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Transpressional strike-slip faulting in the Mount Isa Inlier

In *BMR Research Newsletter* 2 (p. 11), we briefly reported the results of a regional structural reconnaissance of the Mount Isa Inlier, confirming in large part the structural sequence proposed by T.H. Bell and his co-workers. Unlike them, however, we identified a range of thrust directions in the earliest deformational event (D1), and highlighted the importance of deformation in discrete shear zones during younger events (D2–D4). Also, in *BMR 85* (pp.83–84) we cast some doubt on the existence of the giant thrust duplex proposed by Bell (1983: *Nature,* 304, 11 Aug., 493–497) north of Mount Isa.

In order to further examine the influence of the deformational structures on stratigraphic and palaeogeographic reconstructions, the bulk of the effort in the 1985 field season was concentrated in the Lake Julius area (Fig. 1) and the Leichhardt River Fault Trough (LRFT), in the Prospector 1:100 000 Sheet area. From this work, we discovered that:

- the eastern margin of the LRFT, which we located, was repeatedly reactivated during both deposition and deformation;
- the D3 (and D4?) deformational events previously thought to have been limited to discrete wrench-faulting and the development of a weak non-penetrative cleavage, have had a substantial influence on the structure of the Lake Julius area, and by inference on much of the inlier; and
- wrench faulting produced substantial transpression in the inlier during D3/D4, resulting in strike-slip, normal, and reverse faults, and large-scale folds. Though earlier structures were substantially reoriented in some places, many of the structures in the LRFT are now considered to have developed during this late transpressional stage, rather than during thrusting or penecontemporaneous faulting as previously suggested.

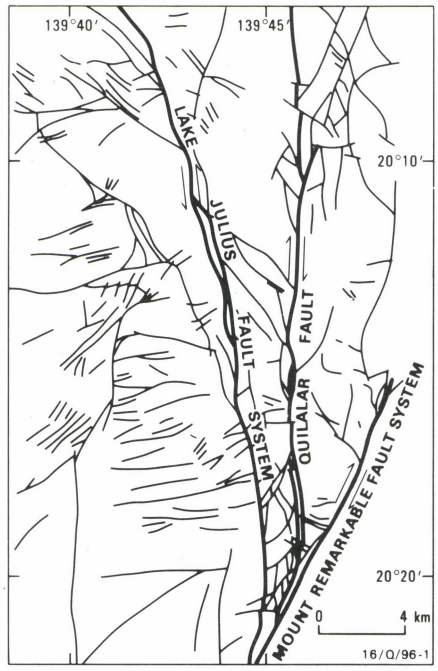

Fig. 1. Fault pattern in the Lake Julius area.

Sedimentary phosphate discovered on the South Tasman Rise

Marine sedimentary phosphate was discovered on the South Tasman Rise 275 km south of Tasmania during the recent joint BGR–BMR cruise of the Federal Republic of Germany's research vessel *Sonne*. The dredge site was at latitude 46°12.7′S, longitude 147°0.5′E in 1600–1810m of water. This discovery constitutes one of the most southerly known occurrences of sedimentary phosphate.

The phosphate forms the matrix within a manganese-encrusted, scoriaceous, clinopyroxene-phyric, altered, palagonitic basalt breccia, and also infills fractures and vesicles within the breccia. The sedimentary phosphate consists of a collophanic matrix which contains abundant angular quartz grains, and minor K-feldspar, oligoclase, biotite, glauconite, and epidote, together with Neogene planktonic foraminifera. A potassium-rich zeolite compositionally similar to phillipsite lines many of the vesicles.

Research is currently under way to determine the origin and age of the phosphate, and possibly establish whether it represents an isolated occurrence or part of a more extensive deposit. Preliminary results suggest similarities to occurrences on the Blake Plateau, off the coast of South Carolina (Manheim & others, 1980: *SEPM Special Publication,* 29, 117–137).

For further information, contact Dr Geoffrey O'Brien or Dr Hugh Davies at BMR.

The LRFT

The LRFT was previously described by Derrick (1982: *BMR Journal of Australian Geology & Geophysics,* 7, 81–92) and Sweet (1983: *BMR Journal of Australian Geology & Geophysics,* 8, 163–165) as the main rift structure in which the Haslingden Group was deposited. In the Lake Julius area, the Quilalar Formation can be traced — over an interval of a few kilometres — from where it unconformably overlies the basement Kalkadoon Ganite to where it conformably overlies several thousand metres of Haslingden Group. In the context of modern rift basins, the Haslingden Group represents the syn-rift phase, and the Quilalar and equivalent formations the thermal subsidence or sag phase. The LRFT does not appear to have been fault-bounded on its western side, and is thus a half-graben (Sweet, 1983), as are most modern rift basins.

The distribution of the younger Bigie Formation in the Lake Julius area suggests that the eastern margin of the LRFT may have been reactivated during the younger rifting and extension that led to the sag basin containing the Mount Isa Group. The eastern boundary fault of the LRFT, coinciding roughly with the location of the Quilalar Fault, is considered to have been reactivated in both thrust and wrench modes during the subsequent deformational history.

Strike-slip faulting, Lake Julius area

A left-lateral strike-slip fault system, the Lake Julius Fault system (Fig. 1), cuts through the Lake Julius area, and passes northwest to define the southern margin of the Crystal Creek block. It continues south until it is terminated by splays of the northeasterly trending right-lateral strike-slip faults of the Mount Remarkable Fault system. Associated with these master faults is a distinctive array of smaller strike-slip, normal, and reverse faults. This fault array shares many similarities with fault patterns from zones of major wrench-faulting, such as the San Andreas Fault in California and the Alpine Fault in New Zealand.

The Lake Julius Fault system is a transpressional feature, seemingly because the strike-slip faults swing from a northwesterly (in the north) to a northerly trend where they approach the inferred position of the eastern edge of the LRFT. We can recognise in it master faults, en-echelon arrays of both normal and reverse faults, anastomosing fault-bounded compartments, and 'flower' structures, all of which are characteristic of high-level wrench-faulted regimes (Harding & Lowell, 1979: *AAPG Bulletin* 63(7), 1016–1058). These fault patterns formed at intermediate depths in the Lake Julius area, and substantial penetrative deformation also resulted. The deformation had a significant ductile component; D2 folds are considerably tightened (Fig. 2) — even dismembered in places — and both D1 and D2 folds have been rotated locally as a consequence of this ductile component.

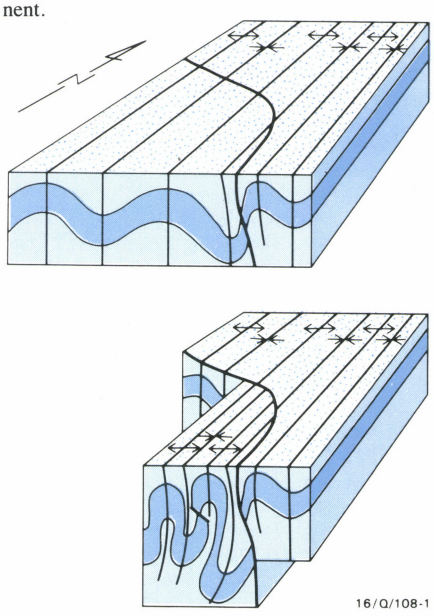

Fig. 2. Ductile effects of transpression in the Lake Julius area.

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Pop-out structure

Perhaps the most remarkable features of the transpressional zone in the Lake Julius area are structures that apparently owe their origin to localised D3 thrusting and block rotation. The sequence of events may have been as follows.

A bend in the strike-slip fault along the southern part of the Lake Julius Fault system (Fig. 3) may have existed where it cut across from one D2 axial zone to the next. Transpression resulted in the thrusting of a block of rock (B in Fig. 3) to the west, through and over the adjacent rocks, thereby removing the bend in the fault and eliminating a major obstacle to ongoing movement. Continued left-lateral faulting and transpression caused this block to rotate 40–50° anti-clockwise along a vertical oblique-slip fault (b in Fig. 3) as it was thrust (along fault c) through the rocks to the west, forming a pop-out.

The result of these movements has been to rotate the northerly trending D2 fold axes in the pop-out structure to a northwesterly orientation; these folds, which superficially have the characteristics of ramp folds related to thrusting, are bounded to the north by the rotational oblique-slip fault (b). This fault also terminates abruptly the strike of the beds to the north (block A in Fig. 3); the same beds with the same strike reappear south of the thrust (c in Fig. 3).

The localised D3 thrusts that contributed to the formation of the pop-out (e.g., thrust c) are blind — that is, relative displacements along them gradually decrease towards their extremities. Maximum relative displacements are in the order of 5–8 km.

Fault geometries similar to that in the Lake Julius area have been recognised in other transpressional terranes — for example, the US Pacific coast, where the San Andreas Fault Zone is bounded in places by convex-upward faults. Shortening during strike-slip faulting results in thrusting at shallow levels, while at deeper levels an oblique-slip component of fault movement is more prominent. Such convex-upward faults with reverse displacement formed in wrench fault zones have been termed 'flower' structures.

Regional strike-slip faulting

Strike-slip faults in the Mount Isa Inlier consist of two major sets: a northwesterly striking left-lateral set and a northeasterly striking right-lateral set. Substantial swings in strike — particularly to a north–south orientation as in the Lake Julius area — occur on both sets. This suggests a control on fault orientation exerted by pre-existing structures, and is also consistent with continuing east–west compression — as appropriate to D2 deformation but with a north–south extensional component. Swings to the north–south trend would have resulted in significant transpression on both fault sets, and the structural complexities described above from the Lake Julius area can be expected throughout much of the inlier.

The Pilgrim Fault, including its continuation traced southward from the aeromagnetic data beneath the Mesozoic cover of the Eromanga Basin, seems to be the major fault in the Mount Isa Orogen. It may therefore be the master fault of a major wrench system, and even such striking faults as the Fountain Range Fault — with about 30 km of right-lateral displacement — would merely be adjustment splays accommodating the effect of movement past a major bend in the Pilgrim Fault.

Origin of east–west faults in the LRFT

The enigmatic pattern of east–west faults in the LRFT, especially to the north of Mount Isa, now has another potential explanation to add to those of Smith, Dunnet, and Bell. Much of this area lies between two major transcurrent faults of opposite sense, and was therefore subject to north–south extension during D3/D4. Some of the east–west faults appear to postdate D2, and to have mainly normal movement, consistent with this extension.

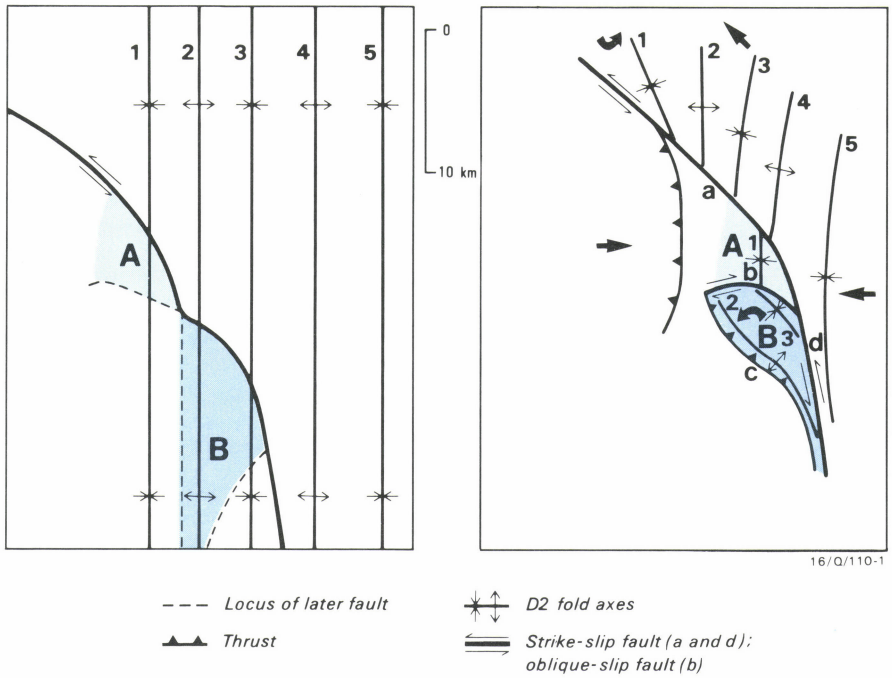


Fig. 3. Schematic evolution of a pop-out structure.

In addition, the transpression along the eastern margin of the LRFT, particularly the development of pop-out structures similar to that in the Lake Julius area, can explain a number of the reverse faults and associated folds. Though our structural interpretation does contrast significantly with that of Bell, it does nevertheless conform with his hypothesis that the deformational history of the inlier began with an extensive thrusting event, for we have identified D1 thrusts in the Lake Julius area and within the Crystal Creek block.

Economic significance of transpression

Gold prospects in the Lake Julius area occur on what appear to be D1 thrusts dilated during D3 transpression. One such minor prospect occurs (at grid ref. 708647, Prospector 1:100 000 Sheet area) south of the thrusted Argylla Formation volcanics, close to the intersection of a D1 thrust with the transpressional zone along the D3 Quilalar Fault. Another site contains a number of old diggings (at grid ref. 725553) near vein fillings where the Quilalar Formation is thrust over the Mount Isa Group south of Sunday Gully; some gold has been panned from this locality. We suggest that the thrusts at these prospects acted as dilational traps focusing the flow of mineralising solutions during D3 transpression.

Another question of interest is the influence of these old strike-slip faults on the Palaeozoic and Mesozoic evolution of the inlier and the adjacent Eromanga Basin. The fault patterns described from the central Eromanga Basin (see *BMR Research Newsletter* 3, pp. 4–5) are similar to those of the Mount Isa Inlier, and transpressional reactivation of these Proterozoic faults may have been an important control on the structural evolution of the basin. Many structures observed in seismic profiles in the basin can be explained by transpressional or transtensional strike-slip faulting. Some of the faults may be reactivated Precambrian strike-slip faults; this suggestion gains support from the Palaeozoic and Tertiary movements that have been documented on the Pilgrim Fault and related faults in the Mount Isa Inlier.

For further information, contact Dr Mike Etheridge at BMR or Mr Andrew Thomas at the University of Adelaide. Dr Gordon Lister, who was responsible for the interpretation expressed in this article, left BMR in February for 10 months to take up the position of Visiting Professor at the Lamont–Doherty Geophysical Observatory.

Honour Dan Bubela

Dr Bohdan (Dan) Bubela of the Baas Becking Geobiological Laboratory has been elected a Fellow of the Australian Academy of Technological Sciences. This select Fellowship has about 200 members in Australia.

Dan's election to this Fellowship is the culmination of many years' work developing physical models which simulate geobiological and diagenetic processes taking place in sediments, and researching techniques to enhance oil recovery.

In the 1970s, Dan — in co-operation with other members of BBGL and BMR — developed and successfully applied a new system which simulates sedimentary environments and permits investigations that previously had not been possible. Use of the system, affectionately known as 'tanks', has clarified several carbonate diagenetic processes — including the formation of radial and tangential ooids, and aragonite in dolomitic sediments. Other studies to which the system has been applied include: the effects of microbial mats on the accumulation and distribution of heavy metals in sedimentary environments; the formation by biological activity of hydrocarbons which were assumed to be the product of late diagenetic cracking processes; and the hydrology of sedimentary deposits.

In 1980, Dan initiated a program of microbiologically enhanced oil recovery (MEOR). This program attracted the support of the National Energy Research, Development and Demonstration Council, so far to the value of nearly $400 000. In the past, a number of techniques have been applied to increase crude oil recovery; most of them, however, are expensive, require application of complex sophisticated chemicals, and are frequently detrimental to the environment (freshwater deposits in particular). By producing microbial surfactants in reservoirs, Dan is attempting to improve oil recovery at a fraction of the cost and without the detrimental side effects of these techniques. His investigation in the laboratory is aimed at assessing the effect of microbiological manipulation on the parameters responsible for the retention of residual oil in reservoirs, and developing a screening procedure to determine the suitability of individual reservoirs for microbiologically enhanced oil recovery.

DEEP-TOW SIDE-SCAN SONAR

A new tool for seafloor studies

BMR's newly acquired side-scan sonar system was used for the first time in November–December 1985 from BMR's research vessel *Rig Seismic* during the second of two cruises collecting data for a multidisciplinary research project off northeast Australia. Although the side-scan imaging was only a small component of one cruise, 207 km of data were collected during testing on the shelf and upper slope. These first results showed the power of the side-scan imaging technique and the enormous value it can have in understanding a wide variety of marine geological environments and phenomena.

The side-scan method

The principle of the side-scan sonar method is quite simple. It can be considered analogous to aerial photography when the sun is low and behind the camera, although there are marked differences in geometry, resolution and information content.

Short pulses of sound are transmitted and echoes received by a transducer pointing sideways from the ship or tow fish. The pulses are transmitted at regular intervals of time, and the resulting echoes from features are usually displayed on a paper recorder. Echoes from near features are recorded first, and echoes from more distant features are recorded progressively later. The groups of echoes from each pulse are displayed by a stylus moving across the paper, so as to build up a picture line by line as the vessel advances. Where successive echoes from a feature appear to be continuous, these lines are placed close together so as to indicate the form and location of the feature with respect to the ship. The swath of data that results as the vessel advances gives a continuous acoustic image of the sea-floor called a sonograph, which is a plan view of the shape and texture of the seabed extending out to the maximum range of the system.

The first return on a sonograph is from the seabed directly beneath the transducer, and on dual channel systems scanning to both the port and starboard sides it will appear as a mirror-image in the centre of the sonograph (Fig. 4). Abrupt relief of the sea-floor is enhanced by the shadows it casts. The relative length of the shadow increases with distance from the transducer because of the increasingly oblique approach of the sound. Positive and negative features can be distinguished by the relative location of the shadow and highlight with respect to the sound source. The texture of the sea-floor also affects the amplitude of an echo, which is a measure of the backscattering strength or roughness of the material constituting the sea-floor. Mud and sand will tend to cause little backscattering, but coarse sediments, such as gravel, will send back much more of the incident sound, each grain making a contribution to a generally higher 'reverberation' level. Variations in texture show up on the sonograph as different shades of grey or black — the shade darkening with increasing roughness of the sea-floor.

The system

BMR's deep-tow side-scan sonar system is the first of its kind in Australia, and is one of the most sophisticated currently available. It consists of an EG&G model 990 SMS tow fish and model 996 digital modem connected through a Hewlett–Packard 2117F-series computer to an EPC 4100 recorder. The tow fish is a microprocessor-based remote data acquisition system, and contains sea-floor mapping and bathymetric and seismic profiling capabilities. It also includes a device for locating its position, and integrated sensors for speed, heading, and water temperature. The fish's hydrodynamic pressure housing incorporates a set of transducers which transmit a unique 59-kHz variable-pulse signal that allows consistent scanning to ranges of 500 m either side of the tow fish. The tow fish also incorporates an accurate linear pressure transducer to measure the depth of the fish, and a broadband hydrophone for use as a seismic receiver. The resolution of the system varies from 0.25 m on the 100 m range to 1.3 m on the 500 m range.

The fish is towed behind the ship by means of a double-armoured coaxial cable which is connected to the modem. The depth of the fish is controlled by the length of wire out and the speed of the ship through the water. The AC power for the tow fish is generated in the modem, and so are its control signals, which are encoded on to the same AC voltage and transmitted digitally down the cable to the fish. All sonar and sensor data are digitised in the tow fish and transmitted digitally up the cable. The data are available in a variety of analogue and digital forms at the modem for display and/or tape-recording. The system is capable of examining the ocean floor in a swath 200–1000 m wide in water depths of up to 6000 m. It has an almost unlimited potential to map the ocean floors adjacent to Australia.

Application of the technique

The side-scan sonar technique is particularly useful in throwing light on ancient marine depositional systems, because it can produce detailed imagery of the effects of depositional and erosional processes in their modern analogues. This can have considerable economic implications for ancient sedimentary deposits which have a known association with the formation of petroleum source and reservoir rocks. The images produced illustrate textural variations, bedforms, and other sedimentary features having seafloor relief. The side-scan technique can also be extremely useful in tectonic studies of environments in which structure is expressed on the sea-floor.

During the second northeast Australia cruise the side-scan sonar system was tested on the outer shelf and upper continental slope, and clearly delineated palaeo-river channels, partly buried Pleistocene barrier reefs, canyons, the morphology of major inter-reef shipping passages, and old shelf-reef platforms (Fig. 4). It will undoubtedly become an important tool in future BMR marine investigations.

For further information, contact Mr Philip Symonds or Dr Peter Davies at BMR.

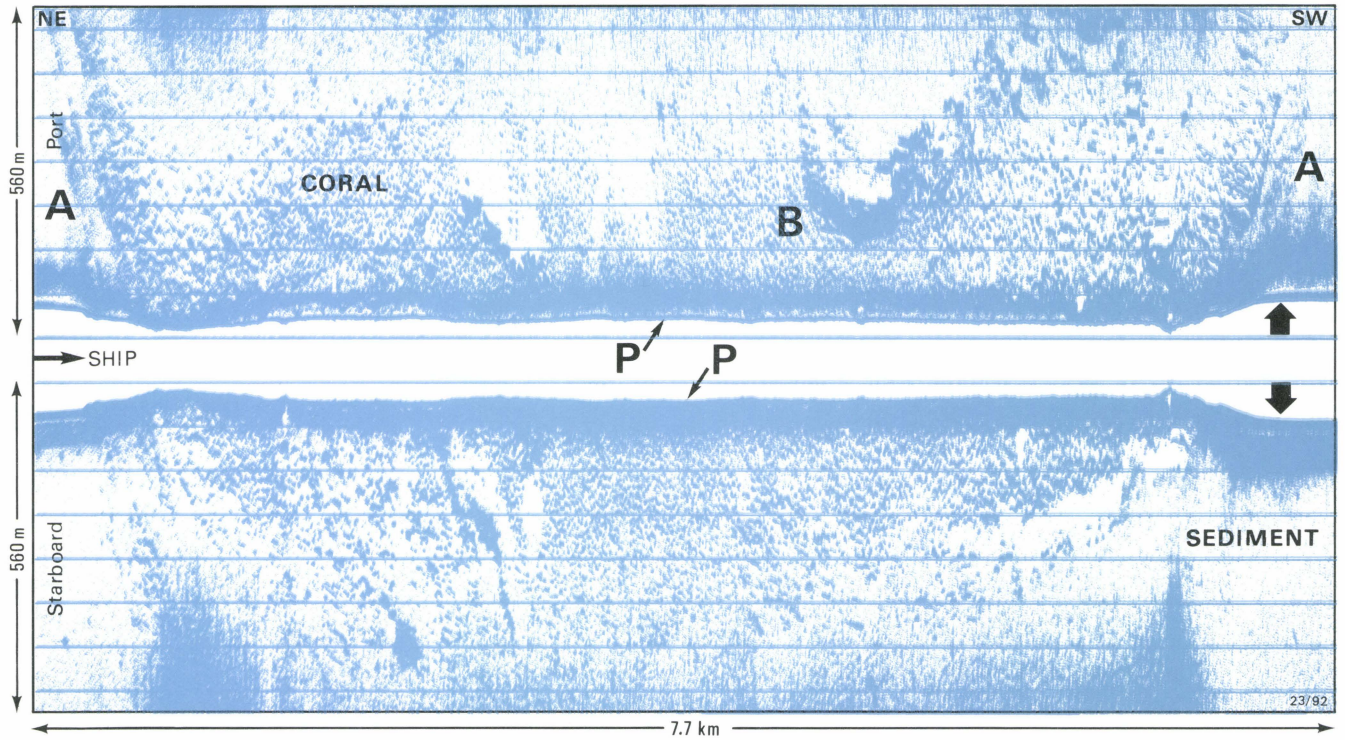


Fig. 4. Sonograph showing part of the Pleistocene platform beneath Faraday Reef. The image contains a lot of detailed textural and morphological information, which may relate to growth structures, erosion due to exposure of the platform during low sea level, or a combination of both. The 'illumination' (insonification) direction of both channels is shown by the broad arrows; A, the edge of the reef platform; B, a cliff bounding an area of coral standing above the general level of the platform; P, bathymetric profile on port and starboard channels.

Australian Iron Ore Industry Mission to Brazil, July 1985

Roger Pratt, Senior Commodity Specialist in the Resource Assessment Division, was a member of an Australian Iron Ore Industry Mission which visited Brazil between 14 and 24 July 1985 to study major iron ore mining and processing operations. The 21-person mission comprised representatives of iron ore companies, trade unions, and senior government officials; it was led by the Chairman — the Honourable David Parker, MLA — of the Western Australian Iron Ore Industry Consultative Council, which was established in 1984 to provide a forum for consultation between governments, employers, and unions in matters of concern to the iron ore industry. The visit was undertaken in accordance with continuing co-operation between Australia and Brazil in respect of mineral commodities and the importance of the iron ore industry to both countries. Roger's impressions of the Brazilian industry — based on material supplied to mission members, his own notes, and the notes of other mission members — are summarised below.

Current state of Brazil's iron ore industry

Brazil's iron ore industry is continuing to expand. The government-controlled major producer, Companhia Vale do Rio Doce (CVRD), is bringing on stream from this year major new capacity in the north — in Pará (Fig. 5) in the Amazon region — to supply export markets, and rationalising mining operations in the south — in Minas Gerais — for Brazil's expanding steel industry. Brazil is the world's second largest producer of iron ore, and replaced Australia as the world's No. 1 ranking exporter in 1984. Australian and Brazilian production, exports, and resources are compared in Table 1.

The industry is large-scale, capital intensive, and efficient, and has access to what are probably the world's largest high-grade economic resources. Mining and port operations in the south are close to large population centres, and infrastructure and rail haulage costs are offset by the transport of general freight. The major ports have natural deep-water access and can accommodate vessels of over 280 000 dwt.

Geology and resources

As in the Hamersley Iron Province, Proterozoic banded iron formations in Brazil host the major iron ore resources — in Minas Gerais and at Carajas.

In Minas Gerais, metamorphosed banded iron formations (itabirites) are associated with other metamorphosed sediments and massive granite intrusions; some of the itabirites are hard or compact, but large resources of friable itabirite which are readily amenable to beneficiation constitute a major part of the remaining economic resources. At Carajas, banded iron formations are associated with other metasediments and mafic volcanics; total resources in some 60 deposits at Carajas exceed 18 000 Mt. Total Brazilian iron ore resources, mainly in Minas Gerais (30 000 Mt), exceed 48 000 Mt.

Table 1. Brazilian and Australian comparative iron ore statistics (Mt) for 1984

	Resources	*Production*	*Exports*
Brazil	48 000	114.0	87.2
Australia	20 790(a) 19 900(b)	89.0	85.5
	40 690		

(a) economic, (b) paramarginal

Production

Current production capacity is 140 Mt/year. Production in 1984 was 114 Mt. Of 32 companies producing iron ore in Brazil, eight companies account for 95 per cent of production, and two of them — CVRD and Mineracoes Brazileiros Reunidas (MBR) — account for 67 per cent of output. Other substantial producers are Ferteco Mineracao SA, SA Mineracao da Trinidade (Samitri), Samarco Mineracao SA, and Companhia Siderurgica Nacional (CSN).

The major operating mines in Minas Gerais are Caue (CVRD), Conceicao (CVRD), and Periquito (CVRD/Cia de Acos Especiais—Itabira) in the Itabira district; Aguas Claras (MBR) at Belo Horizonte; and Timbopeba (CVRD), Capanema (CVRD/Japanese companies), Germano (Samarco), Alegria (Samitri), and Fabrica (Ferteco) southeast and south of Belo Horizonte (Fig. 5).

Mining operations in Minas Gerais have resulted in a depletion of high-grade resources, and iron ore resources will be conserved there in future for the Brazilian steel industry. (Steel production is expected to increase from 18 Mt in 1984 to 25 Mt/year in 1986.) To this end, CVRD will reduce production at its Itabira mines by 15 Mt/year in 1986 — by reducing the scale of mining at both the Caue and Conceicao mines, and by closing the Periquito mine. CVRD will compensate for this loss with production from the Carajas mine, where large-scale mining is expected to yield iron ore at a rate of 15 Mt/year initially — from January this year — increasing to 25 Mt/year in July 1986 and up to 35 Mt/year as markets warrant.

Mining

Brazilian iron ore mining operations are assisted by a number of factors. The softness and friability of ore types result in reduced drilling and blasting, ease of handling, and reduced machinery wear and maintenance. Mining equipment is large-scale and suited to softer ore types. Modern large maintenance facilities are generally strategically situated close to mining operations.

A combination of ore location and natural terrain results in downhill haulage at some major mines, and cost savings result from relatively low waste-to-ore ratios. The use of contractors for overburden removal and for short-distance ore haulage is common, and assists mine operations and production flexibility.

Ore processing

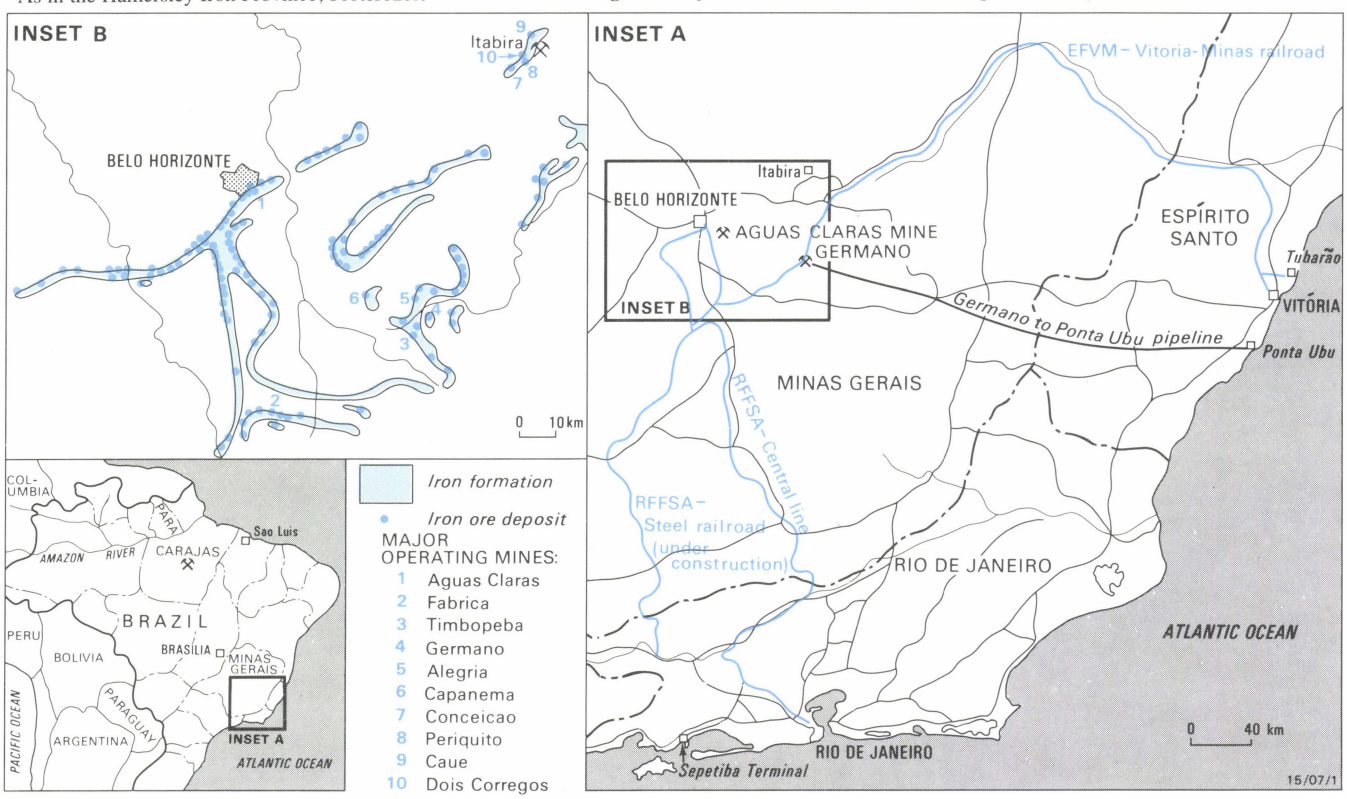
Most companies upgrade the iron ore that they mine, generally by some form of beneficiation, for which more than 40 plants are in operation. Low-grade itabirite is upgraded in order to remove silica, but high-grade ore is also beneficiated to improve the physical characteristics of ore products for specific markets.

Most of the ultra-fines are pelletised. Eight pellet plants are operating with a total capacity of 24.5 Mt/year, though current output is 16 Mt/year.

Ore transport

In Brazil, mine-to-port transport distances are generally longer than in Australia, but railway costs are offset by the transport of other products to shipping terminals and from the coast inland.

Fig. 5. Major iron ore mines and transport routes, Brazil 1985.



CVRD owns and operates the 700-km Estrade de Ferro Vitória Minas (EFVM) railway from Fabrica to Vitória. The line is a double track from CVRD's Itabira mines to Tubarão port, a distance of 550 km. In addition to its own ore (69.6 Mt in 1984), CVRD transports substantial quantities of iron ore for other producers (10.5 Mt) via the EFVM railway for both domestic consumption and export. The company also operates the Carajas project railway, completed in February 1985, which connects Carajas with the port of Ponta da Madeira (under construction), in Sao Luis, a distance of 890 km.

Ore from Aguas Claras and other MBR mines is railed under contract on the government Rede Ferroviaria Federal SA (RFFSA) railway to Sepetiba Terminal — a distance of 640 km.

Concentrate from Samarco's Germano mine is pumped in slurry form by pipeline to Ponta Ubu terminal — a distance of 400 km — for pelletising and export.

Major conclusions

Brazil is consolidating its iron ore industry to meet domestic and future overseas requirements. Despite surplus capacity and imminent additional capacity it seems unlikely to undercut prices of its major competitors. However, its position as a reliable and competitive supplier of high-grade iron ore to world markets is assured.

The Carajas project, which is a major addition to world iron ore capacity, will assist Brazil both in the development of its own iron and steel industry and to readily expand its iron ore export markets as warranted. The project is supported by major overseas as well as Brazilian finance, and much of its production is already committed under contract to European, Japanese, and South Korean buyers. It is part of a larger regional plan to develop the resources of the Amazon region; the plan also includes hydroelectricity generation, iron smelting, bauxite mining, alumina refining, copper/manganese/gold mining, forestry, and agriculture.

The iron ore industry of Minas Gerais is also part of wider integrated regional development, which includes iron and steel-making and other industry.

Despite a cutback in output in Minas Gerais, surplus production capacity will remain, and could be utilised should market circumstances change.

Australia will continue to enjoy freight cost advantages over Brazil in the southeast Asian market; these are similar to those which Brazil has over Australia in Europe.

The market will continue to demand the superior physical properties of Australian iron ore, which counter-balance the better chemical properties of Brazilian iron ores. However, like Brazil's high-grade resources in Minas Gerais, Australia's premium high-quality lump ores must be regarded as limited, and eventually will be replaced by ores of both poorer physical and chemical properties in the longer term.

For further information, contact Mr Roger Pratt at BMR.

Polymetallic nodules

A commercial product or a collectors' item?

The discovery of polymetallic nodules on the deep-seabed has led to research into the development of mining methods and processes for the mining and recovery of nickel, copper, cobalt, and manganese from these nodules. To date, no mining on a production scale has started, because the estimated production costs are much higher than the production costs of land-based producers.

The Mining Engineering Section of the Resource Assessment Division has completed a study into the economics of mining and processing polymetallic nodules from the deep-seabed.

After reviewing published reports on deep-seabed mining, the Section considered a hypothetical mining operation in the northeast Pacific Ocean — around latitude 15°N, longitude 126°W (between the Clarion and Clipperton Fracture Zones, where metal grades and nodule abundance are considered to be higher than elsewhere on the ocean floor). This operation had a capacity of three million dry tonnes of polymetallic nodules per year (polymetallic nodules in their natural state contain about 30% water by weight) for the extraction of nickel, copper, and cobalt, and manganese in the form of ferromanganese. The hypothetical processing operation was based on the west coast of USA.

The hypothetical mining venture was assumed to be Australian-owned. It had to pay both a production charge to the United Nations International Sea-Bed Authority and Australian taxes. According to the United Nations Convention on the Law of the Sea, it operated alongside the proposed mining arm of the Authority, 'The Enterprise'; thus, the likely profitability of 'The Enterprise' was also considered.

The costs of the operation took into account: (i) two mining ships, each with a hydraulic mining system, (ii) three ships for transportation of nodules from the mine site to a port on the west coast of USA, (iii) a Cuprion-process plant to extract nickel, copper, and cobalt, and (iv) an add-on ferromanganese-process plant to concentrate manganese-rich waste from the Cuprion process and produce ferromanganese. Minor costs also included: (i) initial and continuing exploration, (ii) research and development of mining and extraction technology, and (iii) transport of products to market.

The prices of nickel, copper, cobalt, and ferromanganese have fallen steadily over the last ten years in real terms. The demand outlook for the four metals to the end of the century is that the projected small growth will be met by the present spare capacity of land-based producers. The outlook for prices is that no change is expected in real terms, apart from nickel, which may increase in the long term; because of this, calculations of revenue from the hypothetical venture were based on the average metal prices for the month of March 1985 (contemporaneous with the study).

The profitability of the mining operations was evaluated by calculating the discounted cash-flow rate of return (DCFROR). For such a high-risk venture to be commercially successful, a real DCFROR of 18% or greater would be required to attract the necessary investment capital. The calculated DCFROR for 'The Enterprise' was less than 1%, based on point estimates for costs, unit price, and grade. The revenue from the four metals totals $192 per tonne of nodules recovered. For a DCFROR of 18% to be reached, the revenue per tonne would have to rise to $366, which would require the aggregate metal prices of the products to double.

Point estimates for costs, unit price, and grade give no indication of the uncertainty of the estimate. Thus, for each of these parameters, a probability distribution was devised to reflect the uncertainty of the estimate. DCFROR calculations were carried out using sample values randomly selected by the Monte Carlo simulation procedure. These calculations were done using the US Bureau of Mines MINSIM computer program.

The results show that no forecast DCFROR exceeds 4%, which is well below the target DCFROR of 18%. The mining venture, paying taxes and production charges to the Authority, was less profitable than 'The Enterprise'.

The conclusion was that, given the present metal price outlook, deep-seabed mining for polymetallic nodules is unlikely to be undertaken on a commercial basis in the foreseeable future. Polymetallic nodules may remain collectors' items for many years to come.

More details from Mr Peter Ingham, BMR.

Erratum

BMR Report 268

Australian Geoscience 1984

A recent review of ore deposit geology referred to a zone of relatively high-grade gold-bearing ore (100 Mt, 4 g/t Au) defined at Olympic Dam (*BMR Report* 268: p. 18, column 1, last paragraph). These figures are incorrect. The only official ore reserve figures published to date are as follows: probable reserves of 450 Mt of ore comprising grades of 2.5% Cu, 0.8 kg/t U_3O_8´, 0.6 g/t Au, and 6 g/t Ag (Roxby Management Services Pty Ltd, written communication to G.M. Derrick & Associates Pty Ltd, 26 November 1985).

Location of the south magnetic pole

A Bureau of Mineral Resources (BMR) experiment conducted aboard the Australian Antarctic charter vessel MV *Icebird* has succeeded in locating directly the position of the south magnetic pole. This is the first time this has been done aboard a ship. The pole was last visited 34 years ago, by a French Expedition to Adelie Land, when it was still on the Antarctic continent. The current location, at latitude 65° 18'S and longitude 140° 02'E at midday on 6th January 1986, places the pole offshore 152 km north-northwest of the French Antarctic research base Dumont d'Urville and 3370 km south of Adelaide.

The magnetic poles are the principal points on the globe where the Earth's magnetic field points vertically upwards (south magnetic pole) and vertically downwards (north magnetic pole). Unlike the geographic poles, which are determined by the rotational axis of the Earth and are fixed, the magnetic poles drift gradually in response to slow changes in convection patterns of molten iron in the core of the Earth. Superimposed on this drift is a rapid daily motion due to magnetic fields produced by electrically charged particles moving around the Earth. The diameter of the paths traced out daily by the poles ranges from as little as 20 km, to many hundreds of kilometres on days when the magnetic field is highly disturbed by emissions from the Sun.

Two of the observations made an hour apart by Rodney Hutchinson, the BMR geophysicist on board the MV *Icebird,* indicated that the pole had moved some 50 km. Measurements were made using a sensitive magnetometer, specially designed and assembled by BMR's Engineering Services Unit, and mounted on a non-magnetic boom protruding from the stern of the *Icebird*. The observational technique was designed to compensate for the magnetic effect of the vessel and disturbances due to its motion.

More detailed observations of the daily motion of the south magnetic pole are planned for next Antarctic summer, over a period of a few days when MV *Icebird* will again pass near the pole. The information will contribute to our knowledge of the morphology of the geomagnetic field in the Australian/Antarctic region, and to our understanding of current systems in the ionosphere which perturb that field in polar regions.

The study is being undertaken by Dr Charles Barton from the Bureau of Mineral Resources in Canberra, in collaboration with Dr Patrick Quilty from the Antarctic Division of the Department of Science and Dr Anthony White from Flinders University of South Australia.

For further information, contact Dr Charles Barton at BMR.

The Nth-root stack

A process for enhancing the interpretation of geophysical data

Typically, multichannel geophysical data are stacked to improve the signal-to-noise ratio. Almost invariably some form of linear stacking is applied, in which a weighted average is taken as the best estimate of the parameter. Although the linear stack is the best process available for most types of data and application, other stacking techniques can give more useful results for other types. One example is where the data contain large spikes, and in such cases linear stacking or averaging is not particularly beneficial.

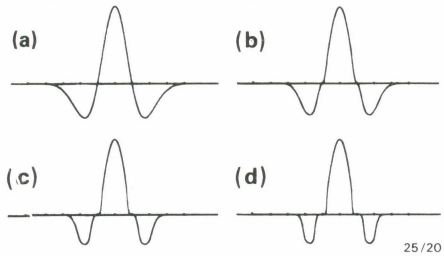


Fig. 6. Example of the distortion of a signal caused by Nth-root stacking, and the consequent signal sharpening. Analytical results have been used to simulate the effect that would be achieved by stacking an infinite number of noisy wavelets. (a) Linear stack (identical with the original wavelet without noise); (b) 2nd-; (c) 4th-; and (d) 8th-root stacks.

Muirhead (1968: *Nature*, 217, 533–534) introduced the Nth-root stack as a means of eliminating false alarms caused by spiky data during the automatic detection of seismic events using seismic arrays. He recognised that by taking the Nth-root of the input signals before averaging, and then raising the average value to the Nth-power (with retention of sign throughout), he was able to reduce the amplitude of spikes far more than in a linear stack, and thereby reduce the number of false alarms triggered by spikes. This rejection of spikes is fairly obvious, and simple to demonstrate. However, the process is non-linear, so no general transfer function can be written and used to describe its properties.

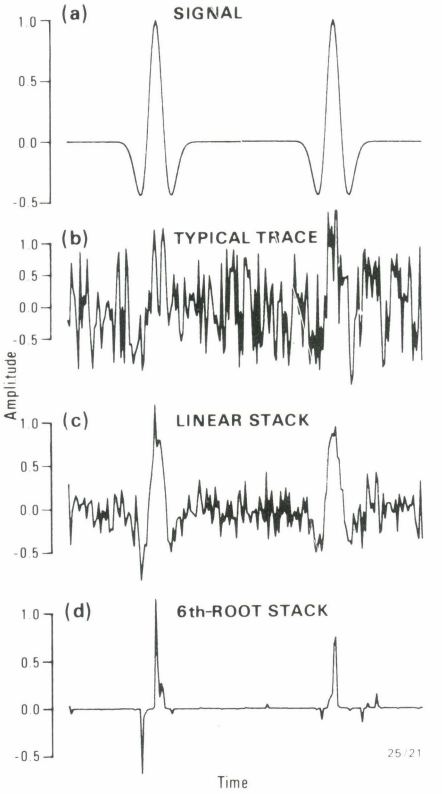


Fig. 7. An example of the contrast enhancement of Nth-root stacking. (a) Signal trace containing two wavelets; (b) typical trace in which random noise has been added to the signal trace, 12 traces generated; (c) linear stack of the 12 traces; and (d) 6th-root stack of the 12 traces.

Previously the properties of Nth-root stacking have been described only qualitatively using sets of synthetic seismic data. Consequently it has not been possible to predict how the process would affect signals in the presence of noise other than spikes, and this has severely impeded broader application of the process. Recent work (McFadden & others: submitted to *Geophysics*) has demonstrated analytically how the process works, why its properties exist, and what those properties are. The power of the process has now been demonstrated using both synthetic and real data, and with a fuller understanding of the process has come the recognition that Nth-root stacking has a useful role to play in the processing of a fairly wide range of seismic and other geophysical data.

It is now possible to predict those applications in which Nth-root stacking will be inferior to linear stacking, and those in which it will be superior. Although the variance of the result from an Nth-root stack is often less than for a linear stack, in all cases the signal level in the output from an Nth-root stack will be attenuated compared with the true signal level, the attenuation depending in a complicated way on the number (m) of data channels, the order (N) of the stack, the signal-to-noise ratio, and the noise distribution. Because the signal-to-noise ratio varies across a wavelet, peaking where the signal is greatest and approaching zero at the zero crossing points, the attenuation of the signal varies across a wavelet, thereby causing signal distortion. The main visual effect of the distortion is a sharpening of the legs of the wavelet. When there is no signal, the variance of an Nth-root stack is at a minimum and decreases approximately as m^N, whereas the variance for a linear stack decreases as m. As a result, the attenuation of the signal is accompanied by a much greater attenuation of the background noise, leading to a significant enhancement of the contrast between signal and background, making signal detection much easier in many cases. Nth-root stacking will therefore be particularly powerful in applications where signal sharpening and contrast enhancement are important, but signal distortion is not.

Figures 6 and 7 have been prepared, using noise with a uniform distribution, to demonstrate signal distortion and contrast enhancement resulting from the use of an Nth-root stack. Figure 6 shows the result that would be obtained by stacking an infinite number of wavelets — with a moderate amount of noise added — using linear, 2nd-, 4th-, and 8th-root stacking. The linear stack produces no wavelet distortion, and so is identical with the original signal. Nth-root stacking does cause distortion: those parts of the wavelet where the amplitude is large suffer little attenuation, but near the ends of the wavelets and the zero crossings a much greater attenuation occurs. The amount of distortion increases as N increases.

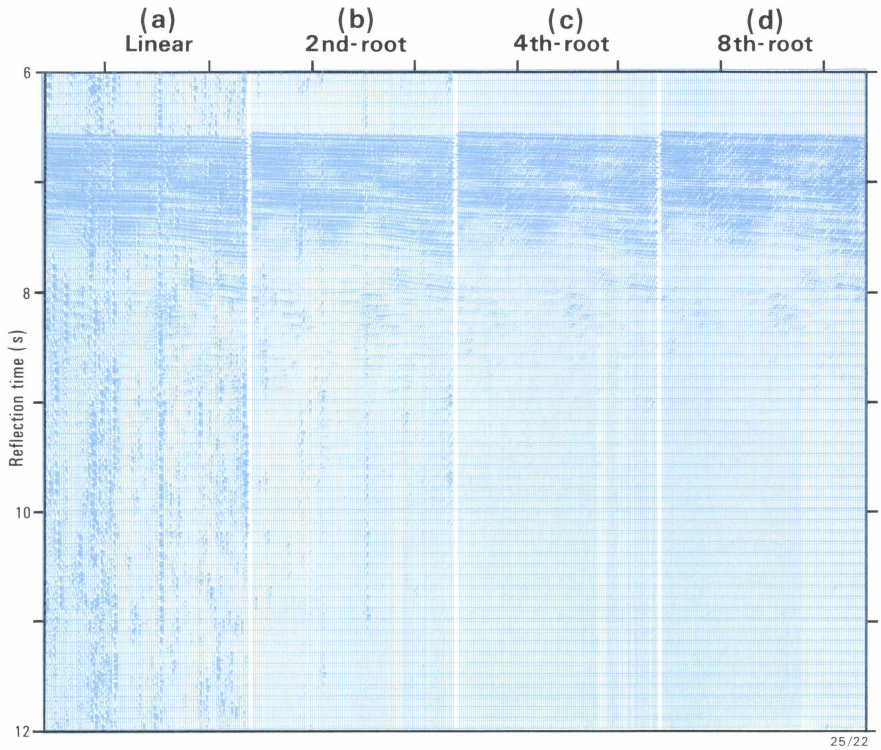


Fig. 8. Stacks of 12-fold CDP reflection data from the Solomon Sea. (a) Linear stack; (b) 2nd-; (c) 4th-; and (d) 8th-root stacks. The data contain random bursts of noise on single channels. The noise is clearly visible on the linear stack despite having been averaged over 12 channels, but it is far more attenuated on the Nth-root stacks, especially the 4th- and 8th-root stacks. In all displays, the amplitudes have been normalised for display purposes.

Figure 7 shows the effects of linear and 6th-root stacking of 12 synthetic traces to which noise has been added. The 6th-root stack clearly shows the position of the wavelets, without time shifting, far more clearly than the linear stack. Where there is no signal, the noise is substantially reduced in the 6th-root stack relative to the linear stack, and it is this increase in contrast that allows a clear identification of the signal presence.

Figure 8 is an example of how Nth-root stacking can be used in conventional seismic reflection profiling. It shows a short segment of a long 12-fold seismic profile in the Solomon Sea,

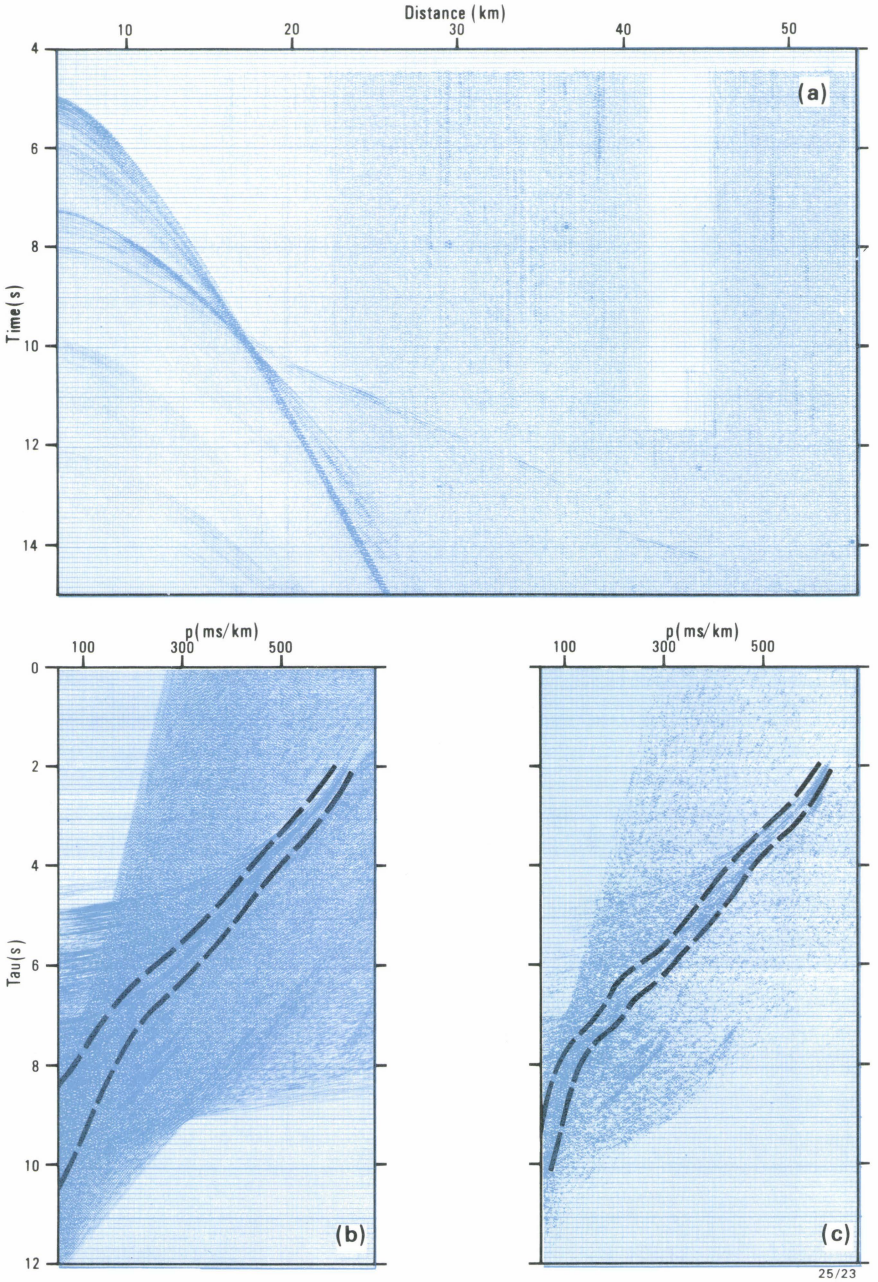


Fig. 9. Slant stacks of ESP data from the North Atlantic. (a) Raw data; (b) linear slant stack; (c) 4th-root slant stack. In the slant stacks the tau–p curve representing the refracted and wide-angle reflected energy has been highlighted by a dotted envelope. The 4th-root stack has a much clearer tau–p curve than the linear stack because of its higher contrast against the normal background noise and the energy from the sub-critical reflections.

in which the data contain random bursts of noise on individual channels. Figure 8a is a conventional linear stack of the moveout-corrected data; the noise bursts are still unacceptably large despite having been averaged over 12 channels. In the original processing of the data, several man-weeks were required to edit out the noisy traces. Note that in the 2nd-root stack (Fig. 8b), the noise bursts have been reduced, and in the 4th and 8th-root stacks (Fig. 8c,d) they have effectively been eliminated from the displays. The 8th-root stack has some distortion of the waveform, but individual horizons can still be traced easily across the display.

As previously noted, when signal distortion is unimportant, the contrast enhancement properties of Nth-root stacking can be extremely useful. Figure 9a shows data from an expanding-spread profile (ESP) in the North Atlantic. The data were to be interpreted to give the variation of velocity with depth through the crust by first transforming the data into the tau–p domain, and then inverting the tau–p curve to give the velocity variation with depth. In this application, sub-critical reflections were to be ignored, and therefore constitute signal-generated noise. Figure 9b shows the data in tau–p space transformed using a conventional linear slant stack. The dotted lines encompass the interpreted tau–p curve to be inverted for velocity variation with depth. The approximate position of the tau–p curve can be seen, but its exact position in tau–p space is masked by the blurring effects of normal background and signal-generated noise. Figure 9c shows a 4th-root slant stack of the data, generated using the same signal-muting and display parameters as the linear slant stack in Figure 9b. The most obvious improvement is in the suppression of the sub-critical reflections and the background signal, and the resulting enhancement of the contrast between the tau–p curve and the background, especially in the lower left corner. The position of the tau–p curve is much clearer than in the linear slant stack because the coherent energy has stacked into a much narrower corridor, as indicated by the dotted lines. As noted in *BMR Research Newsletter* 3 (p. 10), an Nth-root algorithm has now been included in the software for BMR's marine tau–p studies.

For further information, contact Dr Phil McFadden at BMR.

The oldest age determined for Pilbara greenstones

New Sm–Nd isotopic data measured by G. Gruau and B. Jahn (Institut de Géologie, Université de Rennes, France), in collaboration with the joint BMR–GSWA Pilbara volcanic geochemistry study, suggest an isochron age of 3695 ± 47 Ma for peridotitic komatiites, high-Mg basalts, and tholeiitic basalts of the North Star Basalt and Mount Ada Basalt, Talga–Talga Subgroup, lower Warrawoona Group (Fig. 10). The samples were collected from an area about 10–20 km northeast of Marble Bar. The initial $^{143}Nd/^{144}Nd$ ratio is somewhat higher than that calculated for chondritic mantle about 3700 Ma old, which suggests a slight depletion in the light rare-earth elements before the volcanics were erupted — conceivably in conjunction with earlier mantle melting events.

The 3695 Ma age is the oldest determined so far in the Pilbara Block. Previous isotopic studies there have yielded a U–Pb zircon age of 3452 ± 16 Ma for a dacite flow in the Duffer Formation (Pidgeon, 1978: *Geological Society of Australia, Special Publication* 7, 187–192) and an Sm–Nd isochron age of 3560 ± 32 Ma for ultramafic to dacitic volcanics in the upper North Star Basalt (Hamilton & others, 1981: *Earth and Planetary Science Letters*, 37, 421–428). Isotopic age studies of Rb–Sr, Pb–Pb, U–Pb, and Sm–Nd systems in gneisses of the Pilbara batholiths intruding the volcanic sequences have previously yielded ages of 3300–3500 Ma.

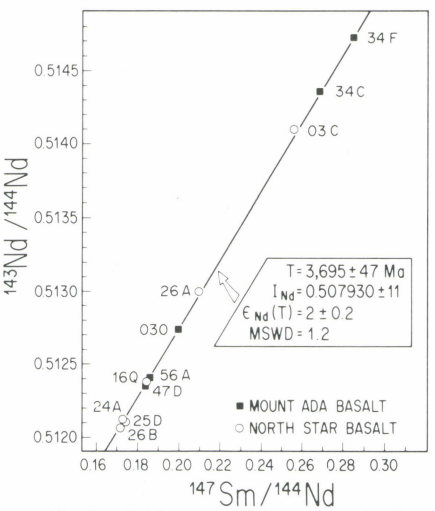


Fig. 10. Sm–Nd isochron for mafic and ultramafic lavas northeast of Marble Bar. (Courtesy of G. Gruau and B. Jahn)

The only older components of rocks known on the Australian continent are zircons dated by ion probe as 4100–4200 Ma old in the northwestern Yilgarn Block (Froude & others, 1983: *Nature*, 304, 616–618). These zircons constitute detrital components of a younger quartzite, and their provenance remains unknown. The possibility that the recently dated Pilbara mafic lavas have been contaminated by older zircons, as is thought to be the case in Kambalda (eastern Yilgarn Block), must not be overlooked. However, the stratigraphic consistency between the 3695 Ma age for the North Star Basalt and Mount Ada Basalt lavas, and the 3452 Ma age for lava in the overlying Duffer Formation, lends credence to an interpretation of 3695 Ma as a primary magmatic age.

Andesitic to dacitic volcanics associated with the Talga–Talga Subgroup yield an Sm–Nd isochron age similar to that of the ultramafic-mafic lavas, albeit with a different initial $^{143}Nd/^{144}Nd$ ratio, which suggests they are derived from a source distinct from that of the ultramafic–mafic lavas.

More details from Dr Andrew Glikson, BMR.

The Ocean Drilling Program

Proposed Australasian sites

The Ocean Drilling Program (ODP) is an international alliance of government bodies and scientists whose objectives are to explore the history of the ocean basins and margins of the continents. The organisation is currently funded by the US National Science Foundation (NSF) and scientific institutions in Canada, France, Federal Republic of Germany, and Japan. Drilling proposals can be submitted by any interested party and are not restricted to the funding nations. Planning and program advice is given by JOIDES — the Joint Oceanographic Institutions for Deep Earth Sampling — through a number of regional and specialist panels.

The original Deep Sea Drilling Project (DSDP) was established at Scripps Institution of Oceanography, and from 1968–83 drilled 624 sites, which — among other achievements — determined the age of the ocean floors and confirmed the principles of plate tectonics. The continuing program (ODP) is being undertaken with the superbly equipped drillship JOIDES *Resolution* (SEDCO/BP 471), which is dynamically positioned, has a total suspended drillstring of over 9000 m, and can drill in water depths of 8000 m.

ODP's first year of operation (1985–86) is concentrating on drilling sites off the coast of Spain, in the Norwegian and Labrador Seas, and on the mid-Atlantic Ridge. The Indian Ocean and Pacific Ocean regions will be drilled in 1987–89. Potential sites within the Australasian portion of these oceans have been presented as a compendium — *Consortium of Ocean Geosciences (COGS) Publication* — of which BMR was the principal contributor. Following from this, site proposals in five high-priority areas (Fig. 11) have been prepared by the Division of Marine Geosciences & Petroleum Geology, and are currently under consideration by ODP. The rationale for these proposals is outlined below.

Otway Basin/west Tasmania margin (area 1)

This proposal calls for four non-re-entry sites (estimated drilling time of 43 days) to examine the tectonic development and depositional environments on a classic extensional margin which has been affected by wrench faulting owing to prolonged contact of the Australian and Antarctic Plates. The sites, in water depths of 3226 to 4750 m, should resolve:

- the ages and nature of Australian/Antarctic rifting and breakup;
- depositional environments within the late infra-rift and syn-rift stages;
- the ages and origins of some of the 18 regional unconformities in the area; and
- the biostratigraphic record.

Exmouth Plateau/Argo Abyssal Plain (area 2A/2B)

This proposal, prepared jointly with Dr Ulrich von Rad (BGR, Hannover), is for three sites on the Exmouth Plateau and one on the Argo Abyssal Plain. It is hoped that re-entry will not prove necessary. The Exmouth Plateau sites, in water depths of 900–4050 m, are designed to provide vital information on a classic starved margin which has undergone two phases of breakup. Information gathered should reveal:

- the age and nature of rifting and breakup;
- the depositional environments within the pre-rift, syn-rift, and post-breakup stages; and
- the relationship of sedimentology and biostratigraphy to changes in palaeoclimate, palaeo-

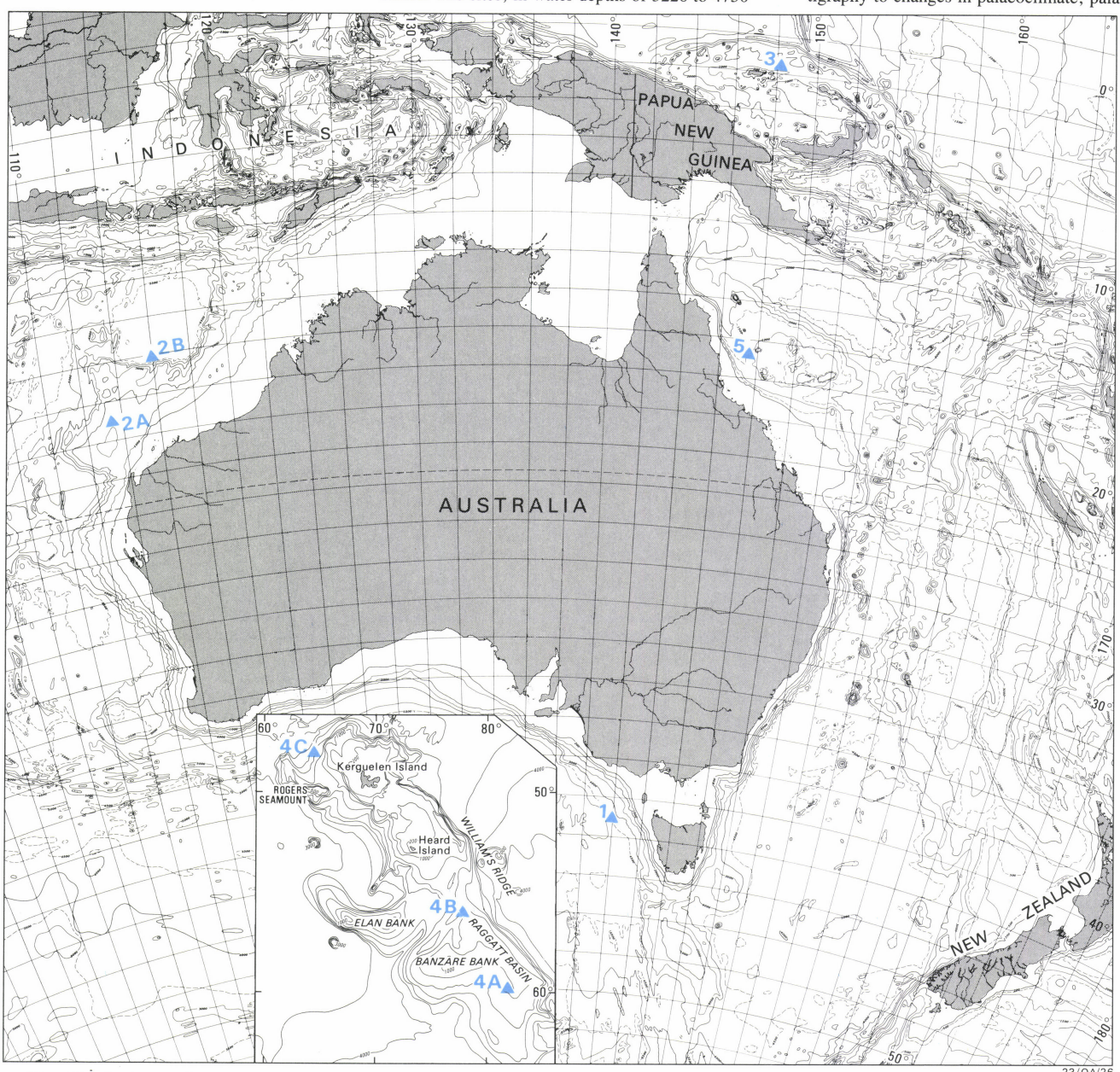


Fig. 11. Bathymetric map of the Australasian region (with Kerguelen Plateau insert) showing proposed ODP drilling sites.

oceanography, sediment supply, sea-level fluctuations, and sediment history.

The Argo Abyssal Plain site, in a water depth of 5700 m, has been selected to investigate the sequence overlying the oldest oceanic crust, Callovian–Oxfordian, in the Indian Ocean. Particular attention would be directed to:

- Jurassic–Cretaceous eastern Tethys palaeocirculation, abyssal palaeoceology, and biostratigraphy;
- the dating of Indian Ocean magnetic M-series anomalies;
- subsidence history and Tertiary oceanic circulation changes; and
- a reconnaissance for mid-Cretaceous black shales.

Bismarck Sea, PNG (area 3)

This drilling proposal, prepared jointly with USGS scientists led by Dr Mike Marlow, is for five single-bit sites in this highly complex region of the Melanesian borderlands. Investigations at two forearc sites north of Manus Island in water depths around 2000 m should reveal the nature of:

- the offscraped sediment pile in the extinct (Eocene–Miocene) Manus forearc convergence zone; and
- the extensive overlying lava flows which may be related to the opening of the Manus Basin farther south.

An island-arc site near Mussau Island has been proposed because it offers the opportunity to investigate:

- the volcanic crust above a feature that seismic reflection data imply is a magma chamber;
- volcanic basement rocks;
- possible hydrothermal fluids and metallic deposits; and
- the history of this end of the Mussau–Bougainville island arc.

Two trench sites are suggested in order to test the proposition that the Mussau Trench, between the Pacific and Caroline Plates, is newly active, and, if so, to determine its impact on the Manus Trench. The first site, in the Mussau Trench, would:

- provide information on underthrusting along the Caroline Plate boundary; and
- document the effects of incipient subduction.

The second site, in the Manus Basin east of the Mussau Trench, should:

- disclose the relationship between recently deformed trench fill and the inner trench slope; and
- indicate whether the trench is again the site of convergence.

Kerguelen Plateau (area 4A/4B/4C)

The BMR proposal for this enigmatic feature in the central southern Indian Ocean calls for the drilling of up to 10 holes in the Australian region around and south of Heard Island. The primary objectives of these holes would be:

- to elucidate the nature and age of the crust beneath the plateau (oceanic or continental? — this has major implications for reconstruction of Gondwanaland);
- to determine the tectonic and depositional history of the plateau, including the age and nature of sequences within the major sedimentary basin on the southern plateau;
- to provide palaeo-oceanographic, palaeoclimatic, and biogeographic information on the Antarctic margin using holes over a range of latitudes and water depths; and
- to determine the age of the crust immediately flanking the southern part of the plateau.

Because of the world-wide interest in this feature, it appears that one leg (60 days) will be spent drilling on the plateau, probably in late 1987 or early 1988. Many of the BMR-proposed holes will probably be drilled.

Great Barrier Reef/Queensland Plateau (area 5)

The Great Barrier Reef is the largest epicontinental reef system on Earth, and the Queensland Plateau is one of the largest marginal plateaux; they are separated by a deep rift basin. This sedimentological and structural association is a recurrent theme throughout geological history, and, as this region is the most complete example on Earth today, its study would produce a directly applicable analogue. Further, the region is unique for the study of carbonate/clastic interactions on tropical passive margins, and contains a superb record of ocean history. Specific objectives would be to determine and document:

- the effects of northward plate motion on the growth and evolution of the Great Barrier Reef; (do the reef and associated facies carry an imprint of this motion?)
- the effects of sea-level change on slope sedimentation facies; as major and minor facies variations are clearly visible on seismic sections, a major objective would be to correlate sea level, facies, and seismic stratigraphy in an area where the seismic coverage is excellent;
- the changing response of chemical and physical oceanography in the western Coral Sea as a result of plate motion and sea-level variations;
- the nature of submarine fans and slump deposits and their relation to sea-level fluctuations and tectonics; the unique carbonate/terrigenous facies variations may well reflect a correlation between the type of process and sea-level position;
- the influence of passive-margin subsidence history on sedimentologic evolution in northeast Australia, where a series of subsidence pulses—the last some 3.5 Ma ago—may correlate with specific sediment packages and sea-level fluctuations;
- the subsidence history and related reef growth history of the Queensland Plateau; existing data suggest that reef growth and differential subsidence increasing to the north were initiated during the Eocene–Oligocene;
- whether Queensland Plateau reefs are older than reefs of the Great Barrier Reef, and to define the effects of sea-level variation on reef establishment;
- the sedimentologic facies and depositional mechanisms affecting the western margin of the Queensland Plateau; and
- the seismic stratigraphic relationships between the Great Barrier Reef margin, the Queensland Trough, and the relatively starved but carbonate-dominated western Queensland Plateau margin.

For further information, contact Barry Wilcox, Neville Exon, Jim Colwell, Peter Davies, or Phil Symonds at BMR.

Mineral potential of the southwest Pacific

The untapped mineral potential of the Solomon Islands and Vanuatu is highlighted in a recently published paper by BMR marine geologist Hugh Davies. The paper, 'A review of the mineral potential of the southwest Pacific', was initially presented at a cross-disciplinary session of the 15th Pacific Science Congress in Dunedin in February 1983, and was published late last year in a volume entitled 'Environment and resources in the Pacific', edited by A.L. Dahl & J. Carew–Reid *(UNEP Regional Sea Reports and Studies* No. 69).

The paper on mineral potential establishes a simplified picture of geology for each of the island nations and territories, classifying most land areas as either collisional or volcanic, and relating the mineral resources to these two environments. A table compares value of annual production of minerals per unit area for nations of similar geological setting, and demonstrates that, while Australia and Papua New Guinea have a similar ratio (around $1000 per km^2), New Caledonia has a ratio an order of magnitude greater, and the Solomon Islands and Vanuatu at least two orders of magnitude lower. The author concludes that the Solomon Islands and Vanuatu are either anomalously mineral deficient or underexplored.

Hydropower, hydrocarbons, offshore mineral potential, and the possible nature of undiscovered mineral resources are reviewed briefly. Undiscovered mineral resources may include ores of mercury and tungsten; uranium in a volcanic association; uranium and other metals of the carbonatite association; platinum group metals; and concealed deposits of phosphate. The paper closes with brief reference to the impact of mineral development, including a few words on projected earnings from the Ok Tedi project as they were estimated before development.

Preparation of the review was assisted by the generous co-operation of specialists working in the southwest Pacific islands. Although the information is somewhat dated, because of the delay between compilation and publication, the paper may be a useful reference for the exploration geoscientist or mineral economist because of the considerable volume of data presented and the extensive bibliography.

For further information, contact Dr Hugh Davies at BMR.

Northeast Australia research cruises

During two research cruises by *Rig Seismic* off northeast Australia in September–October and November–December 1985, data were collected in water depths ranging from 30 to 3500 m in key areas throughout the vast region between Townsville and the Gulf of Papua. The cruises, in which thirty BMR scientists and technicians took part, were part of a project whose objectives were to determine the regional stratigraphy and structural framework; the relations between tectonics, sea-level change, and style of sedimentation; and the lithofacies, age, and depositional processes adjacent to a large epicontinental reef system.

The region off northwest Australia contains the Great Barrier Reef, the largest epicontinental reef system on Earth, and the Queensland Plateau, the largest marginal plateau of the Australian margin. Understanding their origin is important because they constitute a modern analogue of a sedimentological and structural association — reef/adjacent rift trough/marginal plateau — which has been common throughout the geological record (e.g., in the Devonian of the Canning Basin) and in places has formed significant petroleum provinces.

Data were collected from the Townsville and Queensland Troughs, the Osprey Embayment, the Torres Shelf/Pandora Trough area, the outer shelf and slope of the Great Barrier Reef, and the western margin of the Queensland Plateau; specific areas were surveyed in order to fill important gaps in data coverage or to solve particular problems delineated by previous work in the region. The data include: 3860 km of multichannel seismic reflection profiles (both airgun and high-resolution sparker data), plus magnetic and gravity data; 9 sonobuoy refraction profiles; 207 km of side-scan sonar data; samples from 22 dredge sites; and 190 m of core from 93 coring stations, which tripled the size of the regional data set.

Processing and interpretation of all of these data are now under way, and will continue throughout 1986. The preliminary results of the cruises, including onboard interpretations, will be published as a cruise report in the *BMR Report* series.

For further information, contact Mr Philip Symonds or Dr Peter Davies at BMR.

Proof of explosive origin for the Lawn Hill circular structure

Recently discovered shatter cones prove the explosive origin of the Lawn Hill circular structure (Fig. 12), an annular outcrop of Middle Cambrian limestone surrounding a core of Proterozoic siltstone 250 km north of Mount Isa. The cones were recognised by Ken Mitchell, a senior field assistant with BMR who visited the structure on 17 July 1985 and found them — together with pieces of possible melt rock — in the core. They occur as fragments in colluvium, and in situ in the Proterozoic siltstone. A few weeks later, Alastair Stewart spent two days investigating the structure.

The origin of the Lawn Hill circular structure had been a puzzle since it was first mapped in 1968. In 1980, John Ferguson suggested that the Lawn Hill structure might have been caused by impact. Later that year Geoff Derrick (BMR), Ian Wilson (GSQ), and Laurie Hutton (GSQ) visited the structure to look for evidence of impact or explosion (*GSQ Record* 1980/34), but their investigation showed that the central core had not been uplifted, and they concluded that the Lawn Hill structure could not have formed by either mechanism.

Geological setting

The circular structure is 18 km across, and rests unconformably on mid-Proterozoic siltstone and volcanic rocks. It has no bowl or crater. The limestone annulus forms low hills surrounding a Cainozoic colluvial plain, 8 km across, from which rise low ridges of Proterozoic bedrock. The entire structure is part of a peneplain dipping northeast at 0.1°.

Bedrock of the core is fractured and cleaved siltstone of the Lawn Hill Formation. The annulus comprises two well exposed Middle Cambrian formations (Fig. 12). The Thorntonia Limestone is medium-grained, and contains beds and nodules of chert. It is flat-lying in the Georgina Basin 10 km to the west, but in the Lawn Hill structure is commonly tightly and irregularly folded, and highly brecciated. The breccia, comprising angular chert fragments and subangular carbonate fragments in a carbonate matrix, occurs as cross-cutting, sharply bounded masses ranging from a few to many metres across; some clasts consist of folded limestone. No shatter cones have been found in the limestone or limestone breccia. The Border Waterhole Formation interfingers with the Thorntonia Limestone, and is a massive sedimentary breccia comprising angular clasts of chert in a chert matrix.

Shatter cones

The shatter cones are a few centimetres across, composed of siltstone of the Lawn Hill Formation, and radially striated from the apex (Fig. 13). Parasitic cones on the flanks of larger cones are common. Tectonic deformation lamellae are present in a few quartz grains in the siltstone, but shock-deformation microstructures such as multiple sets of closely spaced lamellae, anomalous birefringence, vitreous phases, reduced refractive index, crystal cleavage, crystal faults, and mosaic extinction are absent. Owing to the poor exposure, only five cone orientations could be measured

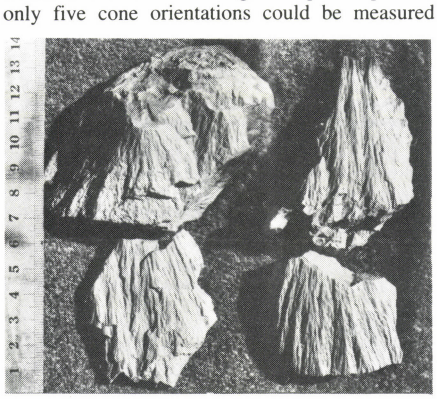


Fig. 13. Typical colluvial fragments of shatter cones collected by Ken Mitchell from the core of the Lawn Hill circular structure. Scale in centimetres. (BMR neg. M2682/2)

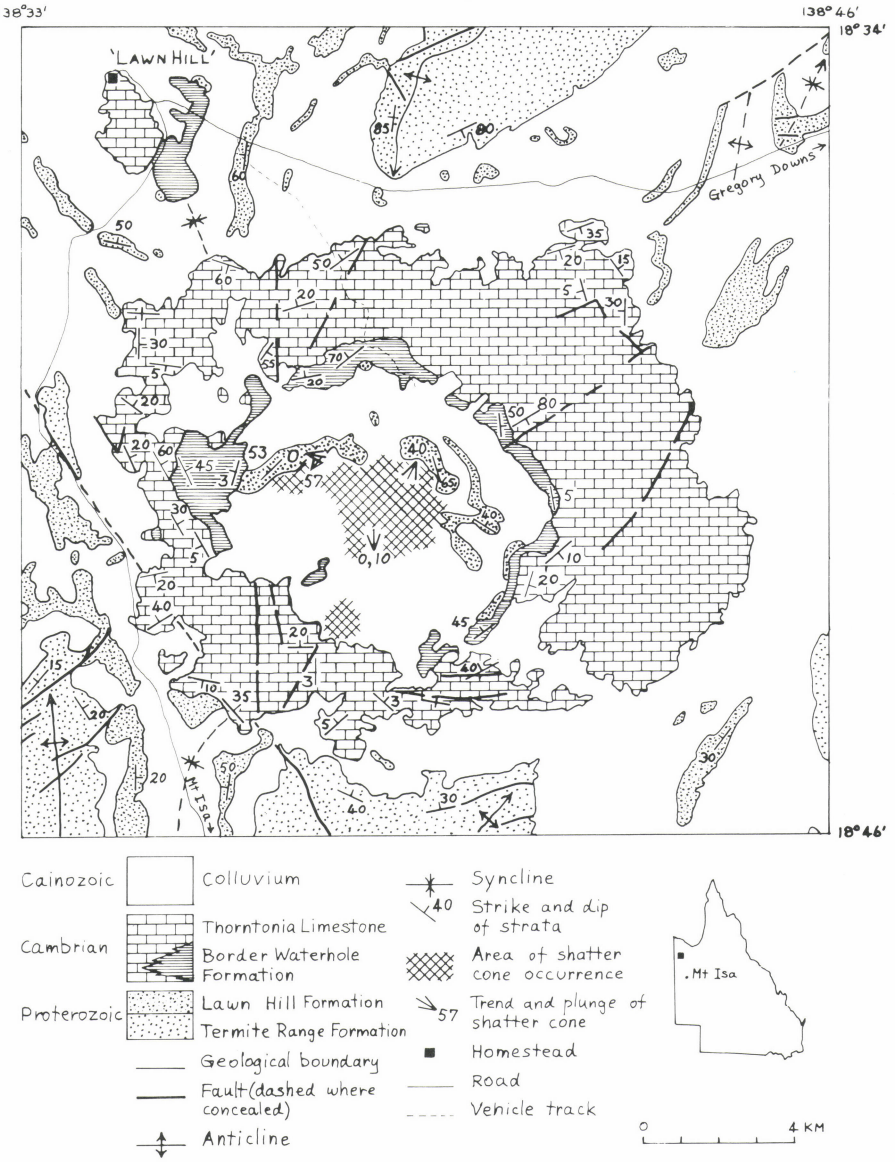


Fig. 12. Geological map of the Lawn Hill circular structure (modified after Sweet & others, 1982: Geology of the Lawn Hill Region, 1:100 000 geological map, published by *BMR*).

(Fig. 12). All five apices point away from the centre of the circular structure, two horizontally and three downward, but are too few to represent a valid sample. Outward-pointing shatter cones have been reported from many cryptoexplosion structures.

Possible melt-rock

Flow-folded fine-grained rock at the centre of the core has a surface sculpture resembling pahoehoe lava, and was suspected of being possible melt-rock, indicative of impact. However, it contains abundant K-feldspar spherulites and small quartz amygdales, and appears to be of felsic volcanic origin.

Origin and age

The shatter cones and annular shape of the Lawn Hill structure indicate an origin by explosive detonation. Shatter cones have been made experimentally in chemical and nuclear detonations and in ballistic impacts at pressures ranging from 25 to 250 kbar (2.5–25 GPa), which are much greater than normal crustal pressures. They have been reported from meteorite craters in Argentina, Estonia, the German Democratic Republic, Ghana, and India, and it is generally thought that cryptoexplosion structures with shatter cones are impact scars of extraterrestrial bodies. Some puzzles remain, however.

Impact scars caused by extraterrestrial bodies should be randomly distributed on the Earth's surface. Yet some cryptoexplosion structures with shatter cones lie on lineaments (for example, the Illinois–Missouri–Kansas lineament in the USA, and the Great Dyke–Bushveld–Vredefort lineament in Africa), in grabens (the Sudbury Structure and Brent Crater, Ontario), or on anticlines (Gosses Bluff, Northern Territory). Recent work at Vredefort Dome suggests that it formed by two intraterrestrial explosions (Lilly, 1981: *Journal of Geophysical Research,* 86, 10689–10700; Simpson, 1981: *Journal of Geophysical Research,* 86, 10701–10706). It seems that shatter cones are not proof of extraterrestrial impact.

At Lawn Hill, several features are critical to an understanding of the origin and age of the circular structure:

- *the folding of the Thorntonia Limestone before brecciation.* The folds could have resulted from explosion, but — if this were caused by impact — they should have formed after brecciation. Alternatively, they could

have formed by slumping shortly after deposition of the limestone, as has been observed elsewhere in the unit, or by solution collapse.

- *the origin of the limestone breccia.* The confinement of the breccia to the circular structure suggests that it originated by the same explosion that produced the shatter cones. However, much of the limestone is not brecciated (and only gently folded), and the breccia masses may have formed by solution and deposition in caves in the limestone; its localised distribution could have resulted from the fractured nature of the Proterozoic bedrock, which facilitated ingress of groundwater and so promoted solution of the overlying limestone. This implies a pre-Middle Cambrian age for the explosion.
- *the absence of shatter cones in the limestone.* The limestone may have been beyond the range of shatter-cone formation, or the explosion may have occurred before deposition of the limestone.
- *the lack of central uplift.* On Earth, impact structures greater than about 3 km in diameter have a centrally uplifted core caused by rebound, which commonly exposes rock from 2–3 km down. At Lawn Hill, the Lawn Hill Formation crops out inside and outside the circular structure, whereas units lower in the succession should be exposed in it.

The Lawn Hill structure must be younger than the Lawn Hill Formation (1670–1500 Ma), and older than the unconformably overlying Armraynald beds of Tertiary to Quaternary age. The northeastward tilt of the landscape, of which the Lawn Hill structure is part, occurred in earliest Cretaceous time, suggesting that the Lawn Hill structure is pre-Cretaceous. Moreover, if the separation of the Lawn Hill structure from the Georgina Basin came about by the Permian–Triassic erosion which preceded Mesozoic deposition on the tilted land surface, then the younger age limit of the Lawn Hill structure could be Palaeozoic.

It seems that the time and cause of the Lawn Hill explosion will remain hidden until further work is done. The shatter cones suggest an explosion of extraterrestrial origin, but the lack of central uplift, and the folding before brecciation, suggest an intraterrestrial origin. The limestone breccia and its distribution suggest a post-Middle Cambrian explosion, but the absence of limestone shatter cones suggests a pre-Middle Cambrian age. The Lawn Hill structure is truly a cryptoexplosion structure.

For further information, ask Dr Alastair Stewart at BMR.

BMR seismic line in SE Queensland probes shallow and deep sedimentary basins

BMR's southeast Queensland seismic survey is providing new insights into the structure and stratigraphy of the sedimentary basins of southeast Queensland, and some surprising results from basement areas. BMR, with the co-operation of GSQ, has shot a six-fold CDP seismic reflection profile from Toowoomba in the west almost to Beenleigh in the east (BMR traverse 16; Fig. 14). Data were recorded down to 20 s to investigate the structure of the deep crust beneath the Mesozoic and Palaeozoic basins in the region.

The top four seconds of the records provide fair to good data from the Mesozoic and Permian basins in the area, and are being used in studies of hydrocarbon potential. The record for part of the line traversing the Laidley Sub-basin of the Clarence-Moreton Basin (Fig. 15) shows a series of superimposed seismic sequences. Of these, the Clarence-Moreton Basin sequence of uppermost Triassic to Middle Jurassic sedimentary rocks is the youngest. It overlies two sequences of Middle Triassic Esk Trough rocks, which overlie another trough of possibly Upper Permian to Lower Triassic sedimentary rocks. These sequences lap on to a faulted, more highly deformed sequence of probable Permian sedimentary rocks. Ties to petroleum wells (Lockrose No. 1 and Baylam No. 1) north of the line, using old single-fold analogue data reprocessed on the BMR DISCO processing facility, confirm the absence of the Ipswich Coal Measures west of the West Ipswich Fault.

This sequence of structures indicates that the Clarence–Moreton Basin and the Esk Trough are intracratonic sag basins overlying a Permian rift or strike-slip basin. The Esk Trough and older rocks are truncated at the eastern end of this line segment by the West Ipswich Fault, a major structure which also deforms the younger Clarence–Moreton sequence.

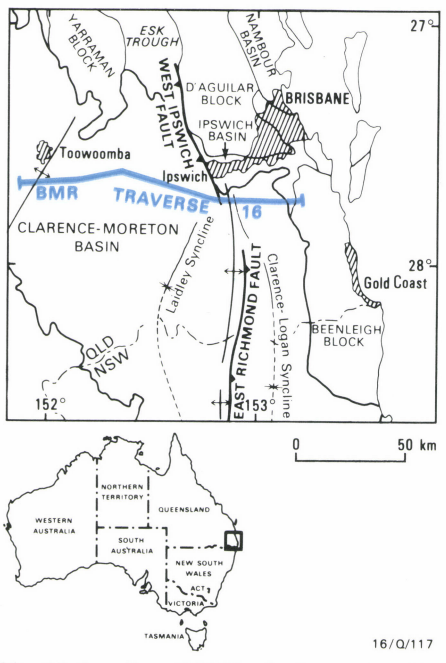


Fig. 14. Location of BMR seismic traverse 16.

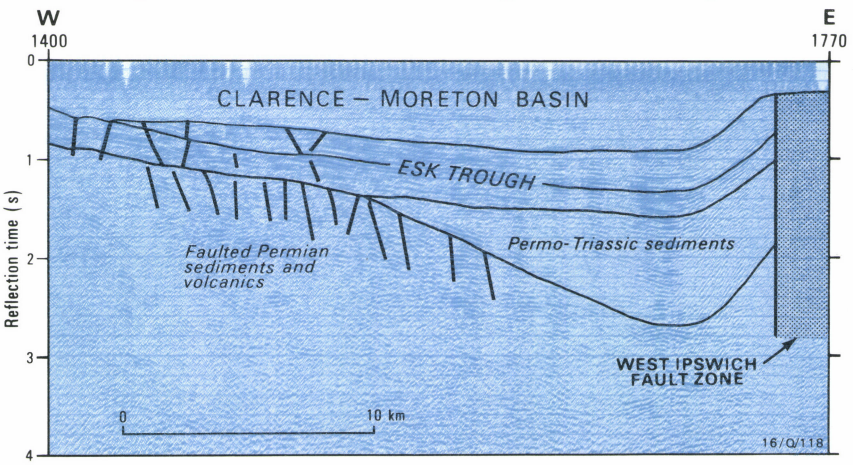


Fig. 15. Geological interpretation of the seismic record of a portion of BMR traverse 16.

The data show that the rocks on the western side of the Esk Trough are not severely deformed, and contain some structures that might be suitable for the entrapment of hydrocarbons, though more detailed seismic investigations would be required to evaluate their trapping potential. Also, though the hydrocarbon source and reservoir potential of the Esk Trough rocks has received little attention, source-rock data from stratigraphic drillholes in the area — as part of the BMR/State survey Clarence–Moreton Basin project — indicate that rocks at the base of the Clarence–Moreton sequence are mature for the generation of liquid hydrocarbons.

Preliminary examination of the 20-s records indicates that the basement beneath the eastern part of the line is probably composed of a thick stack of west-dipping thrust slices. The Beenleigh Block is the uppermost of these. Those underneath appear to be composed of well-bedded rocks, suggesting the existence of a previously unknown sedimentary basin that was sliced up during late Palaeozoic and early Mesozoic deformations of the New England Orogen. This suggestion has profound implications for the interpretation of the tectonics of eastern Australia.

For further information, contact Drs John Lindsay or Russell Korsch, or Messrs Phil O'Brien, Allan Wells (geological interpretation), Kevin Wake-Dyster, or Mike Sexton (data acquisition and processing) at BMR.

Lord Howe Rise cruise : data release

Data from the *Rig Seismic's* first research cruise — southeast of Lord Howe Island, in February 1985 — will be released in June 1986.

The data package will comprise fully processed seismic sections for about 1200 km of track (lines 46/003–46/010, 30 sections), together with seismic field tapes, final stack tapes (unfiltered/unmigrated), and a preliminary 1:2 500 000 track map based on satellite-fix positions. The sections will be available in half-scale (4 cm 5^{-1}) form as a 'compendium', and individually at full-scale.

The seismic data were processed on BMR's VAX/DISCO system. The processing sequence consisted of conversion to internal format, resampling to 2 ms, spherical divergence correction, CDP ordering, velocity analysis at selected points, and 24-fold stack. A gapped deconvolution process was applied before stack, and a spiking deconvolution after stack, followed by band-pass filtering. The stacked data were migrated using the FK method.

The seismic data consist primarily of four lines which extend northeastwards from the Lord Howe Basin, across a broad horst and graben province, to a region of planated basement below the crest of Lord Howe Rise. The penetration is typically about 2 s (or 3000 m) and shows post-breakup and syn-rift sedimentary sequences overlying block-faulted (and, in places, well stratified) infra-rift rocks. The seismic sequences are generally believed to range in age from Late Cretaceous to Recent, but it is uncertain if the infra-rift sequences are entirely metasediments of the Tasman Geosyncline, or in places Cretaceous sediments.

The cruise results have been summarised in *BMR Report* 266 *(Rig Seismic* research cruise 1 : Lord Howe Rise, by R. Whitworth, J.B. Willcox & others, 1985); further interpretation is in progress. Magnetic tapes of final navigation data, water depths, and magnetics should be available towards the end of 1986.

For general enquiries on data release, contact Mrs Margaret Bartlett at BMR.

Towards the completion of reconnaissance aeromagnetic coverage of Australia

One of the major projects of the Division of Geophysics is the reconnaissance aeromagnetic and radiometric survey of Australia carried out by the Potential Fields Section of the Division using BMR's aircraft. The project commenced in 1952, and coverage of the continent is nearing completion. A strategic plan has been set out to complete the entire survey by 1991, and publish the complete set of 1:250 000 aeromagnetic maps for the continent by 1992. At that time there will be a complete digital aeromagnetic database for Australia. To enable this deadline to be met, extra staff and funds for the Potential Fields Section have been provided. In 1983–84 the Section received 52 per cent of the operational funds of the Division of Geophysics, and by 1985–86 this had increased to 59 per cent; this concentration of resources apportioned to the project reflects the priority that BMR has given to it.

The area still to be surveyed is relatively small (Fig. 16), but staffing restrictions have caused backlogs in the production of 1:250 000 maps of areas already flown. The current backlog is about 45 sheets, but the extra staff and funding for contract processing will enable this to be reduced significantly over the next two to three years.

Early BMR surveys were recorded as analogue charts. These old records, comprising 160 Sheet areas, are being digitised so that the entire database can be made available in digital form. So far, the old records from the Yilgarn Block have been digitised, with the result that a large area in southwestern Australia now has a complete digital database (Fig. 16). New maps will be produced for each 1:250 000 Sheet area whose data have been digitised. Completion of this map production is scheduled for 1993.

In the meantime a new series of 1:1M-scale colour magnetic anomaly maps is to be published (see *BMR Research Newsletter* 2) — for the Roper River Standard Sheet area (see *BMR Research Newsletter* 3) and the Murray Basin Special Sheet area. We propose to publish further maps in this series at roughly monthly intervals in the 1986–87 financial year.

For further information, contact Dr Mike McElhinny or Dr David Tucker at BMR.

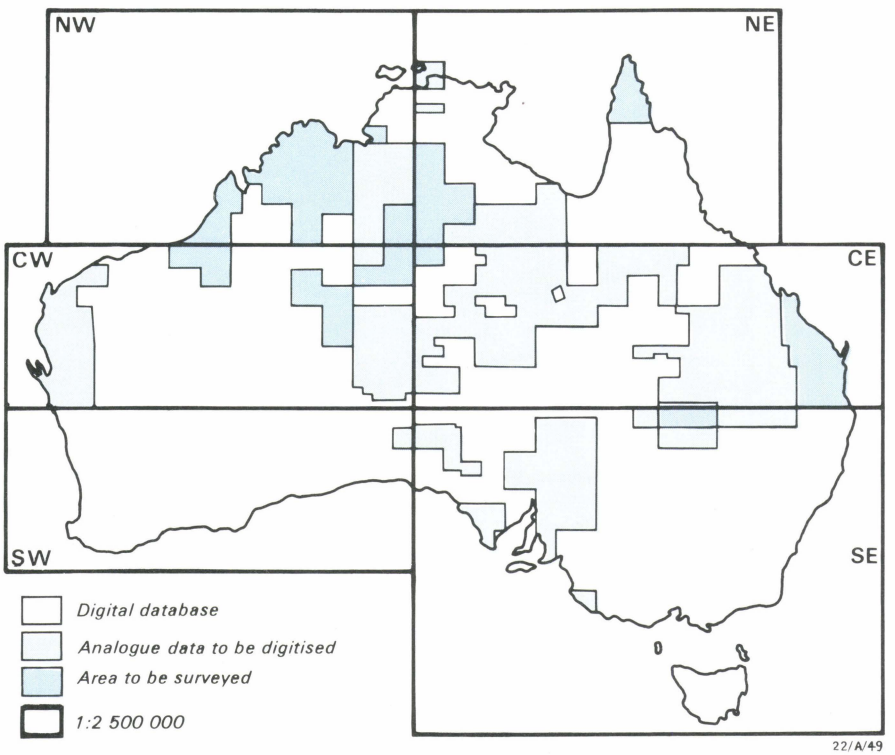


Fig. 16. Extent of aeromagnetic coverage and the digital database in February 1986.

Honour Peter Davies

BMR takes this opportunity of congratulating Dr Peter J. Davies, Principal Research Scientist in the Division of Marine Geosciences & Petroleum Geology, on becoming the 1986–87 AAPG Overseas Distinguished Lecturer.

AAPG has established the Bennison Foundation, which provides the funds to invite one speaker per year from outside North America for one tour. Distinguished Lecturers speak to important scientific societies and university geological departments throughout the United States and Canada, and are invited because of the significant contribution they have made to the application of geological principles to petroleum exploration. Only two Australian scientists have been among the previous recipients of this award.

Peter Davies is a specialist carbonate sedimentologist who is distinguished for his studies of ancient and modern coral reefs and in particular the Great Barrier Reef. His pioneering work into the origin of reefs in northeast Australia, aided by $395 000 of external research grants, has resulted in the development of exciting new concepts for the growth of reefs and their relation to sea-level change and continental margin formation. The recent cruises of RV *Rig Seismic* in northeast Australia have helped place these concepts within a new plate-tectonic understanding of the western Coral Sea.

The author of over 70 scientific publications, Peter finds time to supervise five postgraduate students at three universities. He is also the Chairman of both the International Association of Biological Oceanographers Coral Reef Committee and the Organising Committee of the Sixth International Coral Reef Symposium.

A firm advocate of team research, Peter Davies sees the AAPG Distinguished Lectureship as a reflection on the staff, both scientific and technical, who have worked with him in the Great Barrier Reef and northeast Australia, and recognition of BMR research in the area.

Forthcoming publication

Uranium — world perspective

Forty years ago, uranium was shrouded in secrecy; today, ironically, close international co-operation between the countries of the Western world culminates in a biennial publication, 'Uranium — resources, production and demand', that is more authoritative than the supply–demand data for most elements. The next edition of this publication (the 1985 edition), which is published by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, is expected to be available about May 1986. This publication is commonly referred to as the 'Red Book', and is probably the most authoritative source on the uranium industry — past, present, and future.

The NEA Uranium Group, which meets in Paris about twice a year, is responsible for preparing the questionnaires that are submitted to relevant national authorities, and then preparing the material for publication in the Red Book. During recent times, Australia has been represented in the Uranium Group by Gordon Battey of the Resource Assessment Division.

Australia has more extensive uranium resources than any other nation, and has played a leading role in initiating the improvements in the presentation of data in recent editions of the Red Book. The 1983 and 1985 editions distinguish between in-situ mineable and recoverable resources, whereas in earlier editions many nations, in practice, failed to make this distinction, despite the fact that the definition clearly referred to recoverable resources. In earlier editions, resources were classified as reasonably assured resources (RAR), estimated additional resources (EAR), and speculative resources. Most nations included both discovered and undiscovered resources in the EAR category, which has now been divided into separate discovered and undiscovered resources.

For those wishing to purchase a copy of the Red Book, the Australian agent for OECD publications is the Australian and New Zealand Book Company Pty Ltd, P.O. Box 459, Brookvale, 2100.

For further information, contact Mr Gordon Battey, Assistant Director, Uranium Resources Evaluation Unit, 549 Gardeners Road, Mascot, NSW 2034; telephone (02) 6691177.

Farewell Cliff Ollier

In February, Cliff Ollier reached the end of his three-year secondment to BMR's Division of Continental Geology, and returned to his former position as Professor of Geography at the University of New England.

At BMR, Cliff worked on the regolith of Australia, making use of his former experiences in many parts of the world as a soil scientist and a geomorphologist with an interest in weathering. Whilst the direct results of much of his work may not be seen for some time, they include three regolith maps and reports and several papers on the geomorphology and regolith of the Kalgoorlie region.

Cliff was instrumental in organising some useful conferences and seminars, including the very successful 'Regolith in Australia' symposium, and the symposium on 'Quaternary Studies in Australia: Future Directions'. On the international scene, he has produced two editions of the 'Glossary of morphotectonics' (published in the *BMR Record* series) for the IGU Morphotectonics Project, and edited a *Zeitschrift für Geomorphologie* volume on 'Morphotectonics of passive continental margins' (reviewed in *BMR Research Newsletter* 3, p. 7).

He also applied his interest in tectonics and volcanoes to co-operative work with various people in a number of projects inside and outside BMR. His many co-operative projects include a study of chemical diffusion in laterite formation

with Al Mann of CSIRO; volcanic geomorphology in Victoria with David Wallace of BMR's Division of Petrology & Geochemistry and Bernie Joyce of Melbourne University; morphotectonics of Australia with Gianni D'Addario of BMR's Special Projects & Geoscience Services (SP&GS) Branch; a study of ancient river terraces with Alastair Stewart and David Blake of the Division of Petrology & Geochemistry; palaeodrainage analysis with Gerry Wilford of the Division of Continental Geology; tectonics and drainage of Lake George with Bob Abell of SP&GS Branch; speculation on the relationship between coastal morphotectonics and oil distribution with David Forman of BMR's Resource Assessment Division; and field investigations of remote-sensing imagery with Geoscan.

Cliff's presence in BMR during the past three years has been stimulating, and we look forward to him continuing his involvement with BMR in the coming years.

Research on radioisotope-rich granites

In September 1985, Dr Doug Mackenzie attended a conference at St Austell, Cornwall, England, on 'High heat production (HHP) granites, hydrothermal circulation and ore genesis'. The aim of the conference was to present and discuss current research on a particular class of evolved granites containing high concentrations of radioactive isotopes which give them a high thermal output.

Most of the papers dealt with granites and mineralisation. Of particular note were those on:

- geochemical criteria for the recognition of HHP granites;
- the geochemistry and origin of the South Mountain Batholith, Nova Scotia, host of North America's largest tin deposit;
- the geochemistry, alteration, and mineralisation of the Nigerian HHP granites;
- comparisons between Sn–W mineralisation in Thailand, Cornwall, and Malaysia;
- comparison of radioelement distribution, fractionation patterns, and heat production of selected radiothermal granites in the UK;
- experimental and theoretical aspects of transport and deposition of cassiterite, wolframite, and magnetite;
- theoretical modelling of hydrothermal circulation in and around HHP granite plutons;
- hydrothermal circulation and isostasy in southwestern England granites;
- hydrothermal fluid evolution and mineralisation in the Dartmoor–Bodmin area;
- fluid types from fluid inclusions in southwestern England granites;
- Sn–W mineralisation in the Krušné hory–Ertzgebirge granite pluton;
- the Mole Granite and wolframite-bearing quartz–topaz rock at Torrington (NSW); and
- a thorough review of the petrology and mineralisation of southwestern England granites.

One strong overall impression that emerged from the conference was that the speakers were divided into basically two schools of thought on granite genesis. The dominant school, led by members of the British Geological Survey, propounds that granites are derived from the mantle modified variously by elements originating from subducted lithosphere and, in places, continental crust; this modification theory, as presented in some of the papers, seemed rather contrived. The other school favours deep crustal melting as the source of granites, but even its members commonly showed a lack of understanding of S-type granites and the 'restite' model as propounded by White, Chappell, and others.

A major conclusion drawn from the conference was that there are two 'end-member' models for the emplacement of HHP granites, and for fluid evolution, hydrothermal circulation, and mineralisation in and around them. In one of these end-member models, highly evolved, moderately fluid-rich, and possibly metal-rich plutons are emplaced at very shallow (1–2 km) crustal levels into 'tight', competent, relatively dry wallrocks, which may include volcanics associated with the intrusion. Fluid pressures, or volumes, generated during crystallisation are insufficient to cause significant fracturing of the wallrocks, but may produce extensive internal fracturing. Fluids and metals are derived entirely from the granite, and alteration and mineralisation are almost entirely confined to the granite cupola — that is, little or none extends into the wallrocks. This type of mineralisation tends to be dominated by wolframite.

In the other end-member model, typified by the Cornish deposits, granite is emplaced at deeper levels (2–5 km) in relatively 'wet' country rocks. Fluid pressures and volumes sufficient to cause extensive fracturing of the roof rocks are generated during crystallisation. Subsequent entry into the system of fluids from the wallrocks contributes to extensive hydrothermal circulation systems involving a high proportion of groundwater. Alteration and mineralisation are controlled by fracturing, and can extend hundreds of metres into the country rocks. This style of mineralisation tends to be dominated by cassiterite, though many deposits contain both cassiterite and wolframite, and gives rise to an outward gradation — with decreasing temperature away from the intrusion — of mineral deposits containing base-metals that may be derived, at least in part, from the country rocks. Hydrothermal circulation may continue for many millions of years after emplacement, and extensive kaolinisation is a common accompaniment to this style of mineralisation.

Intermediate styles of Sn–W mineralisation do occur, but there are many examples throughout the world of both these end-member styles.

For further information, contact Dr Doug Mackenzie at BMR.

International Volcanological Congress, New Zealand

Explosive volcanism, geochemistry, hazards, and metallogenesis

The rapid growth in volcanology over the last few years was clearly demonstrated at the International Volcanological Congress that was held in New Zealand (Auckland, Hamilton, and Rotorua) in February this year. 1986 is the centenary of New Zealand's most famous historical eruption — that of Tarawera fissure volcano in the Okataina caldera complex of the Taupo Volcanic Zone. The centenary meeting was sponsored by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and by the Royal Society of New Zealand, and it attracted about 480 participants world-wide. Congress organisers were inundated with attendance applications, and submitted papers were so numerous that many of the six main symposia had to be run concurrently; contributors had to be urged to present their work in poster sessions. Advances made in many areas of volcanology since 1965, when New Zealand last hosted a major international volcanological meeting, must have impressed many of those who were able to compare the proceedings of both meetings.

Mechanisms of explosive eruption and volcaniclastic deposition dominated two of the six symposia — one on pyroclastic flows, the other on magma–water interactions and phreatomagmatic deposits. Both topics are highly relevant to the volcanology of North Island, where studies of tephra have yielded exciting new results on ignimbrites (pyroclastic flows are not necessarily valley-confined — some apparently can climb mountain ranges) and on the role of water in magma fragmentation (widespread phreatomagmatic deposits point to especially violent interactions of rhyolitic magmas with the waters of caldera lakes such as Taupo).

The largest symposium at the Congress dealt with the geochemistry of eruptive magmas and tectonic controls on petrogenesis, and here the whole gambit of magma genesis in different tectonic regimes was discussed. The ongoing problem of elucidating the relative importance of mantle, crustal, and subducted components in the generation of arc–trench-type magmas (island arcs and continental margins) was raised, and despite the application of a wide range of geochemical signatures (^{10}Be is currently the trendiest isotope) consensus is still lacking. Several papers dealing with intraplate continental volcanism were of particular interest to those of us involved in producing the Australia/New Zealand volume on the Cainozoic intraplate volcanism of eastern Australia and New Zealand (the search continues for a model for the non-felsic — non-'hot spot' — volcanoes of eastern Australia).

Symposium 6 also dealt with tectonics and volcanism, but in a wider sense. It steered away from geochemistry, and incorporated, rather, the geophysics, geochronology, and structural geology of volcanic areas at plate margins. Side-scan sonar (for example, SeaMARC II) is unveiling the volcanic geology of the sea-floor as if oceans had been drained away and images had been obtained from the air (see article describing the principles of side-scan sonar on p. 3). New volcanoes, complex related tectonics, and new insights into volcano development at plate margins, are being revealed by these exciting new systems.

Volcanic hazards were discussed in Symposium 4 as the memory of the Nevado del Ruiz disaster in Columbia last November hung about the corridors and rooms of the University of Waikato in Hamilton, where most of the symposia sessions were held. More than 20 000 dead in Columbia was a stunning reminder to volcanic-hazards specialists at the Congress that mitigation must be tackled, urgently and effectively, by means of long-term training in volcanology and baseline studies of high-risk volcanoes if disasters similar to that at Armero are to be avoided. The IAVCEI Executive Committee at the Congress initiated, partly in response to the Ruiz eruption, a 'High Risk Volcanoes' project in which volcanological training and research in developing countries of the circum-Pacific are identified as high priorities. Ruiz, and the hazards to aircraft causes by drifting volcanic ash clouds (very much an Australian concern), were also discussed at evening meetings of IAVCEI Working Groups.

The revenue-earning potential of volcanology was dealt with in a symposium on metallogenesis in volcanic terranes and water-dominated geothermal systems. Interest in gold was, predictably, evident, and those who made field visits to the geothermal areas of the Taupo Volcanic Zone wondered just how much of it lay beneath their feet. A proceedings volume of papers for this symposium was on sale at the Congress; it includes 30 contributions — all short papers or expanded extracts — published with the support of the Australasian Institute of Mining and Metallurgy.

The New Zealand organisers of this important volcanological congress can take pride in their efforts. The Congress was an unequivocal success.

For further information, contact Dr Wally Johnson at BMR.

US/Australia Joint Scanner Project

Technological advances in remote sensing applied in Australia

Remote sensing, the rapidly developing science of surveying, monitoring, and managing Earth resources from aircraft and spacecraft, took a significant step forward in Australia with the commencement in October 1985 of a new two-year research project — the US/Australia Joint Scanner Project.

The initial funding for the project was provided jointly by BMR and CSIRO. Under their joint-management, a consortium of eight federal and State agencies, one university, seven private companies, and a British agency combined with NASA and the Jet Propulsion Laboratory (JPL) to conduct a series of multidisciplinary remote-sensing projects with arguably the single most advanced aircraft/remote-sensing package in existence.

A C–130 (Hercules) aircraft and its unique instruments was provided by NASA and the JPL. During the mission in Australia, from 28 September to 29 October 1985, this package acquired data over 54 remote-sensing test-sites, including six that BMR had nominated. At specific flying altitudes between 3000 and 5000 m a.s.l., data were simultaneously acquired from three advanced instruments: the NS001 Thematic Mapper Simulator, the Thermal Infrared Multispectral Scanner (TIMS), and the Airborne Imaging Spectrometer (AIS).

BMR sites and objectives

The Divisions of Continental Geology, Petrology & Geochemistry, and Geophysics have established a multidivisional project to analyse the data that were acquired over BMR's nominated sites, which are annotated below (Fig. 17).

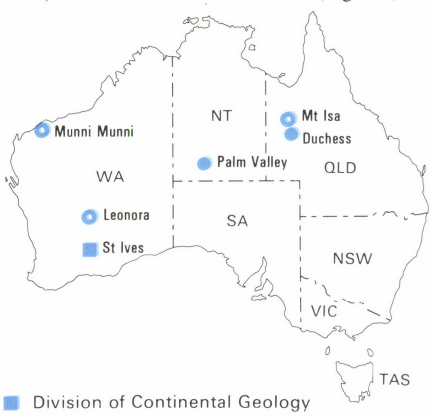


Fig. 17. BMR's nominated sites in the US/Australia Joint Scanner Project.

- Mount Isa region (Eastern Creek Volcanics, Sybella Granite, Mary Kathleen mine area) — to research the expressions of mineralogical changes associated with structure and metamorphism
- Duchess — to research the differentiation and delineation of phosphatic and non-phosphatic rock units
- Palm Valley — in conjunction with detailed airborne geophysics, to attempt to determine whether there are any subtle surface mineralogical changes indicative of gas seepage
- Munni Munni — to research the spectral and thermal signatures of basic and ultrabasic rock types
- Leonora — to research the expressions of mineralogical changes associated with rock types and structures
- St Ives — to investigate the spectral and thermal expressions of surficial weathering phenomena and regolith materials.

Primary research will be conducted between late 1985 and late 1987 during which time the data are being restricted to the project contributors. The results from that effort will probably be reported at a special symposium late in 1987. The data collected during the project will continue to produce useful information well beyond 1987, and will provide a significant basis for applying future aircraft and spacecraft satellite sensing in the Australian environment.

The sensor package and its geoscientific applicability

Developments in digital scanning devices are now trending towards increased numbers of narrower sensing bands (compare, for example, the wavelength distribution of the 128 AIS bands with that of the four Landsat MSS bands in Fig. 18); these sensing bands are specifically placed to obtain the maximum information about the phenomena being sensed. In the past, the available sensing bands on spacecraft have been selected primarily for agricultural monitoring. The significant contributions to remote-sensing research by the geoscientific community has now resulted in some sensors being designed for geological applications.

The NS001, TIMS, and AIS sensors, which are of progressively increasing importance to geoscientific applications, sample atmospheric windows at wavelength intervals that sense different chemical phenomena.

NS001

The NS001 was designed as the aircraft prototype of the thematic mapper instrument flown on the Landsat 4 and 5 satellites. The aircraft scanner has eight bands with an instantaneous field of view (IFOV) of 2.5 mrad (which allows a ground resolution of 2.5 m at 1000 m altitude above terrain):

Band	*Bandwidth (μm)*
1	0.45- 0.52
2	0.52- 0.60
3	0.63- 0.69
4	0.76- 0.90
5	1.00- 1.30
6	1.55- 1.75
7	2.08- 2.35
8	10.4 -12.6

Band 7 is especially useful in geoscientific data gathering; its 2.08–2.35 μm bandwidth enables it to detect the strong radiation absorption feature with a wavelength of about 2.2 μm that is generated by electronic processes associated with O-H bond stretching and A1-O-OH bond bending vibrations in clay minerals, pyrophyllite, dioctahedral mica, and alunite (Fig. 19). The detection of such absorption can be diagnostic of rock alteration (i.e., clay development).

TIMS

TIMS allows, for the first time, the recording of discrete spectral emittance data in the thermal infrared wavelengths — that is, that portion of the electromagnetic spectrum dominated by thermal radiation (heat) from the Earth's surface.

In the wavelength interval 8.2–12.2 μm, TIMS records six bands of data:

Band	*Bandwidth(μm)*
1	8.2- 8.6
2	8.6- 9.0
3	9.0- 9.4
4	9.4-10.2
5	10.2-11.2
6	11.2-12.2

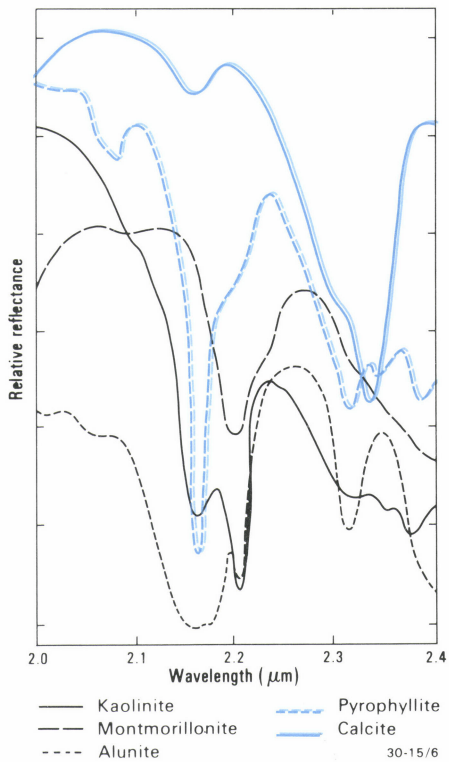


Fig. 19. Spectral reflectance curves of several minerals (after 'Imaging spectrometry: the next step in remote sensing', *NASA/JPL Publication*).

The system has an IFOV of 2.5 mrad, and contains two internal thermal blackbody reference sources which allow calibration of each band to <0.3°C noise-equivalent temperature. TIMS is superior to earlier thermal scanner instruments (1 or 2-bands) because of its eight narrow bands and higher radiometric sensitivity.

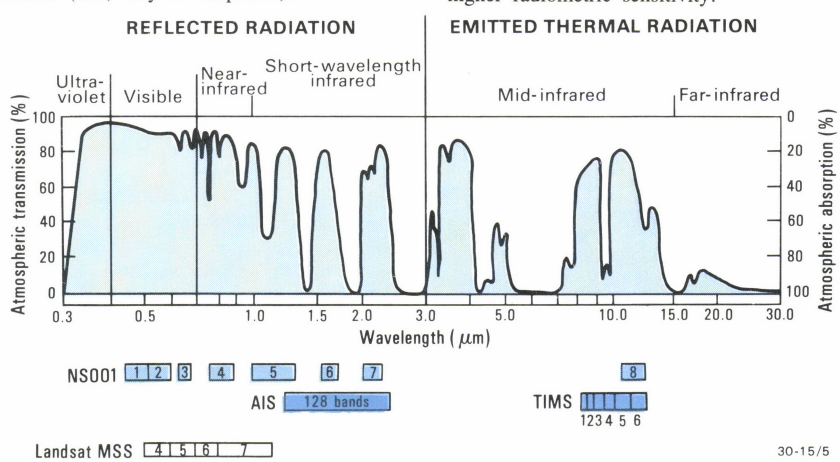


Fig. 18. Available atmospheric sensing windows (high-transmission wavelengths), and the positions of various sensing wavelengths.

TIMS is of considerable interest in the Earth sciences because the 8–13 μm wavelength interval contains a broad minimum in emissivity which is diagnostic of silicates. Within the wavelength sampled, the strength and position of the minimum feature are directly related to the quartz and mafic mineral content of the materials being studied.

AIS

AIS is the first in a series of new remote-sensing instruments that NASA is developing for future aircraft and spacecraft operations. This instrument is the most advanced of its type in existence, and consists of a narrow imaging beam (only 32 pixels wide) with an IFOV of 1.9 mrad. AIS records 128 bands of data per pixel (compared with four bands per pixel on the Landsat MSS satellite). Each band is only 9.6 nm wide, so that the 128 bands effectively produce a continuous spectral reflectance plot. This technology ensures that the specific spectral bands necessary to characterise particular minerals are available for processing.

The value of such a data set can be demonstrated with reference to Figure 19: the AIS bands are sufficiently narrow that they can differentiate the wavelengths of the absorption features in the spectral reflectance curves for each of the minerals illustrated. The wavelengths of these features are determined by the chemical bonding characteristics of the component elements, and are mineralogically diagnostic.

The recording of 128 bands per pixel results in very large volumes of digital data (400 kilobytes per second), and introduces new problems for computer storage, processing, and manipulation. The AIS data are sufficiently advanced that new digital processing techniques will need to be developed to adequately analyse and display the different mineralogies present at the terrain surface.

Research and development of the geological applications of the advanced sensor package in the Australian environment are necessary if geoscientists are to take full advantage of satellite-mounted imaging spectrometers which NASA proposes to put into orbit by 1994.

For further information, contact Mr Colin Simpson or Mr Bob Moore at BMR.

Otway Basin

Processing of recent regional marine seismic data nears completion

Processing of regional 48-channel seismic reflection data obtained on the Otway Basin *Rig Seismic* cruise in June–July 1985 is nearing completion. The 3700 line-km were selected because they tie together networks of privately acquired closely spaced reflection lines with a consistent data set, and because they infill areas of sparse seismic coverage by exploration companies on the continental slope and rise of the southern offshore Otway Basin (Fig. 20). The resulting database — including the privately acquired multichannel seismic reflection data and well data — will be used in a framework analysis of petroleum potential and in a study of the structure, stratigraphy, and evolution of the whole offshore Otway Basin. Preliminary stacked sections of seismic reflection data should be completed in March 1986. Final stacked and migrated versions of all lines will then be produced, and the data are expected to be publicly available in late 1986. The data, which have a recording length of 7.5 s, are of good quality.

On the continental shelf, the data indicate a substantial sedimentary section and the presence of block-faulting — features that are commonly associated with petroleum accumulation on rifted continental margins. On the continental shelf and rise, the data indicate a progressive oceanward-thinning of Upper Cretaceous and younger sediments accompanying southerly down-faulted landward-dipping strata. On the lower continental slope and rise, and on the adjoining abyssal plain, deep crustal events which appear to relate to thinning of continental strata are apparent.

The multichannel seismic data, along with seismic refraction and wide-angle seismic reflection data obtained from simultaneous sonobuoy experiments, will be used to study the transition from continental to oceanic crust.

For further information, contact Dr Paul Williamson at BMR.

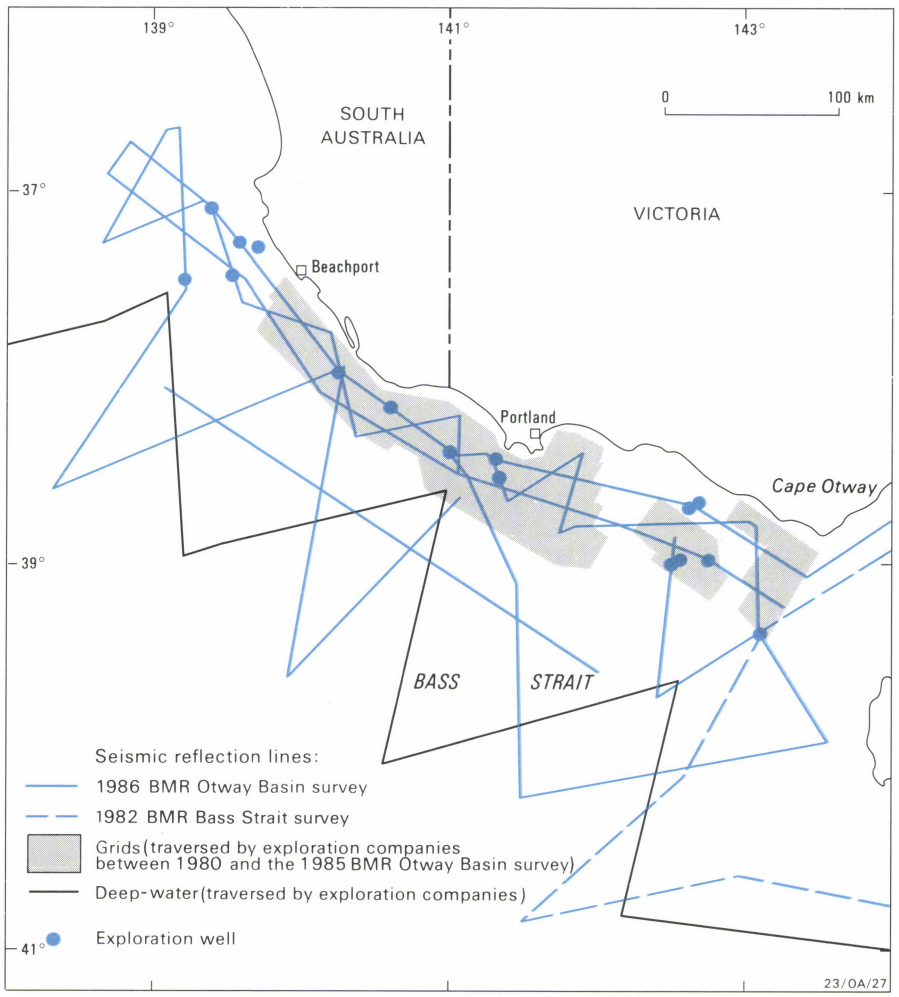


Fig. 20. Sources of data for the BMR offshore Otway Basin project.

Archaean volcanics

(continued from back page)

felsic rocks of this phase are the products of partial melting of basic rocks or fractional crystallisation of basic magmas.

The 3400–3000 Ma phase probably originated by the diapiric upwelling and dynamic melting of light-RE-depleted to chondritic mantle. The resulting light-RE-depleted basalts and high-Mg to peridotitic komatiites are analogous to those generated by late Archaean activity in the Yilgarn Block. This phase is characterised by differential vertical movements between uprising batholiths and downfaulted rift zones in which clastic sediments of the Gorge Creek Group accumulated.

The 3000 Ma felsic igneous rocks originated by ensialic anatexis of the older trondhjemite–greenstone terranes.

The 3000–2700 Ma volcanic phase took place in a relatively stable ensialic crustal environment, and tapped intensely light-RE-enriched subcontinental mantle.

The trace-element data thus reflect the transformation from a primitive crustal environment dominated by simatic material, through a phase of intense vertical tectonic mobility, to a continental crustal environment.

Economic implications

The Pilbara volcanic geochemical study has provided geochemical–stratigraphic controls on, and thus potential guidelines for, the distribution of base and precious metal deposits. Along with isotopic geochronological data, the trace-element patterns help to identify and correlate igneous units where stratigraphic identifications are otherwise uncertain.

Geochemical profiles across volcanic sequences indicate the location of zones rich in volatiles (water, CO_2, S) and alkali elements favourable for the concentration of base-metals; for example, the heavily carbonated Mount Ada Basalt north of Marble Bar and carbonated shear zones and contacts are the loci of some gold mineralisation. Again, iron-rich basaltic and doleritic rocks act as suitable collectors of sulphur, forming sulphides which provide a trap for gold — as suggested by Groves & others (1982: *in* GOLD '82: The geology, geochemistry and genesis of gold deposits, *A.A. Balkema, Rotterdam*, 689–712) in relation to the Golden Mile Dolerite; thus, a study of the relations between Fe and S is of economic relevance. Variations in abundances of trace elements such as Ni, Cr, and Co — related to the magmatic history of the volcanic rocks — help to guide prospecting toward the volcanic units that are likely to contain the highest concentrations of these elements.

The sulphur saturation level of ultramafic magmas is an important criterion, since undersaturated magmas are less likely to have lost sulphide and, thus, platinum group elements (PGE) through crystal fractionation. Future work will include analysis for PGE, in an attempt to locate igneous units whose PGE abundances and sulphur saturation levels are of economic promise.

For further information, contact Dr Andrew Glikson at BMR.

Archaean volcanics in the Pilbara Block

Petrogenetic, tectonic, and economic implications of a trace-element study

The distribution of the rare-earth elements (RE: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) and high-field-strength elements (HFS: Ti, Zr, Nb, P, Y) in Archaean volcanic rocks and, to a lesser extent, plutonic rocks in the Pilbara Block, Western Australia, has been studied recently by BMR and GSWA (R. Davy, A.H. Hickman) in collaboration with workers at the University of Ottawa (C. Pride) and the Université de Rennes (B. Jahn, G. Gruau). The results provide an insight into aspects of mantle–crust relations and the evolution of this ancient segment of the Earth's crust, and have implications for the exploration of base-metals and precious metals.

Mafic–ultramafic volcanics

Trace elements in the mafic–ultramafic volcanic rocks distinguish three principal phases of tholeiitic basalt extrusion (Fig. 21a):

- 3700–3400 Ma (lower Warrawoona Group), marked by low to moderate (Ce/Yb)N ratios (1.0–3.0) and Ce>Zr>Nb>Ti>P>Y enrichment orders;
- 3400–3000 Ma (upper Warrawoona Group, Gorge Creek Group, Warambie Basalt), marked by commonly lower RE fractionation — (Ce/Yb)N ca 1.0–2.3 — and variable HFS element enrichment orders; and
- 3000–2700 Ma (Louden Volcanics, Negri Volcanics, Fortescue Group), marked by very high RE and HFS element abundances, high (Ce/Yb)N ratios (ca 3.4–6.3), and P>Ti enrichment orders.

Intermediate–felsic volcanics and granitoids

Trace elements in the intermediate–felsic rocks distinguish two main phases of igneous activity (Fig. 21b):

- 3700–3400 Ma dacites, andesites, and minor rhyolites (upper North Star Basalt, Duffer Formation), and the trondhjemitic–tonalitic phases of the Mount Edgar batholith, marked by regular upward-curved RE profiles, with little or no Eu anomalies, and (Ce/Yb)N ratios of about 5–15; and
- ca 3000 Ma volcanic and plutonic felsic rocks (Wyman Formation, Mons Cupri Volcanics, Mount Brown Rhyolite, post-tectonic granites), marked by lower (Ce/Yb)N ratios (4–7) and prominent negative Eu anomalies.

Petrogenetic and tectonic implications

The 3700–3400 Ma phase of igneous activity may reflect relative tectonic stability during which a near-chondritic mantle source underlay largely simatic crustal domains including trondhjemitic–tonalitic sialic nuclei. These nuclei, developed mainly between 3600 and 3300 Ma ago, are considered to be the plutonic counterparts of dacites and andesites of the upper North Star Basalt and Duffer Formation. The intermediate–

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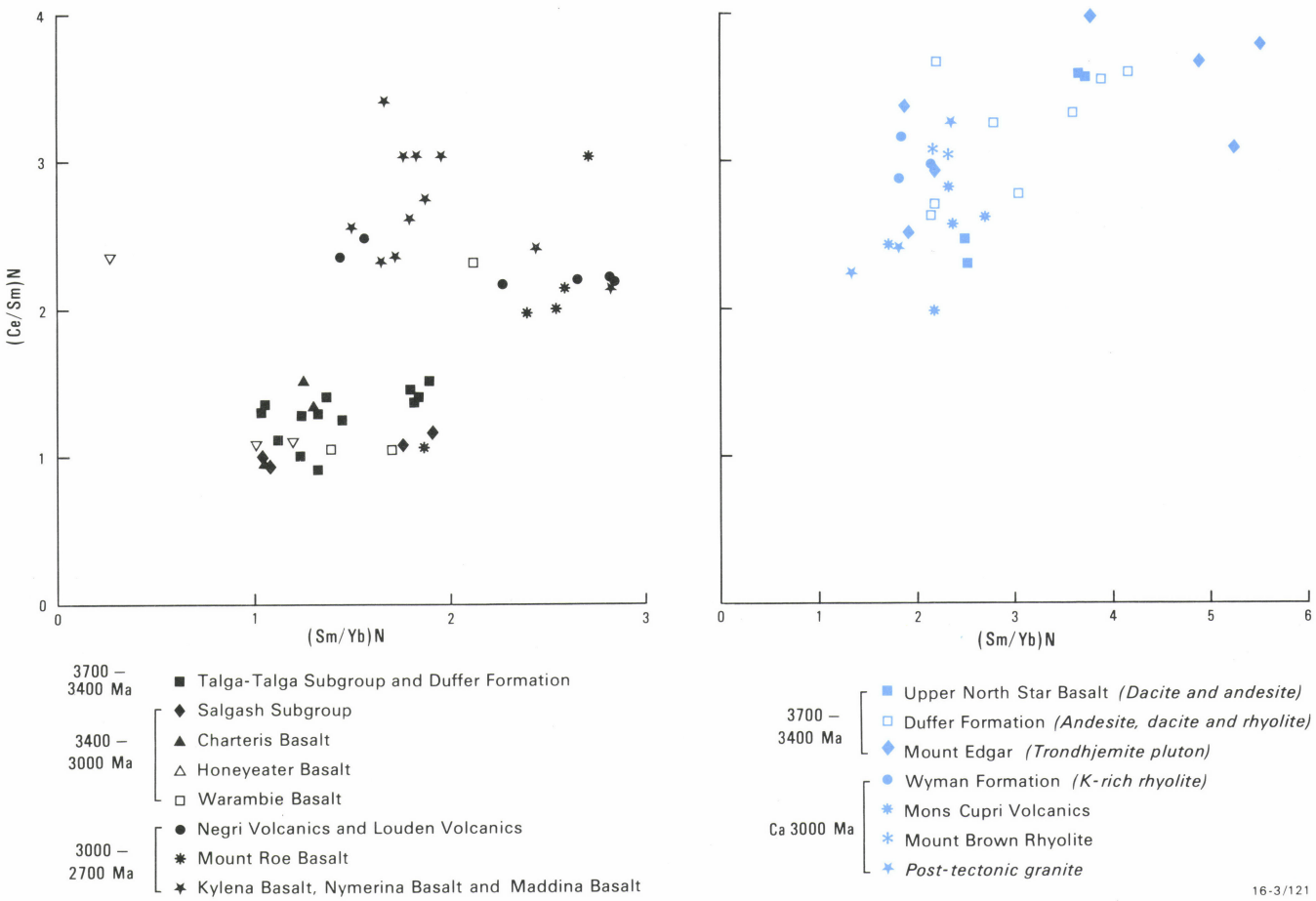

Fig. 21. Relationships between light/intermediate RE-element fractionation, (Ce/Sm)N, and intermediate/heavy RE-element fractionation, (Sm/Yb)N, in *(a, left)* mafic-ultramafic volcanics and *(b, right)* felsic igneous rocks of the Pilbara Block. *(a)* Note the clear distinction in both ratios between the 3000–2700 Ma and older phases, and the less pronounced difference in the (Ce/Sm)N ratio between the 3700–3400 and 3400–3000 Ma phases. *(b)* Note the high (Sm/Yb)N ratio of many samples in the 3700–3400 phase compared with the consistently low ratio (ca 2.0) of samples in the younger ca 3000 Ma phase.

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