicists will hold a joint international geophysical conference and exhibition in Adelaide from 14 to 18 February 1988. The theme of the conference is 'Leave nothing unattempted'.

The Technical Papers Committee is calling for papers (15 or 25 minutes duration) (i) expressing innovation and development in a wide range of geophysical disciplines and technologies; (ii) on marketing, finance, conservation, software, and hardware issues; and (iii) describing case histories that illustrate specific problem-solving. The closing date for titles (supported by no more than 250 words) is 30 April 1987, and for extended abstracts (up to 1000 words and six figures) is 1 August 1987 at the following address:

ASEG/SEG Adelaide '88 Conference
Technical Papers Committee
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PO Box 753, Norwood, South Australia, 5067,
telex AA87129, or facsimile (618) 3332248.

Controls of mineralisation in the Featherbed Volcanics, northeast Queensland

Felsic volcanic rocks and related granitoids associated with caldera-collapse structures or ring complexes have long been recognised as prospective areas for a variety of mineral deposit types, notably in the western USA. Ignimbrite-dominated felsic volcanic rocks of late Palaeozoic age are widespread in eastern Australia, particularly in northeastern Queensland. The Featherbed Volcanics, 100 km west of Cairns (Fig. 7), are located in an intensely mineralised region, but were poorly known geologically and, until the recent upsurge in gold exploration activity, had seen little mineral exploration.

In 1982, BMR, in collaboration with the Geological Survey of Queensland and James Cook University of North Queensland, began research on the Featherbed Volcanics and associated intrusive rocks with the objectives of determining if and how they are related to the extensive known mineralisation, and locating the most prospective sites for undiscovered mineral deposits.

The Upper Carboniferous to Lower Permian Featherbed Volcanics cover an area of about 3000 km^2 at the northern exposed end of the Tasman Fold Belt. The volcanic rocks are mostly confined to a composite volcano-tectonic subsidence structure made up of at least six (possibly nine) overlapping or juxtaposed collapse structures which appear to young to the northwest. The volcanics and associated intrusives comprise two main groups:

- Upper Carboniferous I-type rocks, which crop out on the southern and western sides of the Featherbed complex and in a sag structure in the southeast, and
- Lower Permian A-type rocks, which are mostly confined to an eroded composite caldera-collapse structure — or cauldron (Fig. 7).

Upper Carboniferous I-type rocks and associated mineralisation

Rocks in and around the southeastern sag structure include andesitic to rhyolitic ignimbrites, minor andesite lava, and intrusive rocks of an equivalent compositional range. The thickness of the volcanics in the sag structure is uncertain, but is probably 300–500 m. Upper Carboniferous rocks west of the main cauldron include rhyolitic and dacitic ignimbrites and granodioritic to granitic intrusives. I-type characteristics of these rocks include relative abundance of mafic compositions, ubiquitous biotite, very common hornblende, common pyroxene, and metaluminous to mildly peraluminous compositions moderately high in MgO, CaO, Sr, Ni, and Cr and low in Pb.

Mineral deposits in the Upper Carboniferous I-type rocks are mainly Sn, W, Mo, and base metals, and are particularly concentrated in and around the southeastern sag structure. However, work by students at JCUNQ shows that Upper Carboniferous granites associated with Sn-dominant mineralisation to the south and southeast of the area studied in this project appear to be of A-type character. W–Mo deposits at Wolfram Camp and Bamford Hill on the eastern side of the main cauldron, and at Scardons Top Camp on the western side are related to high-level plutons of intensely fractionated I-type biotite leucogranite dated at about 300 Ma. Some of the gold on the western side of the main cauldron may also be related to Upper Carboniferous I-type intrusive rocks, but that at Red Dome is related to a rhyolitic plug chemically more akin to the Lower Permian A-type rocks.

Lower Permian A-type rocks and associated mineralisation

Rocks within the main cauldron, and some of those between its northeastern margin and Mount Mulligan (Fig. 7) are mainly crystal-rich rhyolitic ignimbrites, with minor rhyolite lava around the margins; intrusive rocks range from granodiorite to granite, the most common being porphyritic microgranite which forms a discontinuous ring dyke around the cauldron. The exposed thickness of the volcanics is up to 600 m, and the total preserved thickness must be at least 1 km in places; the original thickness may have been twice that. Limited isotopic dating indicates a Permian age for these rocks, which are characterised chemically by low MgO, CaO, V and Cr, and high Ba, Pb, Zr, Nb, Y, rare earths, Zn, Sn, W, Ga, and Ga/Al$_2$O$_3$, relative to the Upper Carboniferous I-type rocks.

Known mineral deposits in these rocks are limited to sparse base-metal, Au, U, minor W, and possibly Sn. Base-metal and tin deposits at Dover Castle are hosted by Upper Carboniferous I-type volcanic rocks, but may be genetically related to a granitic intrusion in the mineralised area dated as earliest Permian. Tin and minor tungsten in the Koorboora area, between the southern end of the main cauldron and the Tennyson Ring Dyke, may be related to the Late Carboniferous magmatism, but could equally well be related to the Early Permian A-type magmas.

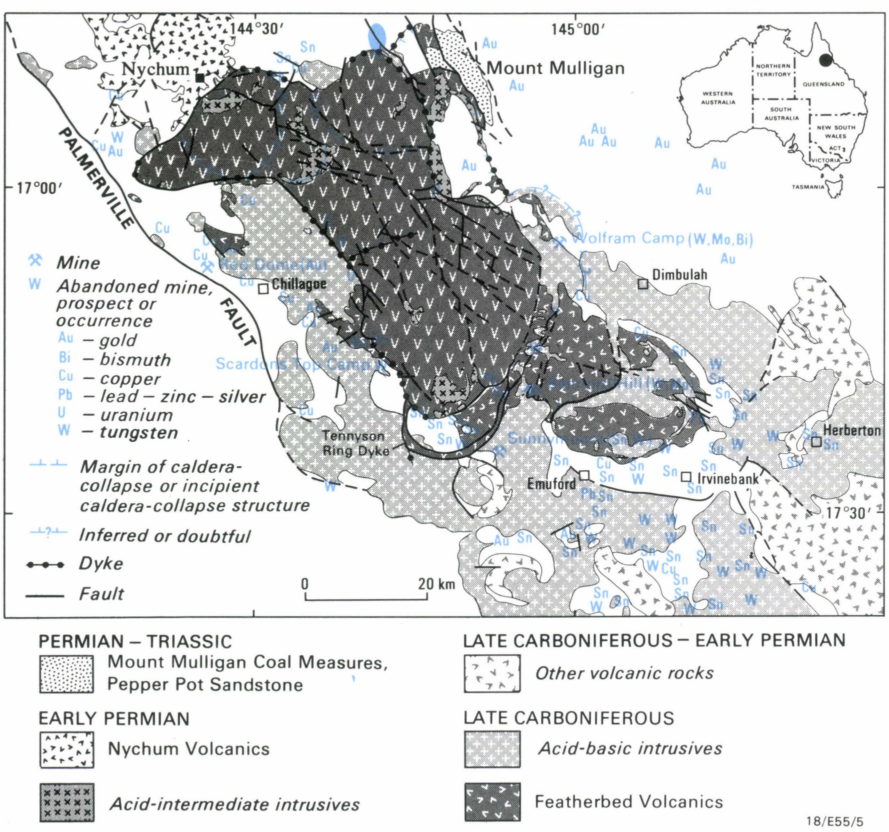


Fig. 7. Geology of the Featherbed Range area.

Implications of contrasting emplacement styles

One interpretation of the foregoing data is that the Upper Carboniferous rocks (and their country rocks) are inherently more prospective, particularly for Sn, W, Mo, and base-metals, than the Lower Permian rocks. The Upper Carboniferous volcanic rocks are much less voluminous and include a much greater proportion of mafic to intermediate rocks than the Permian volcanics, implying that their parent magma bodies were more mafic and therefore denser than those related to the main cauldron. The I-type parent magmas were probably also relatively more hydrous, and this combination of properties would have resulted in their being initially emplaced (before appreciable fractionation) at deeper levels than the A-type magmas. The greater depth of emplacement would account for the sagging of the relatively thick roof of the magma chamber during and after magma withdrawal, rather than wholesale caldera collapse. Extensive fractionation — from dioritic (or perhaps gabbroic) to granitic compositions — resulted in extensive concentration of fluids and ore metals, and the development of hydrothermal systems.

Their composition and volume indicate that the Permian rocks originated from much larger, mainly granitic magma bodies which — because of their lower density, higher temperature, and probably fluorine-rich, relatively anhydrous nature — are likely to have been emplaced at higher levels than the I-type plutons; indeed, there is abundant evidence of extensive intrusion into very high levels in the volcanic pile itself. As a consequence of this high-level intrusive activity, caldera collapse would have been much more likely than it would for the deeper-level I-type intrusive activity. Also, eruptions are likely to have been more voluminous, and fractionation, concentration of ore-forming metals, and generation of hydrothermal systems significantly more limited.

Exploration potential

Apart from emplacement style and chemical composition, other factors should be taken into account when assessing the exploration potential of the Lower Permian A-type rocks. A-type granitoids are apparently associated with much of the Sn-dominant mineral deposits in the Herberton–Irvinebank–Emuford region, southeast of the Featherbed Volcanics (Pollard, 1983; Witt, 1985; Johnston, 1986: all *PhD theses*, JCUNQ), and there is considerable evidence that A-type rocks generally are favourable host and/or source rocks for Sn and Climax-type porphyry Mo deposits (White & others, 1984: Geology of granites and their metallogenetic relations. Part 3: geochemistry. *Proceedings of the international symposium, Nanjing University, Nanjing, China,* 26–30 October 1982, 737–751). The southeastern lobe of the Featherbed Volcanics and the region to the southeast appear to be more deeply eroded than the main Featherbed cauldron, where favourable ore-depositional environments may not yet have been uncovered. Finally, there are extensive areas of hydrothermal alteration — mainly propylitic and sericitic, but also argillic and other types — in the main Featherbed cauldron, particularly around the margins and in areas of structural disturbance in the interior.

Thus the Lower Permian A-type rocks which make up the majority of the Featherbed Volcanics, and which might appear an unattractive exploration target, are probably at least as prospective as the Upper Carboniferous I-types, but for a different range of metals and different styles of mineralisation. The I-types are prospective for W-dominant and base-metal mineralisation — the A-types for Sn-dominant mineralisation, base-metals, U, and possibly Mo; both appear to be prospective for Au, the concentration of which is probably more a function of the existence of long-lived hydrothermal circulation and favourable depositional sites than of chemical character of associated (source of metals, fluids and/or heat) igneous rocks.

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

PEDIN

BMR's national petroleum exploration data index

PEDIN, which is being developed by BMR's Petroleum Branch, contains basic information and statistics on petroleum exploration drilling and geophysical surveys in Australia and its Territories. The database was designed and implemented in 1984 with the support of a NERDDP grant. Additional NERDDP support has been provided for further development of the database in 1987.

The main objective of the project in 1987 is to develop software to facilitate the use of the database both within and outside BMR. Reporting formats are being designed to present the data in a form of most general use to the exploration industry. Additional reporting formats will also be added, and reports will be produced to meet specific requirements.

Full implementation of the database will facilitate petroleum exploration and research on a national basis. It will be central to the development of modern computational techniques and systems for petroleum resource assessment in BMR.

PEDIN contains data on PSSA and P(SL)A wells and geophysical surveys. It also contains information on BMR geophysical surveys, and some basic data on post-subsidy onshore wells and surveys. It will be the most comprehensive database of its kind in Australia.

Data on wells entered into PEDIN include well location (co-ordinates, map sheet areas, basin, States, and permit areas), dates of drilling, equipment, operator, references to well completion reports, information on samples collected and their storage location, drilling objectives, and results (including stratigraphic information). Geophysical survey entries include survey location, basic information on survey parameters, techniques and equipment, and summaries of results and interpretations from survey reports.

PEDIN was implemented on BMR's HP 1000 computer using the HP/IMAGE 1000 DBMS, and is now being transferred to BMR's new mainframe computer, a Data General MV/20000 with an ORACLE DBMS. Open-file data stored in PEDIN on the Data General system will be available for general access.

Information on the PEDIN database will be published, and the database will be demonstrated to a number of government and petroleum exploration industry organisations later in 1987.

For further information, contact Mr John Moss at BMR.

Recent publications and data releases

Since the publication of the last issue of the *BMR Research Newsletter* (October 1986), BMR has released the following publications and data (up to 15 February 1987).

Publications

Reports

248 — Investigation of the characteristics and source of the Magnetic Ridge magnetic anomaly, Cobar, NSW.
249 — Application of geophysics to exploration for heavy-mineral sands deposits.
273 — Australian seismological report 1982.
276 — Review of Cambrian and Ordovician palaeontology of the Amadeus Basin.
Australian Petroleum Accumulations Report
1 — Amadeus Basin, central Australia.
Australian Mineral Industry Quarterly (Vol. 38, Nos. 3 & 4)
BMR 86 (yearbook for 1 July 1985 to 30 June 1986).
BMR Earth Science Atlas of Australia: Map grid overlay.
Petroleum Development Titles Map & Key: July 1986.
Australian Mineral Industry Annual Review 1985 preprint chapter: Uranium.

Maps

1:100 000 geological maps: 5757/pt 5756, Devils Marbles region; 5856/pt 5857, Kurundi region; 5955/pt 5855/pt 6055, Elkedra region.
1:20 000 preliminary geological map: Munni Munni layered intrusion.
1:1 000 000 magnetic domains map: S150 Albany.
1:500 000 regolith terrain: Australia.

Records released on open file

1985/37 — Mundaring geophysical observatory — twenty-fifth year 1983.
1985/39 — Handbooks for MPE-1 photo-electronic magnetometer (horizontal), MPE-2 photo-electronic magnetometer (vertical), and MCC-1 magnetometer controller, 3rd edition.
1985/43 — A proposal for ODP-drilling on the Australian continental margin in the Otway Basin/west Tasmania region.
1986/30 — VALAL and ASSAD: two programs for estimating and summing undiscovered petroleum resources.
1986/31 — Extended abstracts, BMR Research Symposium 1986.
1986/32 — Ranford Hill, Northern Territory: data record of 1:100 000 scale mapping.
1986/34 — Australia's potential for further petroleum discoveries (from May 1986).
1986/35 — Central Australian seismic survey, NT, 1985: operational report.
1986/36 — BMR magnetotelluric system: equipment and software, 1985.
1987/1 — First order regional magnetic survey of PNG, March/April 1985.

Release of data

Airborne geophysical maps

1:250 000: 78 maps, showing either magnetic properties, magnetic contours, radiometric contours, or flight-line systems (in all States).
1:100 000: two maps showing radiometric contours (Tasmania).

Digital data

Digital-point-located airborne magnetic data for five 1:250 000 Sheet areas (WA and SA).

Marine geophysical data

Lord Howe Rise — Survey 46, 1984 seismic stack and migrated sections, track chart, water-depth profiles, and magnetic profiles covering the following 1:1 000 000 Sheet areas: 31° 30'–35° 30', 150° 00'–156° 00'; 31° 30'–35° 30', 156° 00'–164° 00'.
Australia–NZ–USA Tripartite Program 1982 — Solomon Islands/Tonga/Vanuatu.
SW Pacific — USGS seismic data in offshore sedimentary basins in southern Vanuatu, southern Tonga Platform, and the offshore basins flanking the Solomon Islands (8100 km of 24-fold CDP multichannel seismic-reflection profiles). Seismic sections, shot-point location and bathymetric maps, bathymetric profiles, gravity and magnetic profiles are available.
Kerguelen Plateau research cruise 2, 1985 — four navigation data sheets at 1:1M scale.

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

BMR's assessment of EOR potential in Australia

An enhanced oil recovery (EOR) project is being carried out by BMR with the support of a NERDDP grant. The project is designed to provide a detailed assessment of Australia's petroleum resources which may be derived by enhanced recovery methods.

The main objectives of the project are to identify the most likely petroleum fields in Australia with prospects for the application of EOR techniques, and to assess the amount of additional oil which may be recovered using various improved recovery techniques at selected oil-pricing levels.

Oil-bearing reservoirs that appear to be most suitable for the application of improved recovery techniques will be selected with the aid of a basic screening process. Screening of reservoir information already collated for publication in BMR's *Australian Petroleum Accumulations Report* series will assist in the selection of possible suitable reservoirs in the early stages of the EOR project. Later detailed technical and economic information will be sought from the petroleum industry for particular fields and reservoirs selected for study.

The Centre for Petroleum Engineering Studies at the University of New South Wales will collaborate in the EOR project by providing computer-modelling expertise, and by carrying out detailed simulation studies of the selected reservoirs. A consultant with many years experience in the petroleum industry throughout the world will also be employed on the project.

The EOR project is the first such detailed study of prospective methods for improving the recovery from Australia's petroleum reservoirs. The study will highlight the potential value of EOR to Australian petroleum production. In particular, consideration of economic factors in the study will provide guidance to the petroleum industry on the potential of any given application of EOR compared with drilling new field wildcat wells. It will also provide additional information for a better quantitative assessment of Australia's petroleum resources for use in strategic planning and policy evaluation by industry and governments.

Information on all major aspects of the EOR studies will be published under the terms of the NERDDP grant. The confidentiality of detailed information provided by the petroleum industry will be maintained.

For further information, contact Mr Brian McKay (Resource Assessment Division) at BMR.

IEA EOR conference

In September of this year, officers from BMR's Petroleum Branch, in conjunction with the International Energy Agency (IEA), will organise a three-day meeting in Sydney on enhanced oil recovery (EOR). A two-day field excursion to visit Bass Strait offshore production facilities will follow the Sydney meeting.

The meeting, sponsored annually by IEA, will be attended by representatives from ten nations; BMR is the designated lead agency for Australia. EOR research by the member nations covers four task areas involving improved recovery by chemical, thermal, and miscible methods, and interfacial/capillary research. Australia participates in the last two task areas through research at the University of New South Wales and the Australian National University, and both programs are supported by NERDDP grants.

Each year, one of the member nations agrees to host the annual meeting, comprising a workshop, symposium, and field visit. At these annual meetings, the agreed research program is discussed in a (two-day) restricted workshop, and discussion papers dealing with EOR field applications and/or problems are reported to a wider (invited) audience at the symposium which follows. At the Sydney meeting the theme of the symposium will be EOR for 'difficult' oilfields, for which no simple improved recovery solution has been identified.

More details from Mr Brian McKay at BMR.

Omniprobe

Performance and future direction

Successful field trials of the BMR-designed Omniprobe down-hole EM instrument were conducted at Broken Hill during June and July of 1986. The trials demonstrated a strong point of the polarisation-ellipse (PE) technique: directional information was gained from the ellipticity in that the largest anomaly occurred when the orebody was between the transmitter loop and the down-hole receiver. Sensitivity too was high: secondary signal levels were measured down to below 0.1% of total received signal.

The prototype instrument (see *BMR Research Newsletter* 2, p. 13) had recently been interfaced to a microcomputer to simplify development, to increase versatility, and to allow the operator to monitor data quality during acquisition. A new faster algorithm for calculating the PE parameters enabled these to be displayed without slowing the acquisition process (Cull & Cobcroft, 1986: *Geophysical Prospecting*, 34, 569–579).

Field trials site

The site chosen was the Flying Doctor lease of North Broken Hill Ltd, which had been used for pre-prototype tests and so provided a reference for instrument performance. Many other groups have also logged the site and produced much data, allowing comparison of Omniprobe with a wide range of equipment. Four holes — DD3071, DD3040, DD3039, and DD3055 (Fig. 8a) — were logged using each of the four transmitter loops (Fig. 8b).

Performance and the polarisation ellipse

When the EM wave from the transmitter (the primary wave) interacts with the secondary wave from the orebody, the resultant magnetic vector rotates as it oscillates in magnitude. The path traced by this vector is an ellipse which has its major axis determined mainly by the primary wave, and minor axis largely by the secondary wave.

For many years EM prospecting used PE techniques which were unwieldy. BMR's Omniprobe has changed that, as it simply computes the ellipse parameters from amplitude and phase data from three orthogonal sets of coils. With a demonstrated secondary-signal sensitivity of better than 0.1%, Omniprobe is at least comparable with contemporary time-domain (TD) systems. Unlike those TD systems which switch off the receiver during the transmitted primary pulse, Omniprobe uses both the primary and secondary signals. The magnitude of the major axis of the polarisation ellipse gives information on ground transmission, while the ratio of minor-axis magnitude to major-axis magnitude, namely the ellipticity, gives information on the orebody. These PE parameters are continuously displayed during logging.

Omniprobe principles are not peculiar to borehole prospecting. This three-component system escapes the angular or distance precision required by single-component EM surveys where geometric problems can readily produce 'anomalies' similar to those produced by orebodies (McCracken & others, 1986: *Geophysics*, 51(3), 819–832). Both surface and airborne EM work would therefore gain from Omniprobe processing, which combines three magnitudes and three phases to produce a result which is independent of receiver orientation.

Field results

Ten times the ellipticity, namely R, is plotted against depth (Fig. 8c). R is independent of transmitted power, and of the absolute phase of the received signal with respect to the transmitted waveform.

Figure 8c shows results only from DD3071 and loop 1 — the most interesting combination because the hole does not intersect the main lode, and the down-hole receiver is well illuminated by the primary wave. Notice, however, that DD3071 passes through three mineralised filaments with thicknesses ranging from 300–610 mm. Although the other holes and transmitter loops generally produce larger responses, the chosen combination provides not only a better test of system capability but it permits comparison between the responses of the main lode and the intersecting filaments.

Of the three 100-m loops used in logging DD3071, loop 2 produced the largest value of R (0.43 at 109 Hz) from the main orebody, and loop 4 the smallest (0.32 at 109 Hz). Loop 3 gave a value of 0.41 for R at 109 Hz. This result was expected because the orebody was between loops 2 and 3, and the receiver in DD3071; however, the orebody ended under loop 3, but extended beyond the far side of loop 2. Larger percentage differences in the values for R were measured at higher frequencies. When loop 2 or loop 3 was used, the orebody partly screened the receiver from the primary wave, and, as this screen was the source of the secondary wave, a larger ellipticity than that from loop 4 necessarily resulted.

Directional information was therefore provided, although more fieldwork, in which four or more loops of similar size are placed around the borehole, is needed to assess fully the accuracy of direction-finding.

Quite clearly the encompassing loop 1 can give no directional information on a horizontal plane, but it can show the depth of the orebody, and show depths of intersections with the relatively conducting filaments. Centred on 106–8 m are the orebody responses (see Fig. 8c), the shoulders of which hide the low-grade 600-mm long intersection at 116 m. Higher-grade 300-mm and 610-mm intersections at 124 and 136 m are clearly shown. These minor intersections could of course be missed completely if the spacing were increased beyond the 2-m measurement interval used to produce Figure 8c.

The future

If the Omniprobe project proceeds past the prototype stage, then a much higher level of digital processing would be highly desirable. This would decrease the complexity of the hardware and increase the versatility of the system. It would be possible to produce, by means of software operating in real-time, traditional frequency-domain (FD), PE, and TD parameters. The

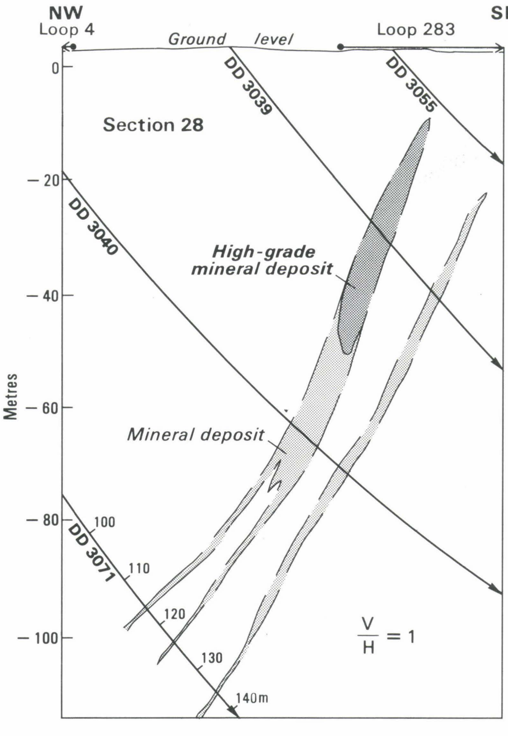
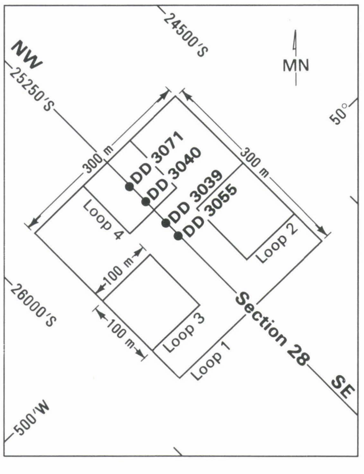
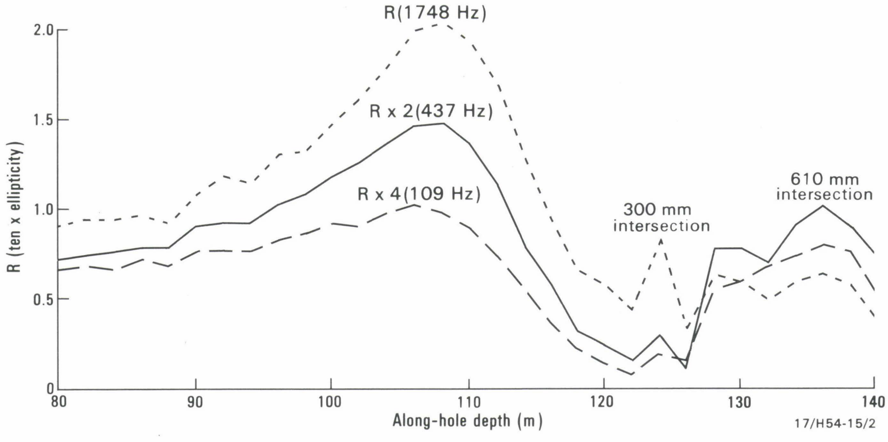


Fig. 8. (a, *left*) Positions of drillholes and mineral deposit through section 28, Flying Doctor Lease, Broken Hill; loops 2 and 3 are equidistant from section 28, which bisects loops 1 and 4. (b, *below*) Configuration of transmitter loops. (c, *bottom*) R plotted against along-hole depth for DD3071; values for R at 437 Hz and 109 Hz have been multiplied by 2 and 4 respectively; transmitter loop 1 was used to produce these curves.





transmitted waveform would be selected by the operator, who could choose harmonics in whatever ratio best combats regional noise. Thus Omniprobe could measure simultaneously FD and PE parameters at several frequencies, and so remove another objection to FD prospecting. Several schemes have been devised to improve the direction-finding, but if this is required more work must be done. Given the above-mentioned features, Omniprobe could become a vehicle for future research in EM prospecting, and finally remove the conceptual boundaries between FD and TD EM.

BMR recognises that for further progress to be made, additional fieldwork and further theoretical studies must be carried out. However, in the present climate only limited practical resources are available. Accordingly BMR would welcome any industrial input into the development of the project or other related areas of EM research.

For further information, contact Mr Malcolm Gamlen (Engineering Services Unit) about the Omniprobe design, or Dr Terry Lee (Division of Geophysics) about EM research in BMR.

Regolith research

The association of commercial regolith deposits with deep leads and supergene enrichment of gold, and the need to understand surface processes for an interpretation of remote-sensing imagery, have stimulated a greater interest in the regolith of Australia. Nowhere is this more evident than in the Kalgoorlie region, where gold mining and exploration are booming. This upsurge in gold as well as diamond exploration in recent years has led to increased exploration industry interest in understanding the distribution, nature, and origin of regolith materials, particularly in Western Australia.

BMR's regolith research over the last two to three years has generated a reconnaissance regolith database for the entire Australian continent, as well as two regional regolith maps and associated reports and various papers which attempt to throw light on the nature and evolution of the regolith in particular areas.

An Australia-wide review (*BMR Record* 1986/27) consists of systematic descriptions of 392 broad regolith terrain units depicted on a 1:5 000 000-scale map and based on dominant topographic and regolith features (soils, weathering profiles, surficial deposits). A comprehensive bibliography is included.

A study of western Victoria (*BMR Record* 1986/33) comprises systematic descriptions of 57 regolith terrain units, and summary descriptions of the geology and geomorphology, in the Hamilton 1:1 000 000 Sheet area.

Whereas the Australia-wide and western Victoria studies were mainly compilations of available data (published information and some remote-sensing data), a study of the Kalgoorlie area also involved reconnaissance field studies, and placed a greater emphasis on the application of remote sensing to regolith studies — especially regolith mapping.

Kalgoorlie regolith mapping

The regolith terrain map of the Kalgoorlie 1:1 000 000 Sheet area is an attempt at classifying and describing the regolith in order to make it more understandable to geologists and, in particular, exploration geoscientists.

Reconnaissance fieldwork in the Kalgoorlie region indicated a degree of complexity in the regolith not previously foreseen (Ollier & others, in preparation: *BMR Journal of Australian Geology & Geophysics*). This complexity, the significant depth of the regolith (>100 m over large areas), and the paucity of deep cuts showing the full extent of the weathered profiles, made it necessary to map geomorphic features as a surrogate for the regolith. The regolith terrain units that resulted are grouped into regolith terrain provinces which reflect the underlying tectonic provinces of the Yilgarn Block, Albany–Fraser Province, and Officer and Eucla Basins.

Extensive use was made of Landsat–4 multispectral scanner (MSS) imagery, and some reference was made to advanced very high resolution radiometer (AVHRR) and coastal zone colour scanner (CZCS) imagery on board the respective NOAA and NIMBUS–7 satellites. The results of the Kalgoorlie regolith mapping will be published as a 1:1 000 000 regolith terrain map accompanied by a series of descriptions of the regolith and associated features of each unit and explanatory text.

Already, the exploration industry has shown much interest in regolith maps as a meaningful way of locating areas for mineral exploration, such as for gold and diamonds, both within and beneath the regolith. Future more detailed regolith studies and mapping could throw further light on the properties of the regolith materials (including various geophysical and geochemical properties), their distribution and depth, the processes that formed them, and their relationship to the underlying geology (e.g., Fig. 9). This could permit refined definition of target areas for mineral exploration through a better understanding of the geomorphological history of the area.

The future direction of regolith research in BMR is at present under review.

For further information, contact Ms Roslyn Chan (Special Projects & Geoscience Services Branch) at BMR

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Fig. 9. Granite saprolite (A) with corestones (B) overlain by a sand sheet (C). The part of the sand sheet below the stone line has resulted from loss of clay and the reorganisation of sand grains derived from the underlying saprolite; the part above the stone line is transported.

New geochronological results from the Davenport province, and implications for the Arunta Inlier

The first U–Pb zircon ages have been obtained recently for felsic volcanics from the Warramunga and Hatches Creek Groups in the Davenport province, which forms the southern part of the Proterozoic Tennant Creek Inlier. In addition, altered felsic volcanics from the Hatches Creek tungsten field and other parts of the province have been dated by the Rb–Sr whole-rock technique.

Warramunga Group

The Warramunga Group, a unit consisting mainly of interbedded greywacke and siltstone but also including felsic volcanics, was deformed before being overlain unconformably by the Hatches Creek Group and its correlative north of Tennant Creek, the Tomkinson Creek beds. Zircons from two samples of porphyritic rhyodacite from the Warramunga Group in the north of the Davenport province have yielded a U–Pb discordia age of 1935 ± 8 Ma. This age is appreciably older than an 1870 ± 15 Ma zircon age previously determined for the Warramunga Group 90 km farther north, near Tennant Creek.

Hatches Creek Group

Unlike the Warramunga Group, the Hatches Creek Group is characterised by quartz-rich sandstones and both felsic and mafic volcanics. Analysed zircons from porphyritic rhyolite in the basal part (Epenarra Volcanics) give somewhat ambiguous results, but indicate older and younger age limits of 1894 Ma and 1820 Ma. An age of 1813 ± 5 Ma is interpreted for zircons from a felsic ignimbrite higher in the Hatches Creek Group (Treasure Volcanics). The present ambiguities arise because of complexities due to inheritance and multiple Pb loss, and further work is now being done to resolve these complexities.

When plotted on an isochron diagram, Rb–Sr whole-rock data for hydrothermally altered felsic volcanics of the Hatches Creek Group from various parts of the Davenport province give a model 2 'age' of 1645 ± 44 Ma. The alteration is most intense in the Hatches Creek tungsten field, where it appears to be related to the tungsten and minor copper, bismuth, and molybdenum mineralisation. The Rb–Sr 'age', which may indicate the approximate time of this alteration event, is at least 120 Ma younger than the U–Pb zircon ages of the Hatches Creek Group, but is similar to an Rb–Sr age of about 1660 Ma reported for the Elkedra Granite, which intrudes the Hatches Creek Group in the far south of the Davenport province.

Arunta Inlier

The Precambrian Arunta Inlier southwest of the Davenport province is poorly known stratigraphically because of complex deformation and metamorphism, and primary age data are lacking. Three broad stratigraphic groupings, called Divisions 1 (oldest), 2, and 3 (youngest), have been recognised within the inlier, and unconformities between divisions are present in places. Schist, metasandstone, and amphibolite assigned to Division 2 are exposed within 50 km of the Davenport province, in the Crawford and Osborn Ranges, where they underlie felsic volcanics and sandstone of the Hatches Creek Group. Contacts between the two units are not exposed, but the relationship is thought to be unconformable, chiefly because of a marked difference in metamorphic grade. The Arunta Division 2 rocks lithologically resemble, and are correlated with, the Warramunga Group, and the Hatches Creek Group is correlated with Arunta Division 3 (Stewart & others, 1984: *Australian Journal of Earth Sciences*, 31, 445–455). Therefore the best current estimate for the age of Arunta Division 2 is 1935 Ma, whereas Arunta Division 3 includes rocks between 1800 and 1900 Ma old.

In terms of the model proposed for the Early and Middle Proterozoic of northern Australia (Etheridge & others, in press: *AGU Geodynamics Series*, 16), the Warramunga Group and Arunta Division 2 belong to cycle 1, and the Hatches Creek Group and Arunta Division 3 are part of cycle 2. The deformation event separating the two sequences corresponds to the 1880–1890 Ma Barramundi Orogeny.

For further information, contact Drs David Blake, Rod Page, or Alastair Stewart (Division of Petrology & Geochemistry) at BMR.

Extensional structures in the Mount Isa Inlier

In *BMR Research Newsletter* 2 and 4, preliminary results of structural investigations in the Mount Isa Inlier highlighted the complexity of deformational events and the difficulty in establishing unique solutions to the present-day outcrop pattern. Continuing studies since 1984 have documented a phase of early brittle deformation in the Duchess Belt and in the Mitakoodi Quartzite east of the Duchess Belt (Fig. 10). There is a strong possibility that this phase was regionally extensive and related to low-angle normal faults forming detachment zones during an early stage in the tectonic evolution of the inlier. The location of these early faults may have economic and exploration significance because mineral deposits are associated with similar structures in other parts of the world.

The Mitakoodi Quartzite on the western limb of the Bulonga Anticline adjacent to the Pilgrim Fault comprises quartzite and calcareous metasiltstone with several dykes and lenses of amphibolite. It records a complex four-phase deformational history: the first phase caused extensional imbricate faulting (early faults) and, possibly, substantial stratigraphic omissions in the area; the three later phases resulted in cleavage formation and/or folding.

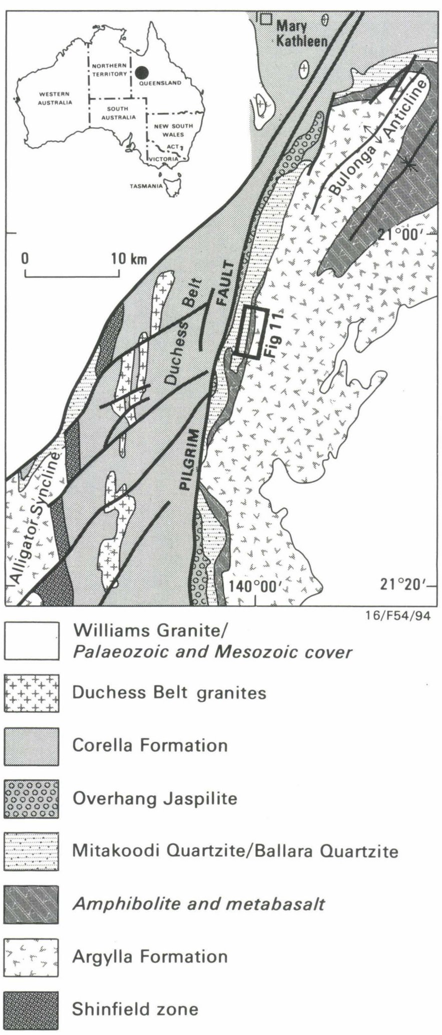

Fig. 10. Geology in the Duchess Belt–Bulonga Anticline area of the Mount Isa Inlier.

Geometry of early faults

The early faults are rotational normal structures with fault planes at a low angle to bedding in quartzite, which commonly has a similar orientation in adjacent fault blocks. In one small area in which an imbricate set of these faults cuts vertical bedding (Fig. 11A), the faults converge to the west (stratigraphically downwards) to a continuous zone of amphibolite intruded along a larger north-trending fault which has a curved listric form. They die out upwards into a calcareous fine-grained metasiltstone unit which includes a layer of quartzite apparently broken apart along strike above the imbricate faults (Fig. 11A). The quartzite block immediately south of the imbricate faults is interpreted as part of the fault complex; the dip of its bedding is formed by reverse drag on the listric fault. Roll-over anticlines and ramp synclines have also been mapped in adjacent areas.

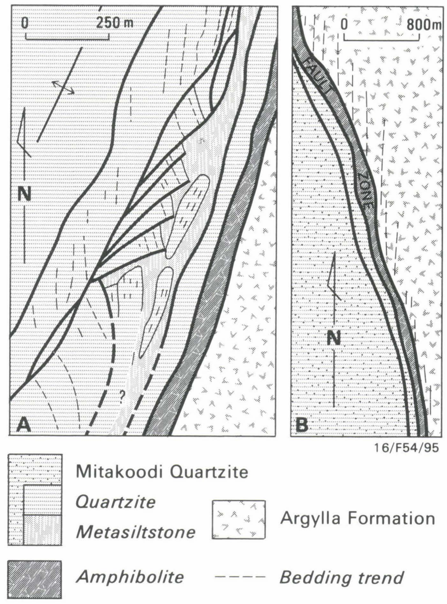

Fig. 11. Maps of (*A*) imbricate normal faults above detachment faults, and (*B*) a detachment zone at the base of the Mitakoodi Quartzite.

The amount of extension across the imbricate fault sets can be estimated from the total strike length of the fault blocks and their overall separation. Percentage extension values (67–81%) throughout the area are remarkably consistent, especially as the angular relationships in the fault complexes may have been modified by later folding.

Amphibolite within the Mitakoodi Quartzite forms anastomosing bands thought to be metamorphosed mafic dykes because of their planar cross-cutting nature; it is not associated with deposition of the sequence. The bands are deformed by and hence older than the regional compressional deformational events, and are preferentially located along rotational faults between quartzite blocks. The association of pre-folding amphibolite intrusion with rotational imbricate fault zones shows that the faults also formed before the earliest folding event, and establishes the faults as early brittle structures in the Mitakoodi Quartzite in this region.

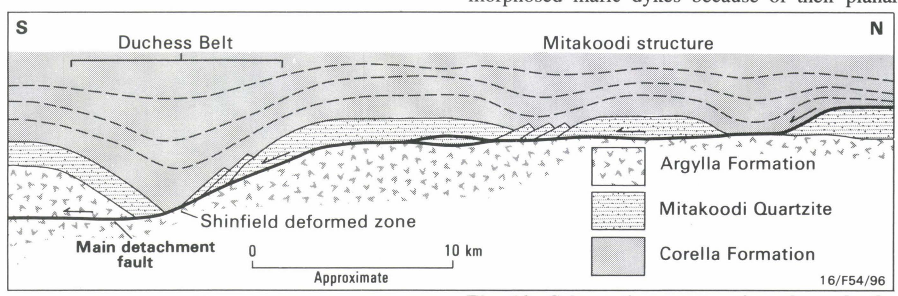

Fig. 12. Schematic cross-section through the area now occupied by the Duchess Belt and Bulonga Anticline before it was deformed by compressional events.

Breccia lenses cross-cut by the earliest cleavage, and parallel to amphibolite or early faults, are inferred to have formed by collapse of hanging-wall material into fault-controlled openings during the late stages of early brittle deformation.

The base of the Mitakoodi Quartzite is separated from underlying Argylla Formation by a unit of amphibolite (Fig. 11B) against which bedding within the Argylla Formation is truncated by a fault. The truncated Argylla metavolcanics are neither thickened nor repeated at higher stratigraphic levels, yet nearly 300 m of them has been removed along this fault, which is thus interpreted as an initially low-angle detachment fault along which amphibolite intruded. The upper surface of the lowest lens of the Mitakoodi Quartzite is also in sharp discordant contact with overlying rocks, and thus may also be a low-angle normal fault.

Regional pattern of extensional event

The belt mapped as Mitakoodi Quartzite forming the western limb of the Bulonga Anticline contains several areas of only thin quartzite and in places none. In this belt, the presence of imbricate extensional faults, ramping-down of quartzite into the underlying Argylla Formation, ramp synclines, and extensional normal faults all suggest that these stratigraphic gaps are the result of an early extensional event. The direction of the main

(continued in column 3, p. 11)

Phosphate deposits monograph

PHOSPHATE DEPOSITS OF THE WORLD, VOLUME 1: PROTEROZOIC AND CAMBRIAN PHOSPHORITES, edited by P.J. Cook and J.H. Shergold, and published (in September 1986) by Cambridge University Press, is the first in a series of multi-author volumes summarising the results of an international research program on phosphate deposits (International Geological Correlation Programme (IGCP) Project 156). As a part of its charter to facilitate and acquire knowledge of mankind's resources, an international project to study sedimentary phosphate deposits (phosphorites) was formally accepted as IGCP Project 156 in early 1977. This book results from the initial emphasis placed by Project 156 on phosphorites of Proterozoic and Cambrian ages. Subsequent volumes will cover Cretaceous–Eocene, and Neogene–modern phosphorites, and a separate volume will provide a co-ordinated account of world phosphate resources.

In volume 1, Proterozoic and Cambrian phosphorites from all continents except Antarctica are described in 26 chapters by an international team of 46 research workers from 15 countries. The book is divided into three parts. The first comprises a series of regional chapters (Australia, China, USSR and Mongolia, Indian subcontinent, Europe, North America, West Africa, Brazil). The second deals with individual deposits of economic significance (Lady Annie, Queensland; Kunyang, Yunnan, China; Lao Cai, Vietnam; Khubsugul, Mongolian People's Republic; Karatau, Kazakhstan, USSR; Hazara, Pakistan; Jhamarkotra, Rajasthan, India; Fontanarejo, Spain; and Volta Basin, west Africa). The third part comprises a series of specialist papers dealing with chemical and mineral characteristics; organic geochemistry, palaeogeography, and palaeoceanography of phosphatic sediments; the biochronology of Proterozoic and Cambrian phosphorites; and exploration criteria. The final chapter draws many of these threads together to produce an overview of the nature and origin of phosphorites. The data presented provide a current understanding of the geographical and stratigraphical distribution, the nature, and the origin of these ancient phosphorites.

The book is a contribution to our understanding of the genesis of phosphatic sediments, and should be an aid to the search for, and exploitation of, phosphate deposits.

For further information, contact Drs Peter Cook or John Shergold (Division of Continental Geology) at BMR.

Petroleum geology of the Siberian Platform

Clues for the occurrence of Proterozoic petroleum

The Siberian Platform occupies an immense area of eastern Siberia (Fig. 13). It consists of an Archaean and Lower Proterozoic basement overlain by Riphean (Middle to Upper Proterozoic) to lower Palaeozoic and younger strata. Nine significant oil and gas fields have been located in Vendian (latest Proterozoic) and Cambrian reservoirs. Total recoverable reserves are uncertain at present, but Meyerhoff (1979: *AAPG Memoir* 30, 225) quoted total reserves of 17.3 Tcf of gas and 435 million barrels of oil and condensate for three of the fields. As part of BMR's current interest in the petroleum potential of the Precambrian of the McArthur Basin (*BMR Research Newsletter* 3, 1–2), an organic geochemist from BMR visited the Soviet Union to gain an insight into the conditions of formation and preservation of petroleum in the Siberian Platform as a guide to the possible occurrence of Proterozoic petroleum in Australia. This report briefly discusses the petroleum geology of these very old rocks.

Structure and sedimentary cover

The platform comprises a series of regional arches and domes (anteclises) and basins (synec-lises). The petroleum occurs in the Nepa–Buotobin Anteclise (VI, Fig. 13). The sedimentary cover varies in thickness from 2 km in the anteclises to 14 km in the syneclises. The Baikalian Foldbelt to the south of the platform contains Proterozoic rocks that were last deformed in middle Palaeozoic time.

Riphean carbonate and terrigenous rocks exceed 5 km in thickness on the margins of the platform, and also occupy narrow rifts within the platform but are absent from some anteclises. In the pre-Baikalian Trough (VII, Fig. 13) the upper part of the Riphean sequence contains up to 350 m of organic-rich shale and carbonate (TOC values 3.5 to 5%), and laps on to the southern part of the platform.

The Vendian–Cambrian rocks represent the period of maximum transgression of the Siberian Platform, and reach a maximum thickness of 2.5 km. Vendian clastic redbeds vary in thickness from 0 to 300 m, and lap on to the Nepa–Buotobin Anteclise from the south, southwest, and northwest. Farther north the Vendian–Cambrian rocks consist of carbonates and some salt beds; these strata are equivalent to and perhaps slightly younger than the Vendian clastic rocks.

The Lower and Middle Cambrian rocks in the southern part of the platform consist of four carbonate–salt cycles with a total thickness of 2.5 km. Upper Cambrian, Ordovician, and Silurian sedimentary rocks rarely exceed 300 m in thickness in the southern part of the platform. Flood basalts of Early Permian and Triassic age cover most of the northwestern portion of the platform, but are absent from the Nepa–Buotobin Anteclise. Mesozoic sedimentary rocks occur sporadically. During the Mesozoic–Cenozoic, the platform was uplifted 1.5 to 2 km in the extreme northwest and 1 km in the southeast.

Major structuring occurred in the most southerly part of the platform during Silurian–Devonian time, when the Baikalian Foldbelt was thrust towards the platform. Folds associated with wrench-faulting form the traps on the northeast part of the Nepa–Buotobin Anteclise. The salt acts as a zone of detachment, since structures in the Vendian to Early Cambrian are not related to those overlying the salt.

Petroleum geology

The oil and gas fields lie at depths of 1.5 to 2.5 km. The main reservoirs are Vendian sandstones, but some overlying carbonates (Vendian–Cambrian) are also productive. Traps in the southwest are formed by up-dip pinch-out of the Vendian sandstones (e.g., Markova Field; 1, Fig. 13). Farther northeast, Vendian reservoirs occur in anticlines (e.g., Sredne–Botuonvinskoe Field; 6, Fig. 13). The traps in carbonates are purely stratigraphic, and rely on preservation of patches of porosity in organic-framework carbonates.

Vendian clastic reservoirs are mainly coastal marine bars. Some alluvial fans lower in the Vendian clastic sequence are also productive. The marine sands have average porosities of 15%, and average permeabilities range from 300 to 600 md. In contrast, the alluvial-fan reservoirs have average permeabilities of around 100 md. Carbonate reservoirs consist of dolomitised stromatolites, but the cavernous porosity is generally filled with salts; intergranular porosities are of the order of 8 to 10%, and permeabilities average 300 md.

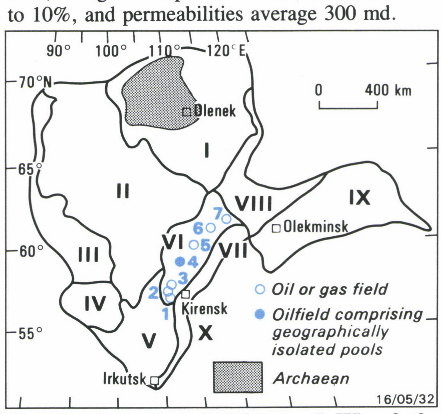

Fig. 13. Tectonic subdivisions (I–IX) of the Siberian Platform, and locations of oil and gas fields (1–8). I, Anabar Anteclise; II, Tunguska Syneclise; III, East Yenisey Terrace; IV, pre-Sayan–Yenisey Syneclise; V, Angara–Lena Terrace; VI, Nepa–Buotobin Anteclise; VII, pre-Baikalian Trough; VIII, Vilyuy Syneclise; IX, Aldan Anteclise. The Baikalian Foldbelt (X) lies outside the Siberian Platform.

In the southern part of the platform, the maximum depth of burial of the Vendian–Cambrian section was about 2 to 3 km, during the Ordovician. About 0.5 km of the section has been removed by erosion. Vendian rocks in the oilfields are at the late stage of oil generation. The source for the hydrocarbons is the organic-rich Riphean rocks lying on the southern slope of the platform and in troughs within the platform. At the present time these rocks are in the late stages of catagenesis. Accumulations of pyrobitumen, and fossil gas–oil contacts, represent the remains of exhumed oilfields in Riphean rocks in the exposed parts of the pre-Baikalian Trough.

A first stage of oil generation probably occurred in Late Proterozoic to early Palaeozoic time. Oil was trapped in the Vendian and Riphean sediments, and some migrated up-dip to the crest of the Nepa–Buotobin Anteclise. The continued burial and folding of the Baikalian Foldbelt in the middle Palaeozoic induced further catagenesis and the destruction of previously formed oilfields on the southern margin of the platform to form pyrobitumen, and resulted in gas generation. Gas–condensate and light oils migrated ahead of the maturation front to the present-day locations.

Factors contributing to petroleum occurrence in the Siberian Platform

1. The southern ramp of the platform faced an actively subsiding trough containing organic-rich sediments. It was ideally placed to receive hydrocarbons migrating out of the trough.

2. The platform, marginal to the trough, provided the shallow-water conditions for the formation of high-quality reservoirs, and provided a primary trapping configuration in the form of up-dip pinch-outs.

3. The platform has remained relatively stable over time, and has not been deeply buried. The reservoir hydrocarbons were not destroyed by thermal processes, in contrast to those in the trough to the south.

4. The reservoirs are capped by evaporites that have maintained a tight seal over the hydrocarbon reservoirs during subsequent tectonic movements. The salt has also acted as a detachment zone protecting the reservoirs beneath from severe disruption.

5. The oilfield area was not involved in the vulcanism that has probably destroyed oilfields in the northwestern part of the platform.

The petroleum accumulations in the Siberian Platform represent a remnant of a much more extensive petroleum province that has been destroyed by subsequent events. The preservational features assume particular importance in considering the petroleum potential of Proterozoic sequences.

Acknowledgements

Thanks are due to the staff of the All-Union Petroleum Geological Research Institute — Leningrad, the Institute of Geology, Geophysics and Mineral Resources of Siberia — Novosibirsk, and the East Siberian Research Institute, Geology, Geophysics and Mineral Resources — Irkutsk for their knowledge and hospitality during the visit. The visit was made under the auspices of the Australia–USSR Scientific and Technological Cooperation Program, which is co-ordinated in Australia by the Department of Science.

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

Extensional structures

(continued from p.10)

regional folding is north to north-northeast, at a high angle to the strike direction of the early imbricate faults. This indicates that the early extensional direction was in a southerly or southwesterly direction, and that detachment faults cut down-section to the southwest (Fig. 12). The presence of these features within the Mitakoodi Quartzite is strong evidence of a regionally important early brittle deformational event affecting a large area of the Mount Isa Inlier.

The presence of similar structures 25 km to the west in the Alligator syncline, discovered and mapped by C. Passchier in 1984–86, and evidence of thinning of the Argylla Formation there across a zone of intense deformation, suggest an extensional origin for that structure. The main detachment surface in the Mitakoodi Quartzite may correspond to the Shinfield deformed zone, and may ramp through the Argylla Formation to cause the stratigraphic thinning and downbowing of the overlying Corella Formation into the synclinal structure now preserved as the Duchess Belt (Fig. 12).

Age of extensional structures

The extensional structures affect the granites of the Duchess Belt which have been correlated with 1740-Ma granites to the north and are older than the earliest compressional event (minimum age, 1620 Ma). The event probably predates the deposition of the younger sedimentary sequences of the Mount Isa Inlier, such as the 1670-Ma Mount Isa Group, and may have important implications regarding late basin development and crustal thinning in the Mount Isa region.

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

Quarterly mineral statistics

New information sheet released

In October 1986, BMR released the first of a new series of information sheets containing quarterly statistics of Australian mine, smelter, and refinery production; and imports and exports of the principal mineral commodities.

The sheet, entitled *Australian Mineral Industry — Quarterly Statistical Summary*, provides timely data on the mineral industry. The first issue contains preliminary statistics for the June 1986 quarter and earlier quarters and years.

BMR plans to release future issues of the *Quarterly Statistical Summary* within three months of the period to which the statistics relate. It will be available to recipients of BMR's *Australian Mineral Industry Quarterly*, which will continue to provide more comprehensive and detailed official statistics of the mineral industry.

For further information, contact Mr Brian Elliott (Resource Assessment Division) at BMR.

New coloured petroleum titles map

The Petroleum Branch of the Resource Assessment Division has released a new computer-scribed six-colour 1:5 000 000 'Petroleum exploration and development titles' map and key.

The information shown on the map was current at 1 January 1986, and will be updated every six months in association with the department of mines of each State and Territory. The key accompanying the map shows the relevant title numbers, title holders, area of the title and expiry date by State and Territory.

The information also includes petroleum exploration permits, licences, leases, and production licences in onshore areas under the jurisdiction of the relevant State petroleum acts, and in offshore areas under the Petroleum (Submerged Lands) Act. A list of Australian petroleum pipelines included in the key shows high-pressure large-diameter (over 100 mm) natural-gas and liquids pipelines, and also major pipelines transporting LPG, ethane, and fuel gas in Victoria.

Copies of the map and key may be obtained at a cost of $10.90 (including sales tax and postage) from the BMR Bookshop.

More details from Mr Eugene Petrie at BMR.

Australia's vanadium resources

A recently completed study of Australian identified vanadium resources has shown that demonstrated resources amount to 9.9 Mt of contained V. Most of these resources (85%) are in the Julia Creek oil shale deposit, 12% are in the Mitchell Plateau and Cape Bougainville bauxite, and the remaining 3% are in the Yeelirrie uranium deposit, Savage River iron ore deposit, and Coates, Barrambie, and Gabanintha titaniferous magnetite deposits (Fig. 14). Inferred resources (2.2 million tonnes V) are all in titaniferous magnetite deposits (mainly in WA); none of these deposits is economic at present.

Vanadium is widely distributed throughout the Earth's crust, but there are few areas where it is concentrated sufficiently for it to be economically exploited by itself. Most of the world-wide demonstrated resources are associated with iron, phosphorus, or hydrocarbons.

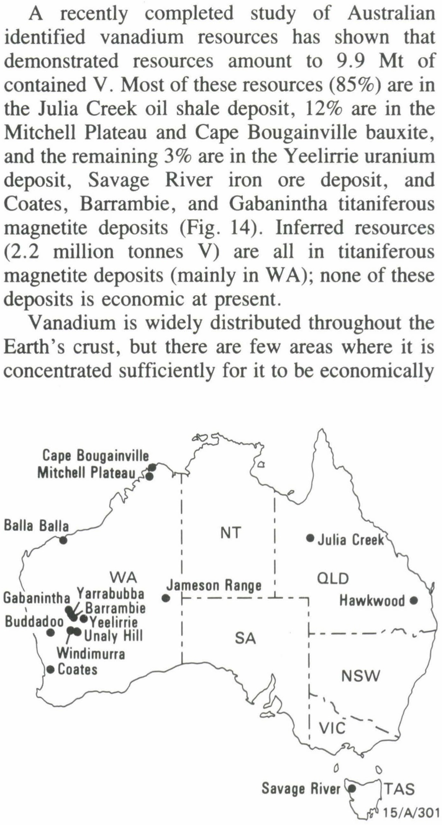

Fig. 14. Deposits containing Australia's identified vanadium resources.

Demonstrated vanadium resources at Julia Creek are large by world standards, but their recovery depends largely on the economics and technology of shale-oil extraction.

Layered mafic–ultramafic intrusive complexes in Australia, which host all the major vanadium-bearing titaniferous magnetite deposits identified to date, are considered to have a high potential for further discoveries of vanadium. These deposits are also believed to have the best potential for economic development.

For further information, contact Mr Roger Pratt (Resource Assessment Division) at BMR.

Boundaries of crustal blocks — Proterozoic and Phanerozoic

The continental crust can be considered to comprise crustal blocks, each with a distinct history of formation or reworking. Recent studies have shown that the boundaries of crustal blocks of Proterozoic and Phanerozoic age have similar geophysical anomalies, implying that they have a similar structure. This finding is important for the recognition of boundaries of other crustal blocks, and for understanding the mechanisms of crustal extension, reworking, and cratonisation. Models of crustal growth and cratonisation during the Proterozoic and Phanerozoic differ in the importance of reworking and cratonisation of pre-existing crust, and the importance of accretion of substantial exotic terranes by plate tectonics.

A range of boundaries has been studied recently: (1) the Yilgarn Block (Archaean) to the Albany–Fraser Block (Proterozoic); (2) the western and eastern margins of the Mount Isa Block (a Proterozoic rift); (3) the Mount Isa and Arunta Blocks (Proterozoic) to the Tasman Geosyncline (Phanerozoic; Wellman, 1986: *BMR Record* 1986/31, 25–28); (4) the Gilmore Suture between the Wagga–Omeo and Girilambone to the Molong–Monaro Terranes (Phanerozoic; Suppel & others, 1986: *Geological Survey of New South Wales, Quarterly Notes*, 64, 1–23); and (5) the western margin of the Yarrol–New England Terrane.

These boundaries have several features in common — the features occurring both at the boundaries that are definitely the margins of rifts (Mount Isa Block), and at the boundaries that are definitely sutures (Gilmore Suture and western suture of the Yarrol–New England Terrane):

- gravity and magnetic trends in the older block are at an angle to the boundary, and are truncated by it; they are subparallel to the boundary in the younger block and on the reworked margin of the old block;
- a major gravity gradient coinciding with the boundary is caused by a major change in crustal structure; it is only gently curved in plan, moderately uniform in magnitude, and of great length;
- gravity and magnetic highs commonly occur over the edge of the younger block owing to upthrusting of the younger block or to mafic igneous activity along its margin; and
- the old block is reworked back to about 50 km from the boundary defined by the gravity gradient; the reworking superimposes trends parallel to the boundary, and imposes a magnetic 'quiet zone' along the boundary (the wavelengths of the anomalies being negative and longer relative to those outside the zone of reworking).

Work on defining the crustal blocks in Australia is continuing. It will be facilitated by the completion of the magnetic coverage of Australia, and the release of magnetic pixel maps.

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

Palaeogeographic maps project

A second stage proposed

As a result of the success of the palaeogeographic maps project, a proposal for a continuation of the project into a second stage has been drafted and is currently being circulated to the exploration industry and within BMR. The stage II proposal is to build on the database established during the first stage of the project, and preserve the project's inherent advantages of continent-wide scope, full Phanerozoic coverage, and precise time control.

The first stage of the project, which is being undertaken within the Division of Continental Geology, is being funded jointly by BMR and APIRA (Australian Petroleum Industry Research Association) representing thirteen sponsoring companies, which will have contributed $343 150 over the three-year life of stage I of the project. Sponsors receive the output of the project twelve months before the general release of material, and are encouraged to comment on draft versions of charts and maps which are circulated among them. The maps provide a useful tool for exploration companies in the assessment of undiscovered resources, in the generation of new play concepts in frontier areas, and in developing an understanding of the geological setting of a region.

By the end of the first stage, in mid-1987, data and interpretative palaeogeographic maps for sixty-six time-slices covering the entire Phanerozoic will have been compiled for Australia at 1:5 million scale. Structure maps at the same scale have also been prepared for the nine periods from the Cambro-Ordovician through to the Cainozoic. Apart from these 141 maps, the sponsoring companies will also have received newly compiled stratigraphic correlation charts for each of the time periods. Source-rock overlays for some of the time-slices are available as an optional extra. An Intergraph computerised drafting system is being used for the production of the maps, which will be published at 1:10 million scale in ten period atlases.

During production of the palaeogeographic maps an extensive database has been assembled; it contains lithological, palaeoenvironmental, biostratigraphic, geochemical, and structural information for thousands of locations both onshore and offshore throughout Australia. Though stage II is still at the early stages of planning, it could potentially include extension of this database to produce an Australian biostratigraphic and radiometric time scale and an Australian relative sea-level curve for the Phanerozoic. Subsidence curves, structural cross-sections, and geohistory analyses for selected basins could also be produced, with the objective of characterising the combination of factors required to produce a 'hydrocarbon-generative basin' in the Australian context. The original database will be maintained and updated, and the map base may be expanded to include the Australian plate margins.

For stage II, which is planned to start sometime in 1987, BMR is seeking a level of industry funding and participation similar to that received in the first stage of the palaeogeographic maps project. Companies not among the sponsors for stage I will be welcome to join the project for stage II.

Further information can be obtained from Dr Peter Cook (Chief, Division of Continental Geology) at BMR, or from Mr Jeff Bailey, Manager, APIRA, 11th Floor, 63 Exhibition Street, Melbourne, 3000; telephone (03) 6548661.

Australia's undiscovered petroleum resources

A new assessment by BMR

An assessment by BMR last year of Australia's undiscovered petroleum resources, according to the new trap-by-trap creaming method (Forman & Hinde, 1986: *AAPG Studies in Geology*, 21, 101–110; Forman, 1986: *BMR Record* 1986/34), indicates the following:

- the continent has the potential for the discovery of an additional 1000–5000 million barrels of crude oil (average estimate 2400; Fig. 15), and an additional 10–45 trillion cubic feet of sales gas (average estimate 23 Tcf; Fig. 16);
- the Bonaparte and Carnarvon Basins have the greatest potential for the discovery of further crude oil and sales gas respectively (Fig. 17);
- of four continent-wide sedimentary sequences considered in the assessment (Jurassic to Recent, Permian and Triassic, Silurian to Carboniferous, and Cambrian and Ordovician), the Jurassic to Recent sequence has the greatest potential for further oil discoveries, whereas the Permian and Triassic sequence offers the greatest potential for further gas discoveries; and
- fault, faulted-anticline, and stratigraphic traps will be of increasing importance in future exploration for petroleum in Australia.

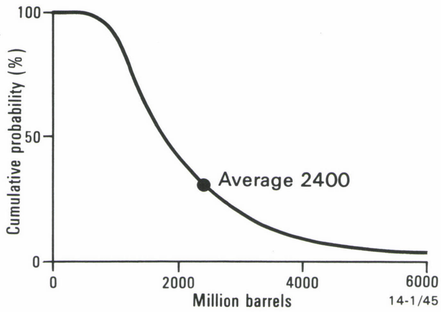

Fig. 15. Australia's undiscovered oil resources (May 1986).

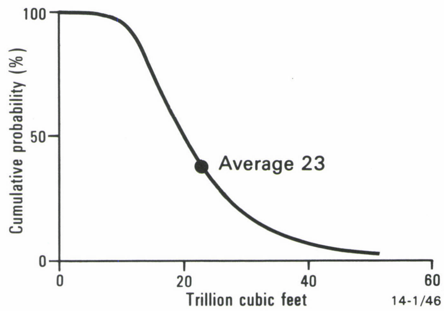

Fig. 16. Australia's undiscovered sales gas resources (May 1986).

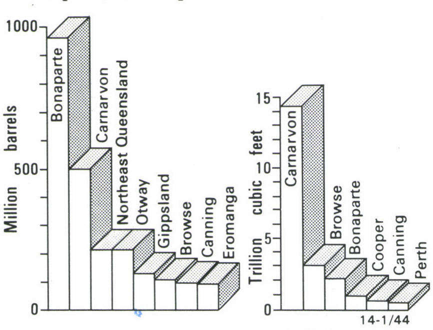

Fig. 17. Average estimates of (*left*) undiscovered oil resources in the eight most prospective sedimentary basins, and (*right*) undiscovered sales gas resources in the six most prospective sedimentary basins.

For further information, contact Dr David Forman (Resource Assessment Division) at BMR.

'The GP Compass'

There is a move underfoot within the USA to stimulate interest in and identify future research directions for geomagnetism and palaeomagnetism (see for example *EOS*, 17 June 1986, p.530). The aim is to counter the view that the heydays of geomagnetism and palaeomagnetism are over, and all that remains are mopping up operations.

Part of this initiative has resulted in the publication in *EOS* of a geomagnetism and palaeomagnetism news and views section called 'The GP Compass'. The instigators and editors of this are Subir Banerjee, Ed Benton, and Laurie Brown. The first edition of 'The GP Compass' appeared in the 21 October issue of *EOS*.

The editors are keen to give 'The GP Compass' an international perspective, and are canvassing input from other parts of the world. The Australian/New Zealand region (including Indonesia, Papua New Guinea, and other neighbouring countries) has been identified as one such region. We therefore have the opportunity to air our news and views before a large, ready-made international audience. We all benefit from the high level of international interest in geoscience in this part of the world. The regular appearance of an Australia/New Zealand region section in 'The GP Compass' will certainly strengthen this interest.

If you have any material you would like included in 'The GP Compass' please send it to Dr C.E. Barton (Division of Geophysics, BMR) for collation in the Australian/New Zealand section, or directly to Professor S.K. Banerjee (Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 5545, USA).

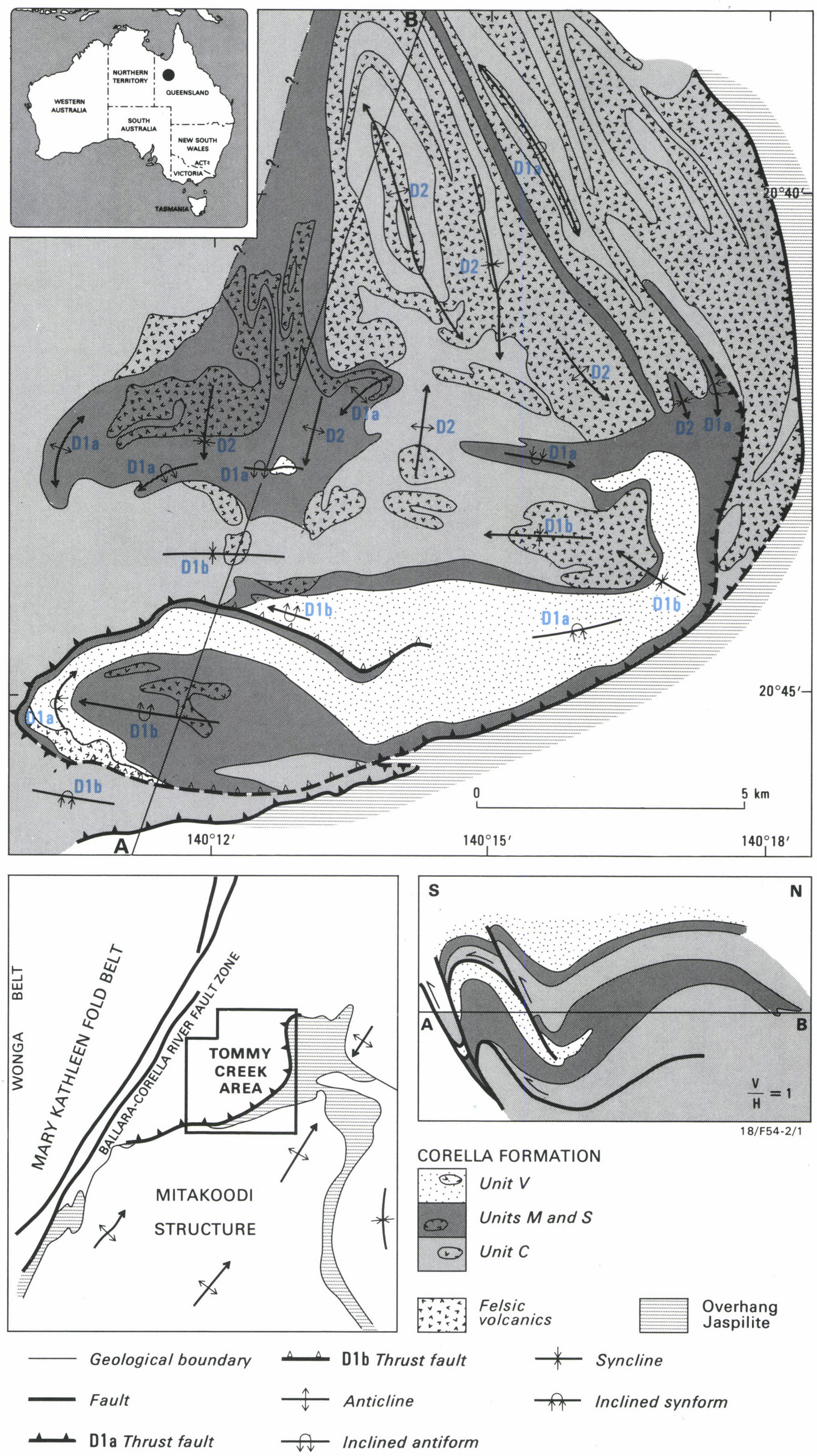

Fig. 18. Structure in the Tommy Creek area.

New data for north Queensland gold deposits

In *BMR Research Newsletter* 2 (p. 9) we briefly reported the results of continuing studies of the genesis of the Etheridge Goldfield in the Georgetown region. Since then we have obtained additional isotopic and fluid inclusion data, also from the Etheridge Goldfield, supporting the early data and interpretations.

K–Ar isotopic age determinations on sericite from the altered wallrocks of a further four deposits also yielded roughly 400 Ma (Siluro-Devonian) ages: Wexford, 398 Ma; International, 426 Ma; Dry Hash, 419 Ma; and Queenslander, 418 Ma. These ages (other than Wexford) may need to be adjusted a few per cent towards 400 Ma to allow for about 1% contamination of the sericite by primary (pre-alteration) muscovite from the Middle Proterozoic host rock. Nevertheless the raw data clearly indicate that the deposits are neither Middle Proterozoic (related to emplacement of the Forsayth Batholith) or Carboniferous (related to the Newcastle Range Volcanic Group and associated igneous rocks).

Deposits in the northern part of the goldfield have simple two-phase fluid inclusions with relatively low homogenisation temperatures (170 to 250°C), salinities of about 10 wt% NaC1 equivalents, and $\delta^{18}O$ values of about 2 to 5 per mil, indicative of meteoric fluid. The Mount Hogan deposit in the south has CO_2-rich three-phase fluid inclusions with higher homogenisation temperatures (about 350°C), salinities of about 10 wt% NaC1 equivalent, and $\delta^{18}O$ fluid values of about 9.5 per mil; such characteristics may be evidence of a magmatic fluid component, or of more highly modified meteoric water.

For further information, contact Mr John Bain (Division of Petrology & Geochemistry) at BMR.

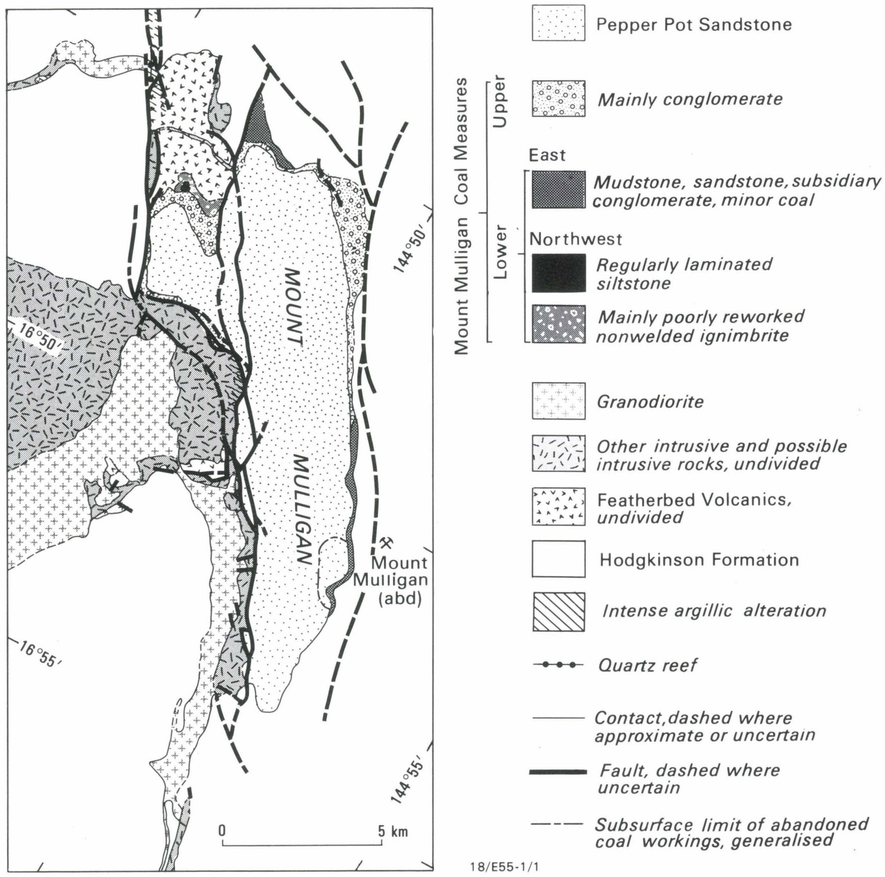

Fig. 19. Simplified geology of the Mount Mulligan area.

Stratigraphy and structure in the Tommy Creek area, Mount Isa Inlier

A detailed structural study in 1986 of the Proterozoic Corella Formation in the Tommy Creek area (Fig. 18) of the Mount Isa Inlier has revealed a picture of complex thrust-faulting and folding during three distinct deformational events. The Corella Formation here is represented by calcareous, pelitic, and psammitic rocks, and felsic, mafic, and intermediate volcanics, all of which have been metamorphosed to the amphibolite facies and multiply deformed. Locally preserved sedimentary structures indicate facing. Early thrust-faults separate these rocks from the lower-grade Mitakoodi structure to the south and east, and the Ballara–Corella River Fault Zone separates the sequence from the Mary Kathleen Fold Belt to the west and north.

Stratigraphy

The lower part of the Corella Formation in the Tommy Creek area consists mainly of calc-silicate rocks with minor bands up to 1 m thick of felsic and mafic metavolcanics. Interlayered with this unit (C in Fig. 18) are thick discontinuous layers of massive felsic metavolcanics (meta-ignimbrites?), most of which were previously mapped as intrusive Tommy Creek Microgranite. In the upper part of the formation, marble, quartzite, and calc-silicate rocks (unit M) are overlain by pelitic schist (unit S), much of which is graphitic, succeeded by intermediate and mafic metavolcanics (unit V). Discontinuous bands of porphyritic felsic metavolcanics present in this upper part are smaller and generally more micaceous than those lower in the sequence, and they occasionally show internal layering. Several probably subaqueous eruptive centres can be inferred for the felsic extrusives.

Structural history

The first two phases of deformation recognised, Dla and Dlb, are considered to belong to the same major deformational event. The younger third phase, D2, is correlated with the regional north–south-trending folding event of the Mount Isa Inlier. The structural history of the area is interpreted as follows.

1. The Corella Formation was thrust over the Mitakoodi structure along a major decollement at the base of unit C during Dla. A smaller thrust developed between units C and S in the south. Thrusting was directed towards the south or southeast, and was associated with intensely non-cylindrical, isoclinal, recumbent folds. An easterly trending axial-plane foliation and a subhorizontal south-southeast-trending extension lineation were formed at this time, and mylonites and shear zones associated with the thrusting developed in quartzites and felsic volcanics. Brecciation took place along thrust planes in all units, but most extensively in calc-silicate rocks of unit C. Metamorphism reached upper amphibolite facies (sillimanite grade), and some anatectic pegmatites were formed.

2. During Dlb, southerly directed reverse faults and associated south-verging tight to isoclinal folds, restricted to the southern part of the area, caused steepening and refolding of Dla structures, formation of a crenulation cleavage axial-planar to the Dlb folds, and development of breccia in units C and S.

A few Dla isoclinal folds have been found in Overhang Jaspilite near the major thrust-fault in the south, but no evidence of Dla, or of Dlb, has been found farther south in the Mitakoodi structure.

3. North–south-trending upright folds ranging from open in the south to isoclinal in the north were formed during D2. These resulted in the development of broad elongate basins and domes, and produced the present complex folding pattern. A foliation associated with the folding was weak in the south, but became more pervasive to the north and west.

4. After D2 the area was affected by minor faulting, brecciation, and 'red-rock' alteration.

Pre-Dl extension

The Corella Formation in the Tommy Creek area is anomalous because it reached a much higher metamorphic grade than adjacent rocks, even though it lies stratigraphically as well as structurally above the Overhang Jaspilite and Mitakoodi Quartzite exposed to the south and east. A possible explanation is that early (pre-Dl) extension resulted in the Tommy Creek area being downfaulted, and subsequently overlain by a much greater thickness of younger rocks than in the Mitakoodi structure, before it was thrust up to its present position during Dla. Early extension has also been suggested for the western part of the Mitakoodi structure by P.R. Williams (see article on p. 10) and in the west of the Mary Kathleen Fold Belt — in the Wonga Belt by P. Pearson and R.J. Holcombe (University of Queensland) and in the Duchess Belt to the south by C. Passchier (Rijksuniversiteit Utrecht).

Age of metamorphism

Two felsic rocks from the Tommy Creek area have been dated by U–Pb zircon: 'rhyolite' at 1603 Ma and 'microgranite' at 1624 and 1600 Ma (Page, 1983: *Precambrian Research*, 21, 223–245). The dated 'rhyolite' is now considered to be a felsic volcanic that was mylonitised during Dla, and the 1986 study shows that the 'microgranite' is a felsic volcanic rock which was recrystallised, again during Dla. The zircon ages of 1600–1624 Ma are therefore interpreted as dating the Dla metamorphism and recrystallisation. This event closely correlates with the D1 metamorphism dated at 1610 Ma near Mount Isa (Page & Bell, 1986: *Journal of Geology*, 94, 365–379).

For further information, contact Miss June Hill at Monash University or Drs David Blake or Mike Etheridge (Division of Petrology & Geochemistry) at BMR.

Long-lived instability as a possible control of mineralisation in northeast Queensland

Epithermal-type and other mineral deposits associated with ignimbrite-dominated sequences similar to those developed during the late Palaeozoic in northeastern Queensland are commonly emplaced after major eruptive stages (e.g., Lipman, 1984: *Journal of Geophysical Research*, 89(B10), 8801–8841). One of the critical factors in maximising opportunities for mineralisation appears to be the occurrence of zones, typically dominated by steep faults with or without intrusions, of recurrent structural instability.

This article describes features indicative of such unstable zones in the Mount Mulligan area of northeastern Queensland (Fig. 19), and outlines the implications of these features for mineral deposit potential in this and other areas of northeast Queensland. The research is part of a continuing project to elucidate late Palaeozoic tectonomagmatic evolution and its relevance to mineralisation in the region, and has been undertaken within a framework of regional mapping by GSQ.

Setting

Apparently Lower Permian sequences of Featherbed Volcanics comprising voluminous welded ignimbrites in the Nychum (Fig. 7) and Mount Mulligan areas (Fig. 19) are in (mainly structural) contact with, or close proximity to, stratigraphically dissimilar (although probably also Lower Permian) Nychum Volcanics, rhyolitic rocks of previously uncertain affinity, and Upper Permian to possibly Triassic Mount Mulligan Coal Measures and Pepper Pot Sandstone. The two areas together contain the most complete stratigraphic–structural record in northeastern Queensland for the interval between climactic late Palaeozoic ignimbrite-dominated volcanism with development of subsidence structures (e.g., Branch, 1966: *BMR Bulletin* 76; Oversby & others, 1980: *in* The geology and geophysics of northeastern Australia, *Geological Society of Australia, Queensland Division*, 247–268) and Mesozoic–Cainozoic cratonic basin sedimentation.

Mount Mulligan area structures

Granodiorite and other intrusive rocks associated with the Featherbed Volcanics were emplaced in part into a major north-northwest-trending fracture (fault?) zone immediately west of Mount Mulligan (Fig. 19). Ignimbrite volcanism may also have been localised along essentially the same zone to the northwest of the mountain, where the abundance and size (up to nearly 2 m) of Hodgkinson Formation clasts in an outlier of Featherbed Volcanics (about 200 m of mainly non-welded ignimbrites) suggest the presence of a vent buried under its own ejecta. Movement along later north-northwest or northwest-trending fault zones is indicated by an absence of the Featherbed Volcanics beneath the northeastern and eastern Mount Mulligan Coal Measures, and by the nature and distribution of lithofacies in the lower part of the unit, particularly in the northwest. Features such as coal and clasts of mudstone in the upper Mount Mulligan Coal Measures, and abundant Featherbed volcanics-type clasts throughout the same interval and in the lower Pepper Pot Sandstone, further attest to the instability of the area during the accumulation of the Mount Mulligan rocks. Later complex faulting took place in the same north-northwest-trending zone in the western and probably eastern parts of the Mount Mulligan area after deposition of the Pepper Pot Sandstone (Fig. 19).

Implications for mineralisation

Intense, possibly gossaneous locally, argillic alteration associated with sporadic quartz veins and one substantial quartz reef occurs in the Hodgkinson Formation, Featherbed Volcanics, and some intrusive rocks in the main north-northwest-trending fault zone and its western branch to the west and northwest of Mount Mulligan (Fig. 19). Neither the Mount Mulligan Coal Measures nor the Pepper Pot Sandstone are known to have been affected by this alteration, suggesting that in this area at least the alteration is broadly related to (although somewhat younger than) the Featherbed Volcanics and associates. The occurrence of altered rock in recurrently activated major structural zones suggests that the potential for mineral deposits in the Mount Mulligan area could be greater than currently appreciated. North-northwest-trending structural features evident in and adjacent to the Featherbed and Nychum Volcanics farther west and south are considered to enhance the prospectiveness of these units; these features await future study.

A corollary to the foregoing is the possibility that some, if not all, known vein-type gold deposits hosted by the Hodgkinson Formation and other lower Palaeozoic rocks in this part of northeastern Queensland are of broadly late Palaeozoic affiliation, rather than being older as has been conventionally inferred.

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

Diamond genesis

(continued from back page)

estimates obtained from diamondiferous peridotites and eclogites. These data, when combined with the important age constraints, indicate that the continental lithosphere beneath the Kaapvaal craton of southern Africa was stabilised to depths within the diamond field (150–200 km) in Archaean times.

Syngenetic mineral inclusions in diamonds are, therefore, able to provide important information on the nature, structure, and thermal history of the deep subcontinental lithosphere. Such information is retained in diamond because of the extremely unreactive nature of diamond in all but oxidising conditions. The restriction of diamond-bearing kimberlites in southern Africa to the Archaean Kaapvaal craton, where crustal rocks are as old as 3500 Ma and have not been affected by orogenic processes for the past 2500 Ma, implies that the cratons have mantle roots whose exent is reflected in the exposed crustal rocks (Boyd & Gurney, 1986: *Science*, 232, 472–476). Understanding the relationship between diamond formation in the mantle roots, the nature of the mantle roots themselves, and the relationship with the surficial geology is, therefore, of direct importance to diamond exploration.

Towards a model for the genesis of WA diamonds

Collaborative studies by scientists from BMR, CRA Exploration Pty Ltd, GSWA, and ANU over the past five years have centred on the Argyle and Ellendale diamond deposits, which are hosted in lamproite of contrasting ages (1200 and 20 Ma respectively) within Precambrian mobile belts surrounding the Kimberley Block. These studies (recently published as *GSWA Bulletin* 132) have shown that the lamproites and lamproite-hosted diamonds have many features in common with diamondiferous kimberlites from southern Africa, but that there are important differences. A major difference is that diamondiferous intrusions in Western Australia are located at or near the margin of the Kimberley Block (Fig. 20); these would be considered 'off craton' in relation to the southern Africa diamondiferous pipes.

Data from petrological and geochemical studies support a model whereby the Western Australian lamproites are derived by small degrees of partial melting within the diamond stability field of ancient, formerly refractory (i.e., chemically depleted in basaltic components, and possibly residual after early Precambrian tholeiitic basalt extraction) subcontinental lithosphere which has undergone long-term (>2000 Ma) enrichment in incompatible elements (K, Rb, Sr, Th, U, Nd, Zr, LREE, etc, high Rb/Sr, low Sm/Nd). This geochemically enriched lithosphere was reactivated in the mid-Proterozoic and mid-Miocene. Mantle enrichment at about 2000 Ma correlates with a major crustal accretion event(s) now recognised in northern Australia.

The early development of enriched subcontinental lithosphere stabilised to depths of 150–180 km beneath the Proterozoic mobile belts in Western Australia is similar to but apparently younger than that documented for the Archaean Kaapvaal craton. In addition, the chemical depletion in basaltic components in the Kimberley Block appears to be less extreme than that in the Kaapvaal craton, where diamonds are associated with garnet harzburgite and a relationship has been demonstrated between diamond content and garnet composition. No such relationship has been found for the Australian deposits, where lherzolite appears to be the dominant rock type of the subcontinental lithosphere.

The apparent similarity of the P–T estimates for diamondiferous peridotites from both the Argyle pipe and southern Africa may indicate either that the lithospheric roots beneath the mobile belts are overthickened (relative to the centre of the Kimberley Block), or, more likely, that early (1800 Ma) cratonisation of the mobile belts has resulted in craton-type (up to 200 km) lithosphere thicknesses over much of Proterozoic northern Australia. While the second interpretation increases the area potentially prospective for diamond, successful prospecting of such large areas requires better knowledge of the subcontinental lithosphere in order to delineate the more favourable regions.

An additional complication to the model outlined above (*viz.* that diamonds form in refractory lithospheric roots) is that diamond may have more than one origin. Further evidence to support a dual or multiple origin of diamonds has come from studies of the Argyle diamonds. In a study of the mineral inclusions and the carbon-isotopic composition of the host diamond from Argyle we have recently found a relationship between diamond morphology, inclusion paragenesis, and C-isotopic composition. Sharp-edged planar octahedra (lacking resorption) from Argyle contain peridotitic inclusions and have $\delta^{13}C$ values similar to diamonds with peridotitic inclusions elsewhere (mostly -5 to -6 vs PDB), whereas the bulk of the Argyle stones — resorped dodecahedra — have eclogitic inclusions and a more ^{13}C-depleted signature (Fig. 21). The sharp-edged octahedral diamonds have very similar morphology to diamonds found in peridotitic xenoliths from Argyle, suggesting that this is their source. The diamonds of eclogitic paragenesis clearly have a different origin, and may differ in age from their peridotitic counterparts; their intensely ^{13}C-depleted compositions, and the compositions of their inclusions, suggest that they may have formed from recycled crustal material.

The significant advances made in the past few years in understanding both diamond formation and the nature and thermal history of the subcontinental lithosphere demonstrate that diamonds have the potential to store unique information about the complex history of the mantle through geological time. This information when integrated with geophysical parameters, such as could be obtained by deep seismic profiling, will provide us with a much clearer understanding of both the nature and thermal history of the subcontinental lithosphere.

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Diamond genesis

The role of the subcontinental mantle

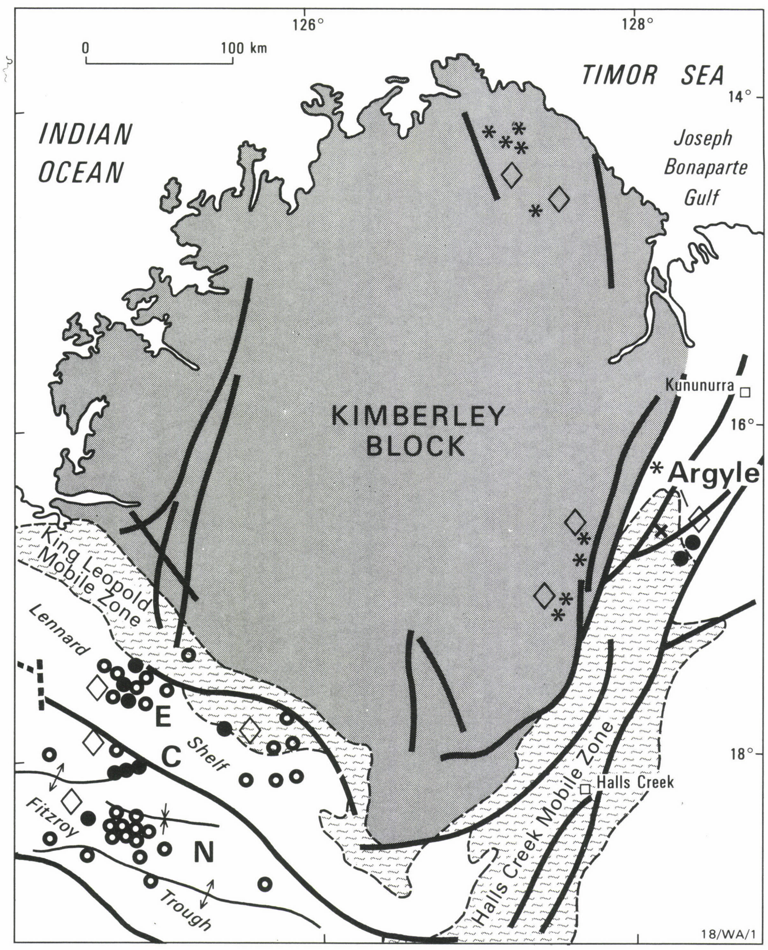
Although diamonds have been mined from kimberlite pipes for more than a century, the precise origin of diamond has been a matter of debate. One of the key questions has been whether diamond is simply an accidental inclusion from deep in the mantle or whether diamond formation is associated spatially and temporally with kimberlite genesis — that is, are diamonds phenocrysts or xenocrysts in their host volcanic? A better knowledge of the origin of diamond is essential for both scientific and economic reasons, especially since the discovery of diamonds in lamproite at Argyle and Ellendale (WA) has confirmed that rocks which differ from the classical kimberlites of southern Africa may also carry diamonds at commercial grades (see *BMR Research Newsletter* 1, p. 10). The extraordinarily rich grade of the Argyle pipe has established Australia as a major producer of diamonds.

Recent research advances

Major advances in understanding diamond genesis in recent years have come from studies of primary (syngenetic or protogenetic) mineral inclusions in diamond — i.e., minerals formed during or before diamond formation, and encapsulated in the diamond during growth. Perhaps the most important of these advances has been made by isotopic dating of syngenetic inclusions in diamonds by the U–Pb, Sm–Nd, and Rb–Sr methods. Until recently such determinations were precluded by the very small size (commonly 100 microns or less) and extremely low concentrations of REE and Rb in such inclusions. In pioneering research, Kramers (1979: *Earth and Planetary Science Letters*, 42, 58–70) obtained a model Pb age >2000 Ma for sulphide inclusions in diamonds from Cretaceous (90 Ma) kimberlites in southern Africa, and demonstrated a xenocrystal relationhip between them. More recently, Richardson & others (1984: *Nature*, 310, 198–202) obtained model Sm–Nd and Rb–Sr ages of 3200–3300 Ma for subcalcic chrome pyrope inclusions of peridotitic paragenesis in diamonds from these kimberlites. In a second paper, Richardson (1986: *Nature*, 322, 623–626) described pyrope–almandine garnets and omphacitic clinopyroxene inclusions belonging to the eclogitic paragenesis from the Precambrian (1200 Ma) Premier kimberlite and Argyle lamproite, and documented Sm–Nd isochron ages of 1150 and 1580 Ma respectively. These ages and the isotopic signatures differ considerably from those of the peridotitic inclusions analysed from the Cretaceous kimberlites, and appear to indicate a closer association of eclogitic diamonds and kimberlite and lamproite magmatism.

Another advance has come from studies of the mineral chemistry of syngenetic inclusions, and the application of experimentally calibrated geothermometers and geobarometers to these studies, thereby enabling estimates to be made of the pressures and temperatures of formation. Such estimates may then be compared with the established stability field of diamond and P–T

(continued on p.15)



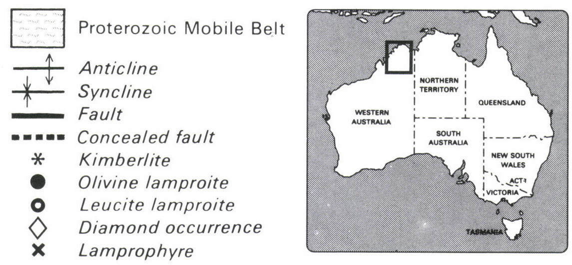


Fig. 20. Distribution of diamond-bearing intrusions in the Kimberley region. E = Ellendale, C = Calwynyarda, N = Noonkanbah fields of the West Kimberley lamproite province.

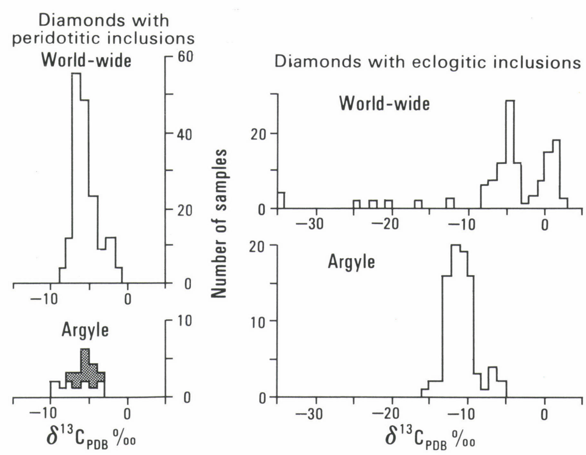


Fig. 21. Carbon-isotopic compositions of the Argyle inclusion-bearing diamonds compared with inclusion-bearing diamonds elsewhere (data from published sources). The shaded area represents diamonds with sharp-edged planar octahedral forms not containing inclusions.

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The purpose of the *BMR Research Newsletter* is to provide the exploration industry with early information on the progress of BMR research and on the availability of new data relevant to exploration and to resource assessment; to provide commentaries on relevant research developments world-wide; and to encourage close liaison between the exploration industry and BMR. Readers' comments and suggestions — addressed to the Director — on the scope and content of the *Newsletter* are always welcome.

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