BMR Research Newsletter

A twice-yearly newsletter for the exploration industry

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Thermogenic gases in the offshore Otway Basin and western Tasmania margin

During January–February 1987, staff of BMR's Marine Division studied the concentration, distribution, and molecular composition of light (C_1–C_5) hydrocarbon gases in sediments as part of a *Rig Seismic* cruise to the Otway Basin and west Tasmanian continental margin (see *Seabed sampling off southeast Australia* and Figures 1 and 2, page 2 this issue).

This is the first time such measurements have been made by an Australian group in marine sediments of the Australian margin; they constitute a new tool in the BMR Marine Division's petroleum assessment program. Analysis and interpretation of the measurements made on this cruise were carried out in conjunction with Dr David McKirdy of the Department of Geology & Geophysics, University of Adelaide.

Biogenic or thermogenic?

Light hydrocarbon gases are ubiquitous in marine sediments and may be of two types, (1) biogenic and produced in the top few tens of metres of recent sediment, or (2) thermogenic and produced in ancient sediments by the action of heat on buried organic debris. Thermogenic gases, produced at depths of a few kilometres in the sediment, may migrate from petroleum reservoirs through microfractures and along faults that extend to the sediment-seawater interface, eventually to escape into the overlying water column. The molecular compositions of gases in pore fluids and sediments in the vicinity of these seeps provide important clues to the 'source' (i.e. biogenic or thermogenic) of the detected gases and, if thermogenic, the maturity of potential petroleum source rocks from which the gases are being produced. For example, biogenic hydrocarbons are dominated by methane with minor amounts of ethane, ethene, propane, and propene, whereas thermogenic hydrocarbons have higher proportions of 'heavier' (i.e. C_3+) saturated hydrocarbons.

Interpretation of the source of the gas is empirical: thermogenic gases are defined as having methane/ethane + propane ratios <500, and ethane/ethene ratios >1. This does not provide an unequivocal interpretation of the origin of the gas and we intend in future to complement these data with carbon isotope measurements to help constrain our interpretations. For example biogenic methane is enriched in the light isotope carbon-12 and is characterised by $\delta^{13}C$ of <–50 ppt, but in contrast, thermogenic methane is enriched in carbon-13 with $\delta^{13}C$ of >–50 ppt. Pore-water measurements of inorganic metabolites, nitrate, and ammonia produced during organic carbon cycling in surficial sediments define the oxic/anoxic transition zone in sediments. Ammonia produced in pore fluids is related to the extent of sulphate reduction, which in turn infers the onset of biogenic methane production in the cores sampled. Data from this cruise indicate that methanogenesis probably was not occurring in the shallow anoxic sediments sampled.

Thermogenic gas at eleven locations

All gas measurements were made at sea by extracting gases from recent sediment collected from 2–3 m gravity cores. The concentrations and molecular compositions of the gases were determined using gas chromatographs in the shipboard geochemistry laboratory. Measurements were made in duplicate on sediment samples collected from nearly fifty locations from the shelf and slope regions in water depths between 200 m and 4000 m (Fig. 1). All sampling was conducted over pre-existing seismic lines so that the gas data could be related to the subsurface geology (Fig. 2).

Anomalous concentrations of thermogenic hydrocarbons were found at eleven localities in water depths of 450–2000 m. Background concentrations were about 1 microlitre/litre of wet sediment. The highest concentrations measured were about 400 times background in the western Voluta Trough (BMR seismic line 48/43, Fig. 2). The eleven sites are probably submarine gas seeps and lie above faults that appear to penetrate to the sea floor. The absence of gas anomalies at other coring locations above faults shows that not all faults necessarily are conduits for the migration of hydrocarbon gas to the sea floor. The molecular composition of the gases indicates that they are dry, and probably of late catagenic origin. The proportion of wet gas for each of the major regions studied was: 1.3–9.9% in the eastern Voluta Trough, 2.5–6.1% on the northern flank of the Voluta Trough, 0.3–2.3% in the western Voluta Trough, and 1.5–4.4% on the west Tasmanian margin.

This work will be followed by more detailed analyses, including integration of the gas data with seismic and geohistory analyses, and further gas studies to be carried out aboard *Rig Seismic* during 1988.

For more information, contact Dr David Heggie at BMR (Division of Marine Geosciences & Petroleum Geology).

Applied Extension Tectonics

1987 BMR Research Symposium, 24–26 November, Canberra

One of the most important advances in continental geology in the last decade has been the recognition that extensions of large magnitude are as much a part of the evolution of continental lithosphere as are the classical compressional orogenies. Continental extension is a genuine orogenic process, giving rise to metamorphism, deformation, igneous activity, major uplift, a range of syn- and post-orogenic sedimentary basin types, and unique styles of mineralisation.

The 1987 BMR Research Symposium, which will focus on the importance of extension tectonics in petroleum and minerals exploration, will be held at the Academy of Science building in Canberra on 24–26 November. A registration fee of $295 covers morning and afternoon teas, lunches, the Symposium dinner after the first day's sessions, Extended Abstracts volume, and other conference material. Because of the size of the venue, registrations will be limited to 200, so early registration is recommended. Registrations will close on 6 November.

The very full program for the Symposium is:

DAY 1: TUESDAY 24 NOVEMBER

9:00 Registration and Morning Tea

10:15 Introductory Remarks — *Mike Etheridge* (BMR)
Official Opening — *Roye Rutland* (Director, BMR)

Session 1 — Character and process of continental extension

10:45 Structural and tectonic models for continental extension — *Gordon Lister* (Monash University)

11:30 Continental extension in the Basin and Range Province, southwestern USA — *Steve Reynolds* (Arizona Geological Survey)

12:15 Thermomechanical modelling of continental extension — *Chris Beaumont* (Dalhousie University)

1:00 LUNCH

2:00 Geophysical character of continental extended terranes — *Peter Wellman* (BMR)

2:40 Structural geometry: normal faults — *Alan Gibbs* (Midland Valley Exploration, Glasgow)

3:15 Structural geometry: transfer faults — *Mike Etheridge* (BMR)

3:40 TEA

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Bureau of Mineral Resources, Geology and Geophysics, Canberra

Department of Primary Industries and Energy

Session 2 — Case studies of exposed extensional terranes

4:00 Active extension in the D'Entrecasteaux Islands, PNG — *June Hill* (Monash University)

4:30 Tertiary extension in the Aegean Sea — *Gordon Lister, Diane Bettess* (Monash University)

5:00 Extensional structures in the Tumut Trough, southern NSW — *Peter Stuart-Smith* (BMR/Australian National University)

5:30 Proterozoic continental extension in the Mount Isa Inlier — *Peter Williams* (BMR)

6:00 CLOSE

7:00 for 7:30 Symposium Dinner

DAY 2: WEDNESDAY 25 NOVEMBER

Session 3 — Basin evolution and petroleum accumulation

8:30 Basin development during continental extension — *Alan Gibbs* (Midland Valley Exploration)

9:10 Extensional models for passive margin evolution — *Mike Etheridge* (BMR)

9:50 Source rock characteristics of extensional basins — *Trevor Powell* (BMR)

10:20 MORNING TEA

10:50 Fluid dynamics of extensional basins — *Larry Cathles* (Cornell University)

11:20 Simplified heat flow and subsidence histories for asymmetric extensional basins — *Greg Houseman* (Australian National University)

11:50 Application of fission-track dating to extensional terranes and their basins — *Andrew Gleadow* (University of Melbourne)

12:30 Analogue modelling experiments of structuring during normal and oblique extension — *Lyal Harris* (University of Western Australia)

1:00 LUNCH

Session 4 — Case studies in extensional basins

1:50 Basin evolution in the northern Browse Basin— *Mike Hall* (BHP Petroleum)

2:15 Upper crustal extension model for the Bowen Basin — *Rodney Hammond* (CSIRO, Division of Geomechanics)

2:40 Geometry of extensional structures in the Fitzroy Trough, Canning Basin — *Mike Etheridge, Barry Drummond* (BMR), *Mike Middleton* (Geological Survey of Western Australia)

3:05 Similarity between hydrocarbon and mineral plays in extensional settings — *Koo Sing Kuang* (Consultant)

3:30 AFTERNOON TEA

4:00 Tectonic evolution of the central southern margin of Australia — *Barry Wilcox, Philip Symonds, Howard Stagg* (BMR)

4:30 Extensional tectonics of the offshore Otway Basin — *Paul Williamson, Clive Collins, Mike Swift* (BMR)

5:00 Structural style of the Townsville Trough and its implications for the development of the Northeast Australian margin — *Philip Symonds, David Capon, Chris Pigram, Peter Davies, David Feary* (BMR)

5:30 Tectonic framework of the North Perth Basin — *John Marshall, Chao Shing Lee* (BMR)

6:00 CLOSE

DAY 3: THURSDAY 26 NOVEMBER

Session 5 — Igneous, hydrothermal and metallogenic consequences of continental extension

8:30 Igneous history related to extension in the Basin and Range Province, southwestern USA — *Steve Reynolds* (Arizona Geological Survey)

9:00 Extensional tectonic setting of igneous activity in the southwest Pacific — *Wally Johnson* (BMR)

9:40 Extensional magmatism in the Australian Proterozoic — *Lesley Wyborn* (BMR)

10:10 MORNING TEA

10:40 Fluid dynamics in high heat flow extensional regimes — *Larry Cathles* (Cornell University)

11:20 Hydrothermal processes during continental extension and their relationship to ore deposition — *Dick Henley* (BMR)

12:00 Extensional tectonic setting of epithermal mineralisation in the Southwest Pacific — *Jeff Hedenquist* (DSIR, New Zealand)

12:45 LUNCH

1:45 Precious metal mineralisation associated with extensional detachment faulting in the North American Cordillera — *Rob Kerrich* (University of Saskatchewan)

2:30 Fluid activity in detachment fault terranes — an examination of the South Mountains microbreccia — *Gordon Lister* (Monash University), *Harry Green* (University of California), *Steve Reynolds* (Arizona Geological Survey)

3:00 Extensional structural setting of intrusive and extrusive activity in the late Palaeozoic of northeastern Queensland — *Brian Oversby* (BMR)

3:30 AFTERNOON TEA

Session 6 — General discussion

4:00 Discussion of all papers and of summary documents prepared by working panels (to be distributed during Symposium)

5:30 CLOSE

ENQUIRIES

Symposium enquiries should be directed to:

Applied Extension Tectonics Symposium
(Attention: Mrs E. Young)
Bureau of Mineral Resources
GPO Box 378
CANBERRA ACT 2601
Phone: (062) 499623 Telex: AA62109 Fax: (062) 488178

Government Geoscience Database Policy Advisory Committee (GGDPAC)

The first meeting of GGDPAC was held in Canberra on 22 July 1987. GGDPAC is a committee of the Government Geologists' Conference and its primary objective is to advise the Conference on matters relating to geoscience database activities.

The Committee will monitor database developments, promote the use of standards, identify gaps in database coverage and recommend ways to fill them, and promote the exchange of data between government organisations and the use of government geoscience databases by industry and researchers.

The creation of GGDPAC is a direct outcome of BMR's national responsibility to coordinate database activity among government organisations, specifically BMR and the State Geological Surveys and their parent departments. The Committee comprises one representative from each of BMR, the six States, and the Northern Territory. BMR's representative — and Chairman of the Committee — is Dr Bob Lowden, and the secretariat is provided by BMR's Database Coordination & Liaison Section.

Among the issues discussed at the first meeting were the need for timely release of data to industry and problems relating to the ownership of databases if government databases become incorporated into larger, commercial database systems. The question of database standards for borehole data was referred to the Standards Subcommittee of the Australian Geoscience Information Association.

For further information, contact Dr Bob Lowden at BMR (Resource Assessment Division).

Seabed sampling off southeast Australia

BMR's vessel *Rig Seismic* occupied 130 stations in a research cruise off southeast Australia in January–February 1987, as part of a continuing geoscience program in the offshore Otway Basin and west Tasmanian margin (Fig. 1). The overall aim was to better define the geological framework and petroleum potential of the region by obtaining new geological, geochemical, and heatflow data along existing reflection seismic profiles.

The initial results were presented in *BMR Record* 1987/11 and at the Otway Basin Workshop held in Canberra in March, 1987. Almost all of the 23 dredge, 54 core, 33 grab, and 20 heatflow stations were successful and provided relevant results. Work carried out on core and grab samples included studies of pore fluid indicators of the state of oxidation and preservation of organic carbon, and headspace analyses for thermogenic gases (described elsewhere in this *Newsletter*).

Detailed model of sedimentation

The dredge and corer recovered pre-Quaternary rocks and sediments at 22 stations, and it is now clear that continental basement and Early and Late Cretaceous detrital sedimentary rocks crop out on the lowermost continental slope in water 4000–5000 m deep. The mid-slope is characterised by Early Tertiary detrital sediments, and the upper slope by Late Tertiary carbonates. The table summarises the character and age of samples recovered during this cruise and on previous cruises in 1985 by the *Rig Seismic* and the West German R/V *Sonne*. Most rock types found beneath the shelf in petroleum exploration wells are also present on the continental margin, but usually further below sea level. Subsidence on the outer margin since the Eocene exceeds that beneath the shelf by an average of 1500–2000 m.

On the present cruise Quaternary sediments were obtained in most cores and grab samples.

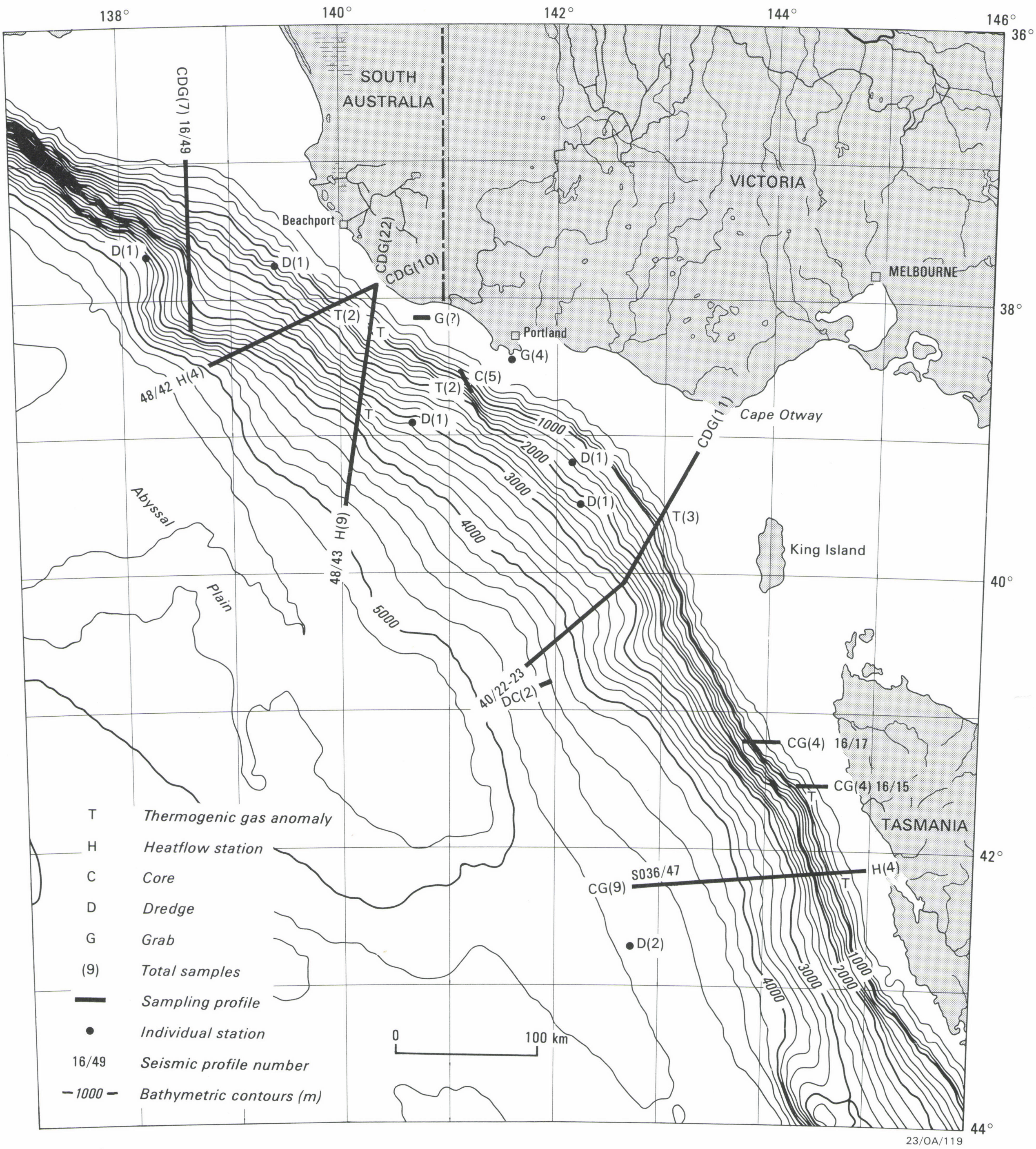


Fig. 1. Bathymetry of the Otway Basin–west Tasmanian margin region, and stations occupied on *Rig Seismic* seabed-sampling cruise of January–February 1987.

Grab sampling has established the nature of the outer shelf Quaternary sands, largely bryozoal, that provide turbidites to the Quaternary sediments on the continental slope, otherwise pelagic and hemipelagic in nature. All these samples will help to establish for the first time a detailed model of sedimentation on the southern margin that can be extended back well into the Tertiary.

An example of how the sampling was related to a seismic profile is shown by the interpreted BMR multichannel seismic profile 48/43 (Fig. 2), which extends 200 km from south of Beachport to the abyssal plain. The profile shows (1) a highly-faulted zone of seaward-dipping faults beneath the shelf and upper slope, above which there are gas anomalies, (2) a zone of landward-dipping faults beneath the mid-slope, and (3) low-angle seaward dipping faults above a decollement beneath the lower slope. Progressively older rocks subcrop further down the slope. Dredge 9, just above the abyssal plain, contained acid and basic volcanics, and metaquartzites, indicating the presence of continental basement rocks, as well as probably younger volcanics. Dredge 8, further up the slope, contained brown mudstone believed to be Late Cretaceous. Core 12, taken in 3150 m of water, just below the regional Oligocene reflector, contained freshwater peat that is probably Eocene.

Heatflow

Temperature gradients measured at 20 stations, by a heatflow probe penetrating the top 3 m of sediment in conjunction with thermal conductivity measurements on sediment cores, have enabled preliminary heatflow values to be calculated. On BMR seismic line 48/43 south of Argonaut No. 1 well, and *Sonne* seismic line SO36/47 west of Cape Sorell No. 1 well, the values vary from 25 to 70 $mW.m^{-2}$ and average 40 $mW.m^{-2}$, which is consistent with the accepted breakup history of the margin, and suggests that the zone of thermal maturation of hydrocarbons generally lies 2–4 km beneath the upper slope.

Samples collected in 1985 and 1987, from *Rig Seismic* and *Sonne*

Sequence and age	*Number and nature of samples*	*Depth range*
Pleistocene to Recent shelf sand	Many grabs	27–294 m
Pleistocene to Recent ooze and turbidite	80 cores	240–4830 m
Late Oligocene to Pliocene marl, limestone and chalk	11 cores, 11 dredges	1150–4370 m
Eocene to Early Oligocene calcareous siltstone and limestone	8 dredges, 1 core	650–4100 m
Eocene peaty sand and peat	3 cores	1757–3710 m
Cretaceous sandstone and mudstone	9 dredges, 1 core	3900–4700 m
Basement metamorphics and volcanics	3 dredges	1800–3750 m

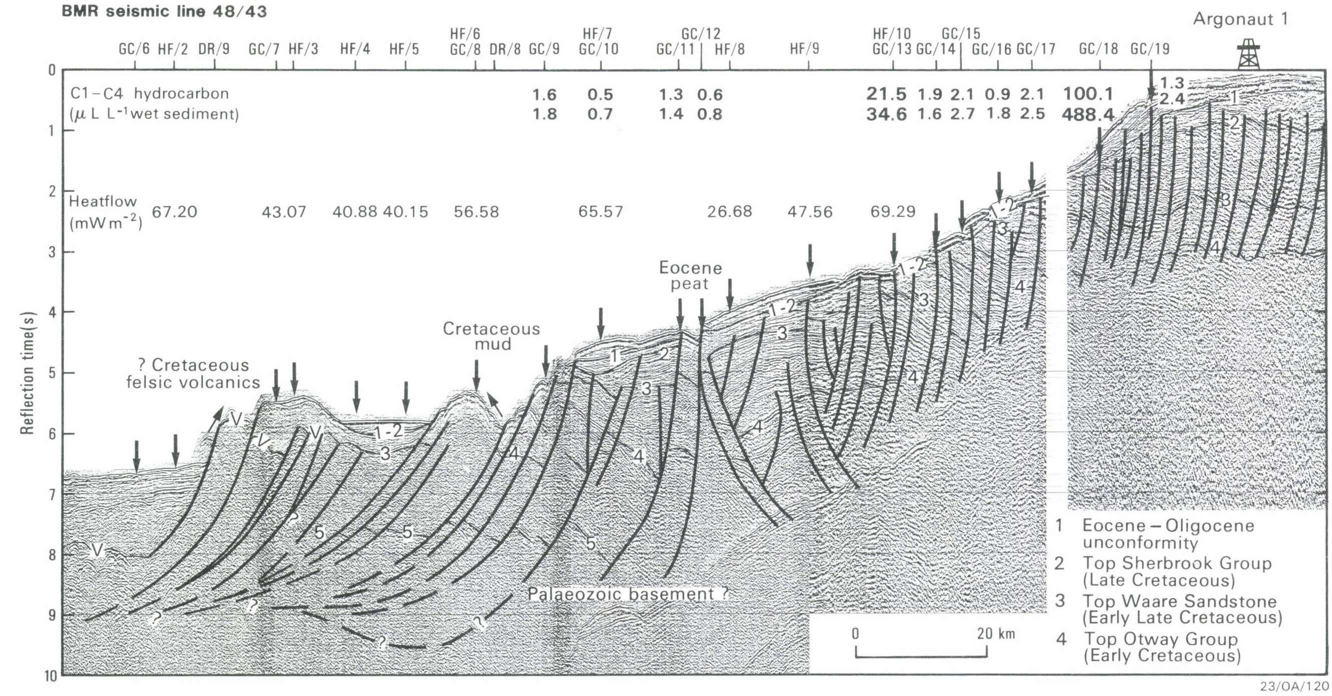


Fig. 2. Interpretation of BMR seismic line 48/43, incorporating seabed-sampling data. Reflector 5 is assumed to be top of Palaeozoic basement and reflector V top of volcanic basement. Note probable detachment fault at 9 seconds, below lower continental slope. The locations of sampling stations are marked along the seafloor profile, and the nature of the samples (HF — heatflow, GC — gravity core, DR — dredge) is shown along the top of the drawing. Hydrocarbon contents of thermogenic gas samples shown here (taken high and low in each core) are discussed in a related article.

On profile 48/43, the heatflow measured on the abyssal plain is 67 mW.m^{-2}, above the lower slope it is 40–65 mW.m^{-2}, above the zone of landward dipping faults it is 26–47 mW.m^{-2}, and on the upper slope it is 69 mW.m^{-2}. This significantly high value in the upper slope of the Otway margin is probably related to post-breakup tectonic activity. Higher heatflow values can be assumed to be associated with a shallower oil and gas window.

The cruise has shown so far that (1) continental basement is present on the edge of the abyssal plain, (2) the rifts in which Cretaceous Otway Group sandstone was deposited extend well to the southeast along the western margin of Tasmania, and (3) most subsidence on the margin is post-Eocene.

Work continues on the geological history of the margin. Another cruise is planned for early 1988 to address outstanding stratigraphic and tectonic problems, and to carry headspace gas studies up onto the continental shelf, where they will be of more immediate significance to petroleum exploration.

For further information, contact Dr Neville Exon or Dr Chao-Shing Lee at BMR (Division of Marine Geosciences & Petroleum Geology).

Geochemical research cruise off northern NSW finds evidence for new mechanism of marine phosphorite formation

In May 1987, BMR's RV *Rig Seismic* completed a 17 day research cruise on the continental shelf and slope off northern New South Wales (Fig. 3). During the cruise, scientists from Australia, USA, and UK participated in a major study combining sedimentology, sedimentary geochemistry, microbiology, oceanography, and seismic reflection profiling.

The main objectives were (1) to determine the geochemical and/or microbiological processes responsible for the *formation of the Quaternary phosphorites* on the New South Wales upper slope at water depths between 350–450 m, and (2) to determine the major controls on the *preservation of organic carbon* in sediments from inner shelf to abyssal environments, and thus help to understand petroleum source rock accumulation on passive continental margins. Other objectives included determining the spatial (and possibly genetic) relationships between the Quaternary and Tertiary phosphorites, and the sedimentation history of the continental margin from the middle Miocene to the present day.

The data collected during the survey included 78 gravity cores, 24 box cores, 49 grab samples, 30 dredge samples, 6 underwater camera stations, and 3 Niskin casts; geologic samples were recovered at water depths ranging from 104–4050 m. In addition, 740 km of high-resolution seismic reflection data were acquired using a 5 cu.in. airgun sound source.

Geochemistry of the pore fluids

The geochemistry of the pore fluids was considered a major key to understanding the mechanisms of phosphorite formation and organic carbon preservation. Pore fluids were separated from 20 gravity and box cores under a nitrogen atmosphere in a refrigerated laboratory in the ship. Porewater (and seawater) analyses performed at sea included NH_3, NO_3/NO_2, Fe^{2+}, Mn^{2+}, F^-, Cl^-, SO_4^{2-}, PO_4^{3-}, and pH. These have since been supplemented with silicate, Ca^{2+}, Mg^{2+}, and alkalinity determinations. Bacterial biomass and activity were measured at sea, as were the oxygen profiles in the sediments (via microelectrode measurements). Samples were also taken for the measurement of bacterial sulphate reduction rates, phospholipid composition, porewater sulphide, and stable-isotope composition of pore fluids.

Iron–phosphate 'shuttle'

Preliminary conclusions are as follows:

(1) O_2 was found to be essentially absent from the outer-shelf and upper slope sediments, penetrating to a maximum depth of only 3 cm. Anoxic diagenesis is therefore the main organic carbon cycling process on the outer shelf and upper slope.

(2) The Fe^{2+} and PO_4^{3-} porewater profiles in the upper slope sediments (350–450 m water depth) correlate closely (Fig. 4a). We propose that the very minor amount of ferric oxy-hydroxide (FeOOH) in the sediments that contain modern phosphate nodules adsorbs PO_4^{3-} in the oxic zone (upper few centimetres of sediment); the FeOOH is probably produced mainly via the oxidation of glauconite. The FeOOH is rapidly cycled into the underlying suboxic to anoxic zone where it is reduced and redissolves, liberating PO_4^{3-}. The Fe^{2+} then diffuses upwards to the oxic zone, where it reoxidises, scavenges more PO_4^{3-}, and is again recycled into the suboxic/anoxic zone. By this mechanism, the PO_4^{3-} concentration of the porewaters may become high enough to precipitate apatite, while the total FeOOH abundance in the sediment remains very low. Thus, an iron-phosphate 'shuttle' (Fig. 4b) is thought to be operating in the sediments. The model needs further testing, but if proved valid, it could explain the origin not only of these phosphates, but perhaps also similar phosphate sequences in Australia and overseas.

(3) Studies of bacterial growth in the sediments containing the modern phosphate nodules indicate

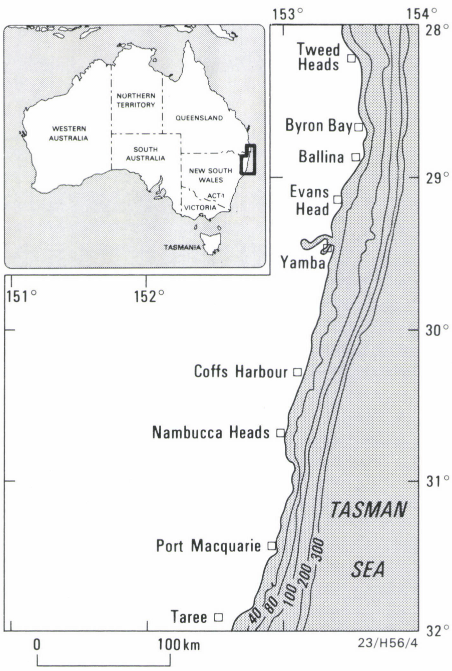


Fig. 3. Location map of geochemical research cruise covering part of the east Australian continental margin.

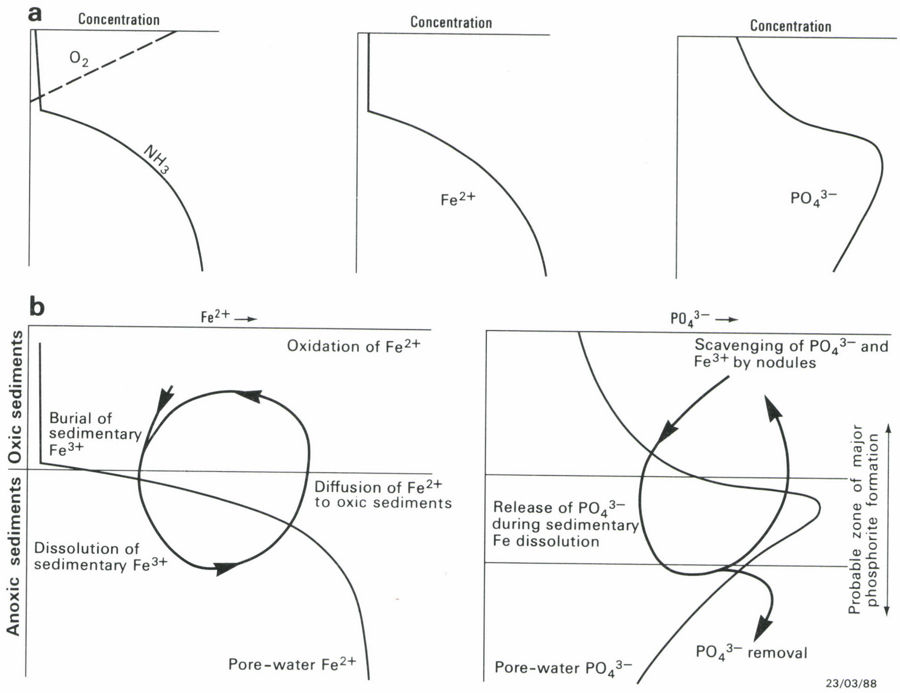


Fig. 4.(a) Schematic O_2, NH_3, Fe^{2+}, and PO_4^{3-} porewater profiles in upper slope sediments (350–450 m water depth) from the east Australian continental margin. (b) Schematic diagram of iron-phosphate 'shuttle' mechanism thought to be responsible for phosphorite formation on the east Australian continental margin.

that >90% of the bacterial growth occurs in the upper 1 cm of the sediments, although slow growth rates were detected to a depth of 70 cm. Slow growth was also detected in the phosphatic nodules. Shipboard estimates of the organic carbon flux required to support the bacterial productivity in these sediments varied from 5 to 30 milligrams of carbon/square metre/day.

(4) Many hardgrounds are present at water depths of 250–380 m between Evans Head and Yamba; they appear to closely control the late Quaternary sedimentation, and may represent previous cycles of phosphate deposition.

(5) Extensive deposits of Neogene phosphate were discovered as far north as Evans Head, and it now appears that a zone of Neogene phosphate enrichment extends from eastern Victoria northwards to at least 29°S.

Processing and interpretation of data will continue through 1987 and 1988. The preliminary results will be published in the BMR *Report* series.

For further information, contact Dr Geoffrey O'Brien or Dr David Heggie at BMR (Division of Marine Geosciences & Petroleum Geology).

North Perth Basin project

This project is centred on the Abrolhos Sub-basin in the offshore part of the northern Perth Basin. The *Rig Seismic* cruise of 1986 collected some 2400 km of 48-channel seismic reflection data and occupied 70 sampling stations (dredging, coring, and heatflow).

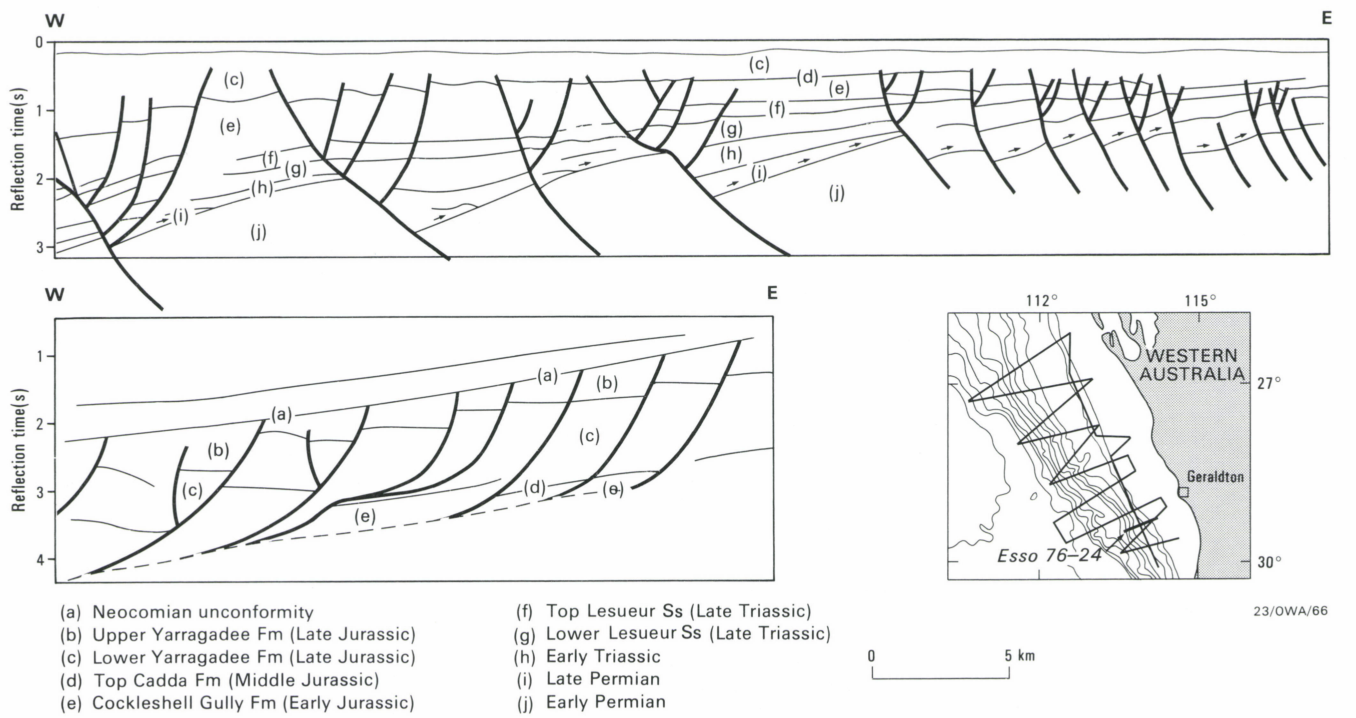


Fig. 5. Interpreted seismic sections across the Abrolhos Sub-basin. Both sections (separated by a 31 km gap) are from Esso Line 76–24.

The continental margin in this region is a classic example of a transform margin: the extremely steep lower continental slope is the manifestation of the Wallaby–Zenith Fracture Zone that formed during seafloor spreading, which began in the Neocomian. Plant microfossils, preserved in rocks that were dredged from the scarp, support this age, whereas abundant Permian, Triassic, and Jurassic microfossils in these same rocks indicate significant reworking of older sediments during the Neocomian.

The preliminary seismic data, coupled with company data and exploration wells, suggest a fairly broad diversity of structural styles in the sub-basin and around its margins. Throughout much of the sub-basin, gently landward-dipping extensional faults, related to the rift phase, appear to have developed in the Late Permian (Fig. 5), whereas on the Edel Shelf to the northeast, extension is considered to have been much earlier, with synrift fill of possible Carboniferous age.

In the sub-basin itself, extension resulted in tilted fault blocks forming a series of half-grabens, with erosion planing off some of the higher blocks. While some Late Permian synrift fill at the base of the grabens is postulated, it was the originally marine, but becoming progressively continental, sedimentation during the Triassic and Jurassic that at first filled the half-grabens, and ultimately blanketed the relatively rapidly subsiding basin. Much of the subsidence during this phase took place on the Darling Fault, and large volumes of sediment were transported from the Precambrian shield into depocentres such as the Abrolhos Sub-basin.

In the southern and central parts of the basin, the sediment sequence thickens considerably from east to west, mainly as a result of a series of normal faults beneath the present-day shelf break, with relatively large throws (1 sec. two-way time) down to the west. Thus there is a thick (>4000 m) Jurassic sequence beneath the outer shelf and upper slope. In the north, however, the Jurassic appears to be largely absent on the shelf, and there is even some conjecture as to whether it occurs to any great extent beneath the upper slope. The Edel Shelf is considered to be blanketed by a Permo-Triassic sequence of mainly marine and, in places, volcanogenic rift-fill sediments, overlying Permo-Carboniferous(?) synrift deposits.

At breakup, during the Neocomian, the extensional faults forming the now deeply buried tilt blocks were reactivated, and composite faults, with 'flower' structures, developed. This style of faulting is believed to have been produced by oblique extension of the crust. Although there was probably some lateral movement on these faults, and the geometry of the faults bears some resemblance to that of wrench faults, they do not appear to be true wrench faults; rather, they are thought to have originated to accommodate the strain produced by oblique extension. However, this particular style of faulting has produced some vertical movement and highly fractured anticlinal structures and rollovers. These have been one of the main targets for the limited amount of drilling done so far in the Abrolhos Sub-basin.

The seismic profiles indicate that the margin has been essentially starved of sediment since breakup. The sediments above the breakup unconformity are very thin beneath the shelf and thicken only gradually beneath the slope. Recent sedimentation trends, as deduced by sampling and sidescan sonar, are similar. The shelf is essentially non-depositional and consists of a limestone plain, with local relief produced by submerged carbonate banks and the reefs of the Houtman-Abrolhos Group. The upper continental slope is mantled by Quaternary pelagic oozes, whereas the much steeper lower slope has little recent sediment and dredging often recovered either Tertiary pelagic limestones or Mesozoic clastic sediments.

For further information contact Mr John Marshall or Dr Chao-Shing Lee at BMR (Division of Marine Geosciences & Petroleum Geology).

Recent publications and data releases

Over the period 16 February to 31 August 1987, BMR has released the following publications and data:

Publications

Bulletins
220 — Geology of the southern McArthur Basin, Northern Territory.
222 — Atlas of isoseismal maps of Australian earthquakes. Part 2.
223 — Geology of Enderby Land and Western Kemp Land, Antarctica.
225 — Geology of the Mount Isa Inlier and environs, Queensland and Northern Territory.

Reports
254 — Volcanic activity in Papua New Guinea before 1944: an annotated bibliography of reported observations.
271 — Data file Austco-2: wells drilled for petroleum in Australia (to October 1985).
278 — Seismic profiles from the central Eromanga Basin, eastern Australia.
279 — 'Rig Seismic' Research Cruise 3: offshore Otway Basin, southeastern Australia.

Australian Mineral Industry Annual Review for 1984

Australian Mineral Industry Annual Review for 1986 preprint chapters: Aluminium, Black Coal, Gold, Iron Ore, Lead, Nickel, Tin, Titanium and Zinc.

Australian Mineral Industry Quarterly (Vol. 39, No. 1)

Petroleum Exploration & Development Titles Map & Key: January 1987.

BMR Journal of Australian Geology & Geophysics (Vol. 10, No. 2)

Australian Petroleum Accumulations Reports
2 — Bass Basin, central Australia.

Resource Reports
1 — Australian uranium resources.
2 — Coal potential of Antarctica.

Geological maps
1:100 000: Ranford Hill, Pine Creek, Late Silurian geology of the Michelago–Cooma area preliminary map.
1:250 000: Geology and metallogeny of the Cullen Mineral Field.
1:500 000: Geology of the Mt Isa Inlier.
1:1 000 000: Irian Jaya, Indonesia (available only from Indonesia).

Hydrogeological maps
1:5 000 000: Hydrogeology of Australia.

Geological map commentaries
1:100 000: Elkedra Region.

Records released on open file
1985/38 — Mundaring Geophysical Observatory Annual Report 1984.
1986/27 — The regolith terrain map of Australia, 1:5 000 000.
1986/33 — Regolith terrain units of the Hamilton 1:1 000 000 Sheet area, Western Australia.
1987/2 — Index of BMR land-based seismic reflection surveys 1949–1986.
1987/3 — Quest for the magnetic poles: relocation of South Magnetic Pole at sea, 1986.
1987/4 — Extended abstracts, Petroleum & Minerals Review Conference, 18–19 March 1987.
1987/5 — 'Rig Seismic' Research Cruise 2, Kerguelen Plateau: explanatory notes to accompany release of non-seismic data.
1987/6 — Calibration of the 54 mm diameter BMR well-logging density tool.
1987/7 — Murray Basin hydrogeological project. Progress report 16 for half-year ending 30 September 1986.
1987/8 — Petrological and petrophysical data from Mesozoic sandstones of the Bundamba Group, Clarence–Moreton Basin.
1987/9 — Extended abstracts: Otway Basin Workshop, 17 March 1986.
1987/10 — Petroleum exploration and development in Australia — activity and results, 1986.
1987/11 — 'Rig Seismic' Research Cruise 1987: Otway Basin and west Tasmania sampling.
1987/12 — In-situ stress measurements with the Hydraulic Fracture Technique.
1987/13 — Mundaring Geophysical Observatory Annual Report, 1985.
1987/14 — The role of clays in formation damage in Mesozoic reservoir sandstones of the Eromanga Basin.
1987/15 — Petroleum & Minerals Review Conference 18–19 March 1987. Petroleum exploration & development in Australia, 1986: an overview. Speaking notes.
1987/16 — SERCEL SN 368 equipment tests, Millmerran, Queensland 1986: Operational Report.
1987/17 — Petroleum & Minerals Review Conference 18–19 March 1987. Factors affecting the availability of Australia's undiscovered crude oil resources. Speaking notes & figures.
1987/18 — Mineral Resources of Australia, 1987.
1987/20 — Structural Geology of Tommy Creek area, Mt Isa Inlier, NW Queensland.
1987/21 — West Surat Basin Refraction Survey 1986: Operational Report.
1987/22 — Petroleum & Minerals Review Conference 18–19 March 1987. Helium Resources & Development in Australia. Speaking notes, figures, and tables.
1987/27 — Results of a geophysical well-logging survey, central Australia, 1986.
1987/28 — Historical development of the Australian mineral industry.
1987/29 — Mawson Geophysical Observatory Annual Report, 1985.
1987/30 — Trace-element geochemistry and petrogenesis of Archaean felsic igneous units, Pilbara, WA.
1987/31 — Petroleum & Minerals Review Conference 18–19 March 1987. Mineral sands industry review. Notes and figures.
1987/32 — Petroleum & Minerals Review Conference 18–19 March 1987. Developments & outlook for lead and zinc in Australia.
1987/33 — Structural setting of the McNamara Group in the Yaringa Creek–Big Toby Creek area, Mt Isa, Qld.
1987/34 — Learmonth geomagnetic observatory installation, November 1986.
1987/35 — Glossary of morphotectonics (3rd Edition).
1987/37 — Petroleum & Minerals Review Conference 18–19 March 1987. Copper in Australia — present, past and future. Speaking notes and figures.
1987/38 — Macquarie Island Geomagnetic Observatory Annual Report 1985.
1987/39 — Rig Seismic Research Cruises 10 and 11. Southern margin of Australia: explanatory notes to accompany release of non-seismic data.
1987/40 — A criterion for the location of crack initiation in hydraulic fracturing experiments.
1987/41 — Australian marine geoscience in Antarctica: background geology program and margin accessibility.
1987/42 — The CSIRO-SGTE-THERMODATA package for thermodynamic computations at BMR.
1987/43 — Macquarie Island Geomagnetic Observatory Annual Report 1986.
1987/44 — Rig Seismic Research Cruise 6, Northern Australian Heatflow: explanatory notes to accompany release of geophysical data.
1987/45 — Accelerograph timing system.
1987/46 — Mawson Geophysical Observatory Annual Report 1986.
1987/47 — Marine heatflow system: instrumentations and technique.
1987/48 — Petroleum geology & geochemistry, Middle Proterozoic McArthur Basin.
1987/49 — Abstracts of conference: Application of Numerical Techniques in Earth Sciences, Canberra, 24–25 August 1987.

Release of data

Airborne geophysical maps
1:250 000: 180 maps, showing either magnetic properties, magnetic contours, radiometric contours, or flight line systems (in all States).
1:100 000: two Western Australian maps showing flight line systems; one Queensland map showing total magnetic intensity contours.

Magnetic contour maps
1:1 000 000: New updated editions of 11 maps.

Digital data
Digital-point-location airborne magnetic data for 17 1:250 000 Sheet areas.

Marine geophysical data
Otway Basin — Survey 48, 1985. Seismic stacked and migrated sections, track chart (between 138° and 144°); 3 releases.

Land seismic data
SE Queensland (1984, 1986). Shot-point location maps: 1:1 000 000 Southern Queensland, 1:250 000 Quilpie, Charleville, Mitchell–Homeboin, Roma–Surat, Dalby, Ipswich, Brisbane. Seismic sections — displayed at 10 cm/s, v/s, 10 traces/s.

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

More power to the Marine Division: RV *Rig Seismic's* seismic source upgraded

In September 1986, BMR's Marine Division took delivery of a new tuned airgun array for installation on the research vessel *Rig Seismic* to improve seismic penetration and source pulse shape. Supplied by Geophysical Service International (GSI), the array comprises 10 guns, each of 2.62 litres (160 cubic inches) capacity, clustered to give effective volumes of 10.49, 7.87, 5.25, and 2.62 litres.

Two spare airguns were included in the 'string' and can be switched in at any time in case an airgun goes off-line. The total volume of 26.23 litres represents a 60% increase on the BOLT airguns that had been used for the first 18 months of the Continental Margin Program. In addition to the greatly enhanced power and penetration of the system, the improved source pulse shape has markedly improved the quality of the shipboard seismic monitors and has reduced the amount of post-cruise processing. The array has been used so far on two *Rig Seismic* research cruises: a framework study of the southern margin of Australia, which focused on the central Great Australian Bight (GAB), and a study of the deep-water Gippsland Basin and NSW margin. Processing of the data from the southern margin cruise is well under way and the results are all that had been hoped for. Figure 6 is a portion of a seismic section from the junction of the Eyre and Ceduna Terraces in the central GAB; more than 5 seconds two-way time of section is visible sub-seabed, corresponding to about 7–8 km of section.

At the end of July 1987, *Rig Seismic* had just completed a major refit in dry dock in Brisbane. The most significant change made was a further enhancement of the seismic-source string through the addition of two more 2.62 litre airguns, and the installation of a second, identical, airgun string. The configuration of a single airgun string is shown in Figure 7. The total volume of the 20 gun configuration used in normal operations is more than 52 litres. It should also be feasible to fire all 28 guns in the array, with a total volume of 73 litres, thus permitting reflection seismic studies of the very deep crustal structure beneath sedimentary basins and across continental margins. Following a shakedown cruise in early August, the new airgun array is slated to be 'run-in' on a major seismic cruise across the Marion Plateau and Townsville Trough off central/northern Queensland in September.

For further information on the airgun array, contact Dr David Falvey, or Mr Roy Whitworth; for further information on the Southern Margin project contact Mr Barry Wilcox, Mr Howard Stagg, or Dr Hugh Davies, and for information on the Gippsland/NSW Margin project contact Dr Mike Coffin, or Mr Jim Colwell, all at BMR (Division of Marine Geosciences & Petroleum Geology).

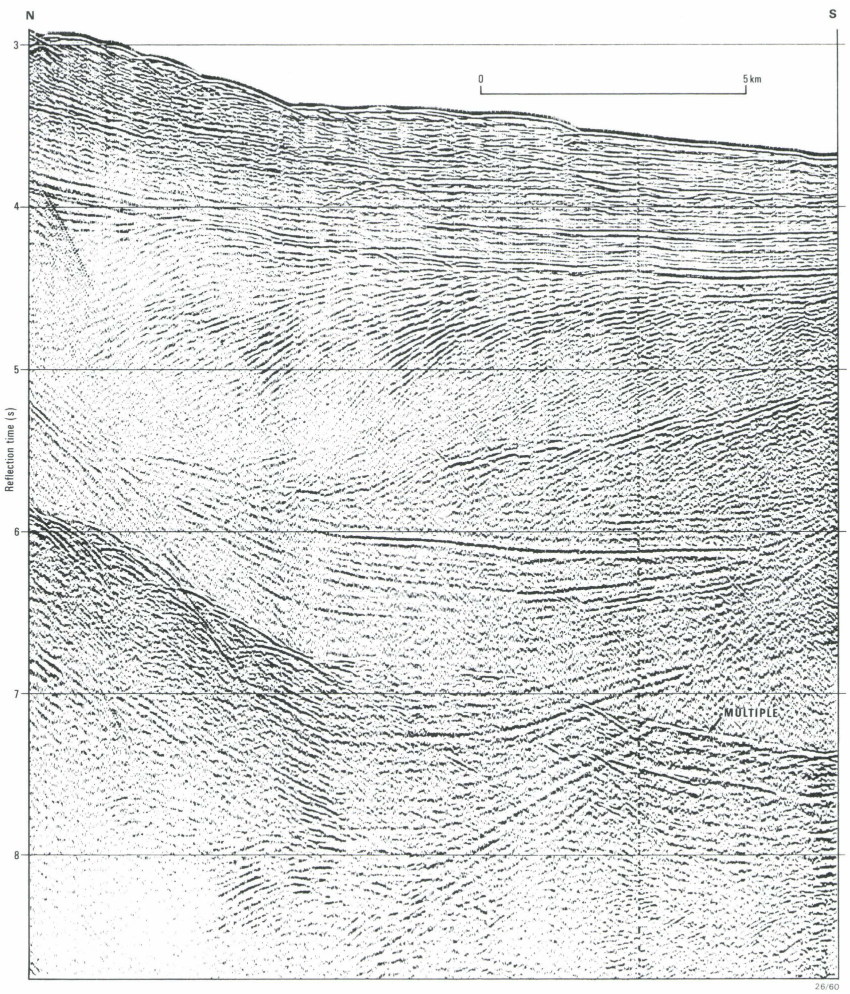
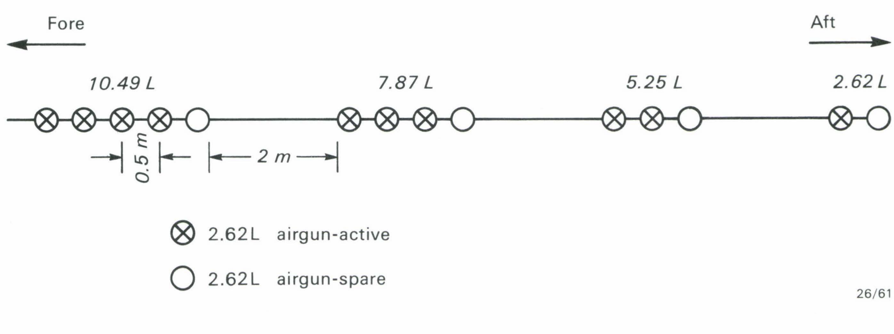


Fig. 6. Portion of a 24-fold stacked seismic section from the continental rise in the central Great Australian Bight, recorded on the RV *Rig Seismic* with a 26.23 litre airgun array source. Note in particular the presence of strong dipping reflections at 8.5–9.0 s two-way travel time.

Fig. 7. Configuration of the new airgun array installed on the RV *Rig Seismic*. Only one of the two identical strings is shown; one string is towed from each side of the stern of the vessel.



Thick-skinned tectonics in central Australia: Deep seismic results from a multidisciplinary study

Deep crustal seismic reflection data from the Proterozoic Arunta Block in central Australia (Fig. 8) have provided exceptional resolution of crustal structure. The dominant feature is a series of moderately dipping faults (Fig. 9) that appear to penetrate deeper than 35 km, in a style of deformation typical of the 'thick-skinned' tectonics of areas such as the Wind River Basin in Wyoming (Smithson & others, 1980: *Earth & Planetary Science Letters,* 46, 295–305). The area also contains a major gravity high flanked by unusually large gravity gradients. The new seismic data allow discrimination between the various tectonic models that have been proposed for the region.

The data were collected in 1985 by BMR's Explosion Seismology Section as part of a multidisciplinary project to investigate the tectonic evolution of the intracratonic central Australian basins and their basement, together with the gravity anomalies. More detailed analysis of the seismic data is being done as part of a cooperative project with RSES, ANU. The field operations were documented in *BMR Record* 1986/37. Part of the study was a major north-south seismic transect across the basins and the Arunta Block. This article refers to that part of the transect extending across the Arunta Block.

Geological setting and tectonic models

The region has had a long tectonic history spanning over 1500 Ma. It contains two Late Proterozoic to Palaeozoic basins, the Amadeus and Ngalia, and an extensive region of exposed Proterozoic metamorphic basement. The gravity anomalies indicate that the region appears to be in mechanical equilibrium, but local isostatic compensation has not occurred (Lambeck & others, in press: *Geophysical Journal of the Royal Astronomical Society*). The Amadeus Basin's depositional history has extended over 600 Ma, and it contains substantial petroleum reserves. Understanding the structural history of the Arunta Block and the cause of the gravity anomalies is important for evaluating tectonic models for central Australia and for petroleum exploration in the Amadeus Basin.

The main structural feature of the crust between the Amadeus and Ngalia Basins is a major thrust zone, the Redbank Deformed Zone (RDZ), separating an amphibolite-facies terrane made up mainly of granitic gneiss (Southern Tectonic Province) from a granulite-facies terrane composed of felsic and minor mafic granulite (Central Tectonic Province). North of the granulite terrane is another amphibolite-facies granitoid terrane, the Northern Tectonic Province. The RDZ is regarded as a fundamental Proterozoic crustal boundary that was reactivated in the Late Devonian (Shaw & Black, in prep.). The Southern Tectonic Province is itself divided by another major thrust zone, the Ormiston Nappe & Thrust Zone (ONTZ).

The uplift of the Southern Tectonic Province culminated in the Alice Springs Orogeny (400–300 Ma). Current tectonic models include the mechanical folding-and-thrusting model of Lambeck (1984: *Australian Journal of Earth Sciences,* 31, 25–48), the 'thin-skinned' crustal-compression model of Teyssier (1985: *Journal of Structural Geology,* 7, 689–700), and the 'thick-skinned' faulted-block model of Shaw (PhD thesis, ANU, in prep.) and Lambeck & others (in press: *Geophysical Journal of the Royal Astronomical Society*). This 'thick-skinned' model is favoured by the deep seismic reflection data.

Deep seismic results

In the interpretation, the seismic section was subdivided into zones of similar seismic signature (1–4, Fig. 9d). The zones are bounded by moderately dipping bands of reflectors that are interpreted as faults as they correlate well with the position and surface dip of known faults (e.g. RDZ) and others inferred from magnetics (letter 'M', Fig. 9a and b). The reflections result from impedance contrasts due either to contrasts in lithology (e.g. ONTZ, separating zones 1 and 2) or to mylonite associated with the RDZ, separating zones 2 and 3. The faults dip consistently north at between 30° and 45° and can be traced down to two-way travel times of 10 to 15 s, i.e. 30 to 45 km depth (based on seismic velocities of around 6 $km.s^{-1}$).

Sub-horizontal, semi-continuous reflections are most conspicuous from 10 to 30 km deep in the Northern Province and deeper in the south. In some areas, especially zone 3, they are truncated against the moderately dipping faults and suggest the sense of displacement on these faults. The reflections probably result from horizontal, discontinuous compositional layering (original crustal layering?) similar to that exposed in the southern part of the granulite terrane. Movement on the moderately dipping faults therefore appears to have involved little or no rotation of the crustal blocks.

In the Central Province, much of the exposed terrane consists of felsic granulite, while large granitoids predominate in the Northern Province. These regions correspond to the zone of sparse poor reflections seen at the top of the seismic section (Fig. 9c). The thickness of the granitic crust in this region can be inferred from the 'thickness' of this region of sparse reflections.

Tectonic synthesis

Structural, metamorphic, and isotopic data indicate a complex Proterozoic history for the Arunta Block. In particular, Rb–Sr and $^{40}Ar/^{39}Ar$ isotopic data (carried out in cooperation with RSES, ANU) indicate an independent evolution for the crustal blocks north and south of the RDZ until 1450 Ma, and possibly until 1100 Ma (Shaw & Black, in prep.; Shaw & others, in prep.); bulk lithology, structural history, and metamorphic grade all indicate that the RDZ is a Proterozoic crustal suture (Shaw & Black, in prep.).

Other isotopic data demonstrate that there was substantial movement on the RDZ during the Alice Springs Orogeny (i.e. 400–300 Ma), resulting in the upturning and southward overthrusting of Arunta rocks over the northern margin of the Amadeus Basin. Argon-loss data constrain the uplift during the overthrusting to a maximum of 8–12 km for each thrust block (Shaw & others, in prep.). This is confirmed by the displacement of the sub-horizontal seismic markers across the major fault zones. The argon data indicate that the movements on these faults were progressively later from north to south. The steep $^{40}Ar/^{39}Ar$ age spectra imply a thermal pulse that appears to record a maximum burial during crustal thickening within a narrow thrust belt.

The deep seismic data indicate that the RDZ dips at about 45°, and it has been mapped to a depth of 15 s or 45 km. They confirm models based on teleseismic travel-time residuals and the anomalous gravity field (Lambeck & others, in press) which suggest that low-velocity crust underlying the northern Amadeus Basin was thrust beneath high-velocity, high-density lower crust and mantle material along the RDZ.

Imbrication and crustal stacking

An interpretation consistent with the geological and geophysical data is that the main movement during the evolution of the basins took place on the RDZ, and resulted in imbrication and stacking of the crust, and exposure of lower crustal material in response to compression within the entire lithosphere. Displacement of the granitic upper crustal layer inferred from the reflection data, and of sub-horizontal zones of 'reflectors' along the moderately dipping faults north of the RDZ, suggests that these faults acted as normal or lag faults during the final stages of movement.

For further information contact Mr Bruce Goleby, Mr Russell Shaw, or Dr Cedric Wright at BMR (Division of Petrology & Geochemistry) or Dr Brian Kennett at RSES, ANU.

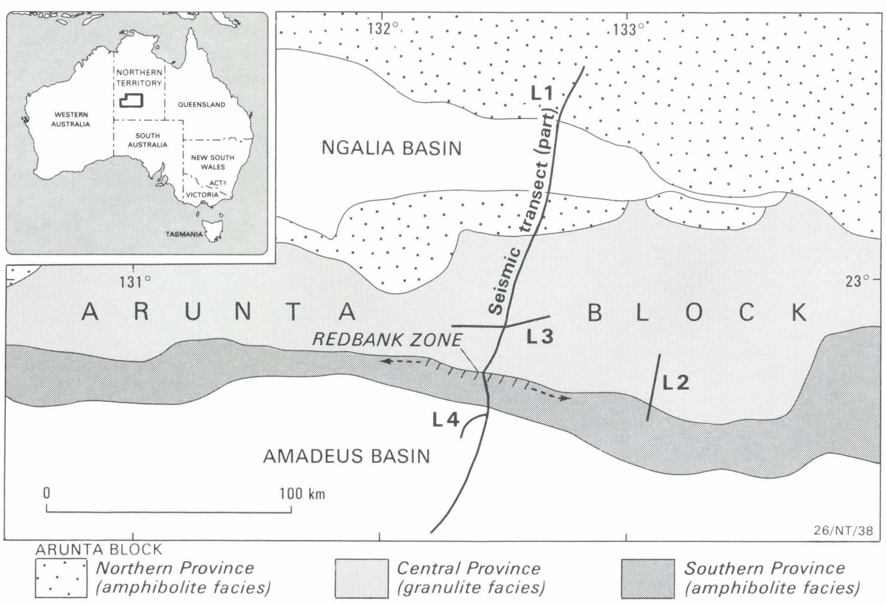


Fig. 8. Geological setting of northern part of 1985 BMR seismic transect.

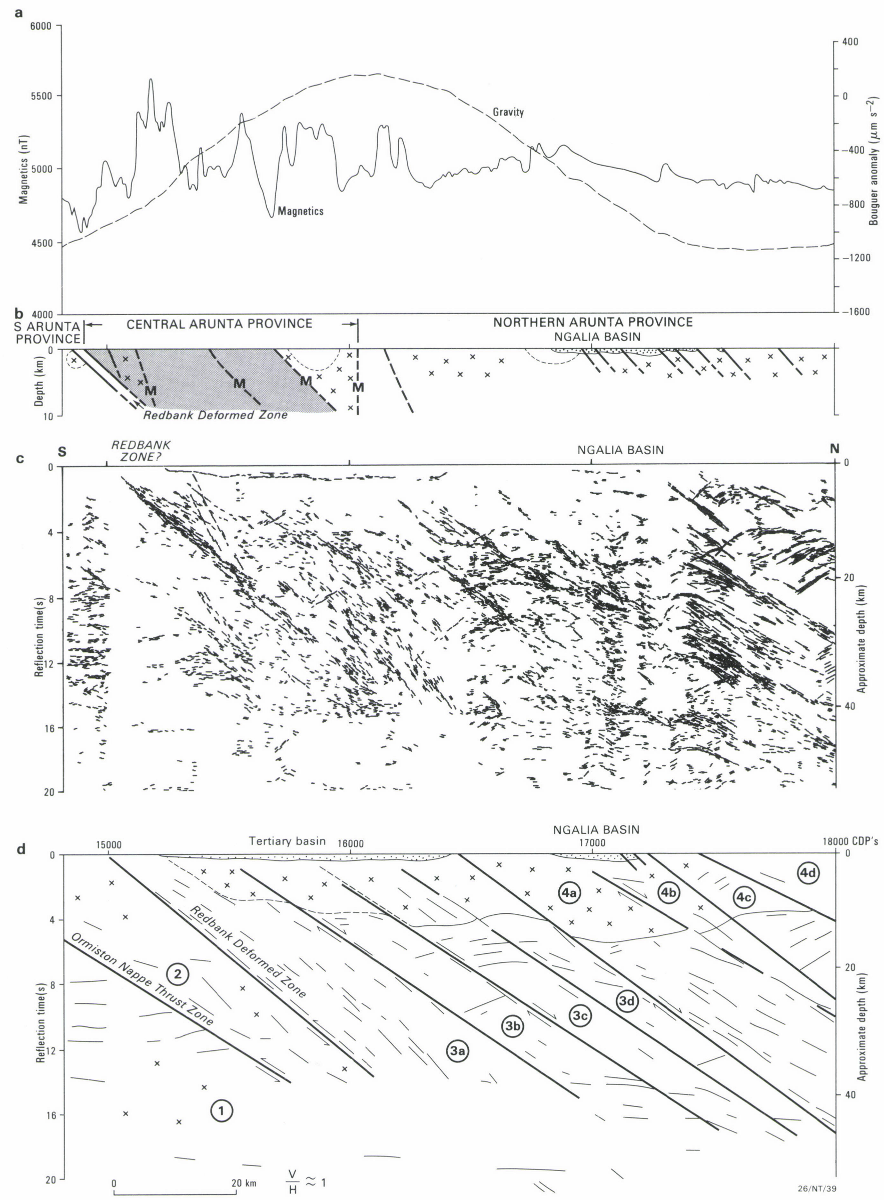


Fig. 9. Geological and geophysical data, central Australian region. (a) Bouguer gravity and aeromagnetic (150 m terrain clearance) profiles along seismic line. (b) Interpreted geological cross-section of area, based on field mapping and magnetic interpretation ('M' = fault inferred from magnetics). (c) Line drawing of deep seismic reflection data from BMR transect, Arunta Block. The lines represent continuous reflection segments of at least 10 traces width. (d) Interpreted crustal model derived from the deep seismic data.

New Hydrogeological Map of Australia

During a meeting of the Australian Water Resources Council in Perth on 9 July, the then Commonwealth Minister for Resources & Energy, Senator Evans, released an important new hydrogeological map of Australia, compiled by BMR for the Council. The 1:5 000 000 scale map and accompanying notes summarise the results of many years of hydrogeological studies by State geological and water agencies, and BMR. The project involved the collaboration of 25 hydrogeologists from these agencies; collaboration was fostered by a working group of the Groundwater Committee of the Australian Water Resources Council.

The map legend is an adapted version of the UNESCO international legend for hydrogeological maps. The adaptation was necessary to match the level of detail on the Australian source maps, the small scale of the final map, and the complete lack of data in many parts of Australia. In this legend, solid colours represent aquifers — their type, distribution, and productivity. This is a significant departure from previous groundwater resources maps of Australia in which solid colour represents water quality.

Where aquifers are superimposed, the one represented is the principal aquifer, defined as the aquifer which produces the best-quality water at highest yield from the shallowest depth. Aquifer types are designated as porous or fractured, and aquifer productivity is shown by tones of the primary colour. Aquifer distribution is described as extensive or local, indicating the availability of groundwater. Aquifer lithology is shown by pattern symbol, and aquifer age by letter symbols.

One of the main problems of single-sheet hydrogeological mapping is the representation of multilayered groundwater systems. On the map a boundary line has been used in some major sedimentary basins to indicate the extent of a significant subsidiary aquifer. The age and position of such an aquifer relative to a principal aquifer is indicated by a letter symbol and a bar. The cross-section on the face of the map, and ancillary information in the map commentary, should also help to overcome some of the limitations of single-sheet presentation.

Hydrodynamic features, including generalised contours on the potentiometric surface, have been shown for major sedimentary basins. In multilayered groundwater systems the potentiometric contours relate to the basal aquifer or aquifer system. The direction of groundwater flow has been indicated by arrows, and other features such as groundwater divides, the limits of confining beds, and the limits of artesian flow have been shown with symbols similar to those of the international legend. In order to represent significant discharge zones of major groundwater systems, groups of springs have been depicted. A groundwater seepage symbol has been used to indicate playas and other features which are the discharge zones of many groundwater systems in the Australian interior. Very old groundwaters have been identified in arid and semi-arid Australia, and a symbol for the isotopic age of such water has been introduced.

On the map, the boundary between fresh and brackish groundwater is defined as 1500 mg L^{-1} total dissolved solids, which coincides with the World Health Organisation's maximum desirable limit for drinking-water quality. Further subdivision of the brackish and saline groundwaters has been attempted on an inset map at 1:15 000 000 scale. In many fractured-rock provinces the salinity pattern is complex, and simplifications have been made on the map. Groundwater of up to 14 000 mg L^{-1} is used in Australia for stock water supplies, and groundwater of up to 180 000 mg L^{-1} is used for industrial and mining purposes.

Temperatures of 30°C and higher have been plotted to represent abnormally warm groundwaters. Some aspects of surface hydrology have been shown, including distinctions between perennial and intermittent streams, and discharge data.

Man-made groundwater abstraction features, and alterations of the groundwater regime, are shown, and symbols have been introduced for the more important cases of regional groundwater pollution, and salinisation due to rising watertables.

The map was drafted on a computer graphics system which allowed enlargement and interactive map editing on a screen at a graphics workstation. It is the most complex geoscientific map produced by BMR with computer-assisted cartography.

The map and explanatory notes are being published as *BMR Bulletin* 227, 'Hydrogeology of Australia', by J.E. Lau, D.P. Commander, & G. Jacobson. With the aid of text-figures the notes complement the information presented on the map sheet.

For further information contact Dr Gerry Jacobson at BMR (Division of Continental Geology).

Thrust sheets in the northeastern Amadeus Basin, NT: stratigraphic repetition enhances hydrocarbon prospects

A new interpretation of the structure of the northeastern Amadeus Basin suggests the possibility of large-scale stratigraphic repetitions in the subsurface. In particular, the Proterozoic–Cambrian Arumbera Sandstone, the main petroleum target in the area, may form structural traps concealed beneath overthrust older Proterozoic strata.

Thrust sheets with southward translations of tens of kilometres in the northeastern Amadeus Basin were recognised by BMR geologists in the mid 1960s during 1:250 000 regional mapping (Wells & others, 1970: *Bureau of Mineral Resources, Australia, Bulletin* 100). Detailed mapping between 1979 and 1981 by Prof. R.Q. Oaks Jnr and graduate students of Utah State University has provided the basis for a new interpretation (by A.J. Stewart) of the extent and number of sheets and their structural history.

The northeastern Amadeus Basin contains Late Proterozoic to Ordovician shallow-marine sandstone, shale, carbonate, and evaporites, and Ordovician to Devonian aeolian to fluvial sandstone and conglomerate, totalling about 7000 m in thickness. The Late Proterozoic strata include several units (the Aralka, Olympic, and Waldo Pedlar Formations and the Cyclops Member of the Pertatataka Formation) which occur nowhere else in the Amadeus Basin, and lithologically resemble coeval formations in the southwestern Georgina Basin, 120 km to the northeast. Evaporites at two levels, one low in the Proterozoic, the other low in the Cambrian, allowed detachment and southward sliding of nappes in Devonian to Carboniferous time.

60 km travel

Figure 10 shows the various sheets currently identified, and contains a balanced (i.e. restorable) cross-section at natural scale. The new interpretation regards all of the sheets as parts of a single large nappe, separated into klippen by later folding and erosion. The distance travelled by the nappe was 60 km southward. The klippen are bounded by north-dipping thrust faults at the front, by south-dipping low-angle normal faults at the back, and by lateral ramps or strike-slip faults at the sides. Because of concealment by superficial Cainozoic cover, the southern limit of the nappe is unknown. The N'Dhala and Purple Range sheets are separated by a stack of imbricate thrust slices (an antiformal stack duplex) that overlies a concealed autochthonous antiform. South-dipping thrust faults at the northern margin of both the Camel Flat sheet and the parautochthon south of the N'Dhala sheet are interpreted as later backthrusts (including a 'back-thrust duplex') that cut the parent sheet after its arrival from the north.

The cross-section shows the exposed Late Proterozoic allochthonous strata of Georgina Basin affinity resting on a detachment fault at the top of the Arumbera Sandstone. The Proterozoic strata have moved to their present position from above the presently exposed Arunta Inlier (basement to the Amadeus and Georgina Basins), and can be regarded as a far-travelled outlier of Georgina Basin rock types.

The subsurface Arumbera Sandstone below the exposed Proterozoic rocks is gently folded, and some of the anticlines are doubly plunging, i.e. closed. The Arumbera flowed 5 million cubic feet of gas per day in 1982 from the Dingo No. 1 well, 30 km west of the area in Figure 1, and is the most prospective potential hydrocarbon reservoir in the northeast Amadeus Basin. Its postulated presence throughout a large area in the subsurface, combined with gentle folding, enhances the prospectivity of the northeast Amadeus Basin. A proposal for a reflection seismic survey of part of the Olympic sheet to test whether the Arumbera Sandstone really is present in the subsurface, as postulated, is currently under consideration in BMR.

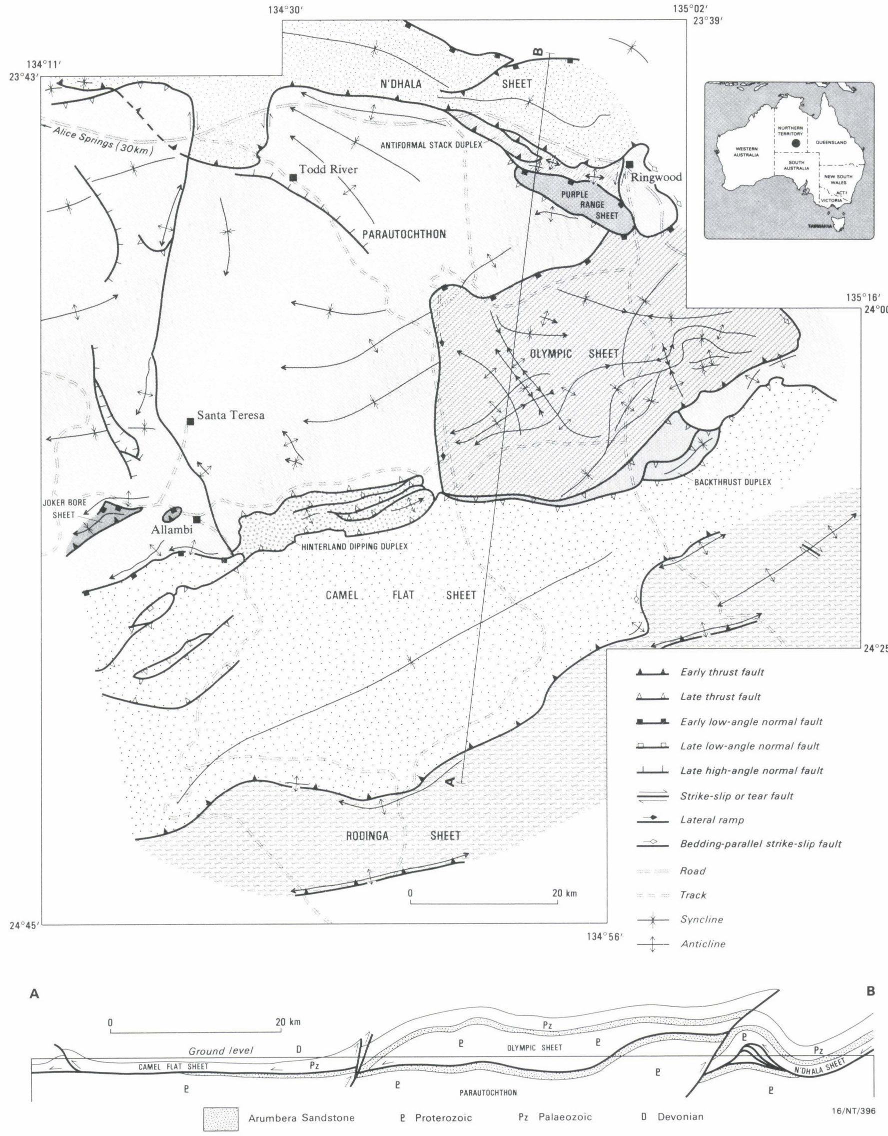


Fig. 10. Thrust sheets in the northeastern Amadeus Basin.

For further information contact Dr Alastair Stewart, BMR (Division of Petrology & Geochemistry).

New model for evolution of Amadeus Basin

A new model has been developed for the evolution of the Amadeus Basin in central Australia that accounts for the sedimentary facies distribution, and explains the close relationship between several deformational events (both extensional and compressional) and development of the basin through time.

The basin is a broad, relatively shallow, crustal depression containing three major sub-basins and a shallow trough along its northern margin (Fig. 11). The sub-basins are separated from a much larger platform area to the south and west by the Central Ridge, which at times acted as a barrier to sedimentation. The basin evolved in three stages, the first two involving crustal extension and the final stage compression; thus, in a sense it can be regarded as a series of three vertically stacked basins.

Repeated pattern

The style of sedimentation and major sequence boundaries were controlled to a large degree by basin dynamics. Apparent sea level rose with the initiation of each extensional stage, and then gradually declined as sedimentation commenced and the peripheral bulge appeared, peaked, and declined. Following the demise of the peripheral bulge, relative sea level again appeared to rise as thermal subsidence became the dominant controlling mechanism. As a consequence, deposition followed a predictable pattern (Fig. 12).

During the major relative sea level cycle following initial crustal extension, shallow-marine clastics were followed by evaporites as the peripheral bulge developed and the supply of clastic sediments was gradually restricted. The evaporites were then replaced by carbonates, which shallowed upward to an erosional surface as the peripheral bulge peaked and began to decline. As thermal recovery again began to dominate, mature shallow-marine clastics were deposited over the erosion surface, i.e. a major sequence boundary. This depositional pattern (Fig. 12) occurred twice, first in the Late Proterozoic (pre-Heavitree Quartzite to base of Arumbera Sandstone) and again in the latest Proterozoic to Ordovician (Arumbera Sandstone to Carmichael Sandstone). Volcanics in the lower part of the succession are consistent with an extensional origin. Tectonism on the southwestern margin of the basin during the early part of Stage 2 introduced clastic sediments to the western end of the basin that were able to bypass the peripheral bulge, displacing the carbonates and evaporites from the western sub-basin.

Sea-level curves and petroleum potential

Relative sea-level is one of the most important parameters controlling facies distribution and thus the distribution of the source and reservoir rocks within a basin.

The shape of the relative sea-level curve in the Amadeus Basin was determined over the longer term by basin dynamics; however, superimposed on this is a eustatic sea-level component. In general eustatic sea-level appears unrelated to basin dynamics; however, when basins such as the Amadeus result from major continental rifting, major sea-level highs follow extension by about 70 Ma as the new ocean ridge system develops.

In the Amadeus Basin, the potential reservoirs are bodies of clastic sediment deposited first during early rapid basin subsidence, before the rise of the peripheral bulge, and then later in basin evolution when subsidence was slow. Evaporites, deposited during early subsidence as the peripheral bulge began to rise and preclude clastic sediment, are potential source rocks (Fig. 12).

Source–reservoir associations such as the Horn Valley Siltstone and Pacoota Sandstone result from the fortuitous interaction between eustatic sealevel rises and basin dynamics.

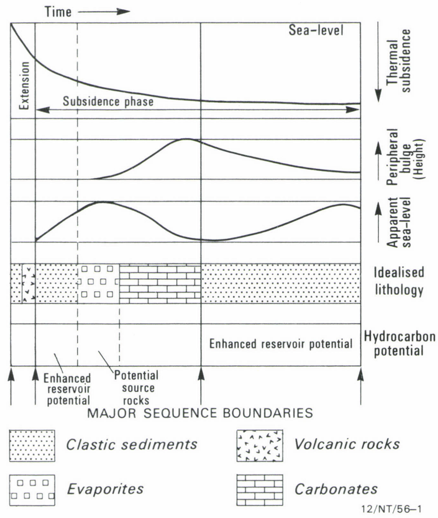


Fig. 12. An idealised sedimentary succession in an intracratonic basin in central Australia showing the relationship between idealised lithology, depositional sequences, and apparent sea level, and their relationship to basin evolution.

Deformation and basin development

The Amadeus Basin developed during an initial period of extension in the Late Proterozoic (about 900 Ma) and underwent another period of extension just before the Cambrian (about 600 Ma), the greatest subsidence occurring near the northern margin during the second phase. At the same time as the later phase of extension, a major compressional event, the Petermann Ranges Orogeny, was occurring along the southern margin together with the development of a small foreland basin. During the third stage, another foreland basin, associated with southward-directed overthrust sheets of the Devonian Alice Springs Orogeny, formed in the northern part of the basin. There was a close spatial relationship between the extensional rift basins and the later thrusts and foreland basins: the extension formed zones of structural weakness that later nucleated the inversion of the basins during shortening.

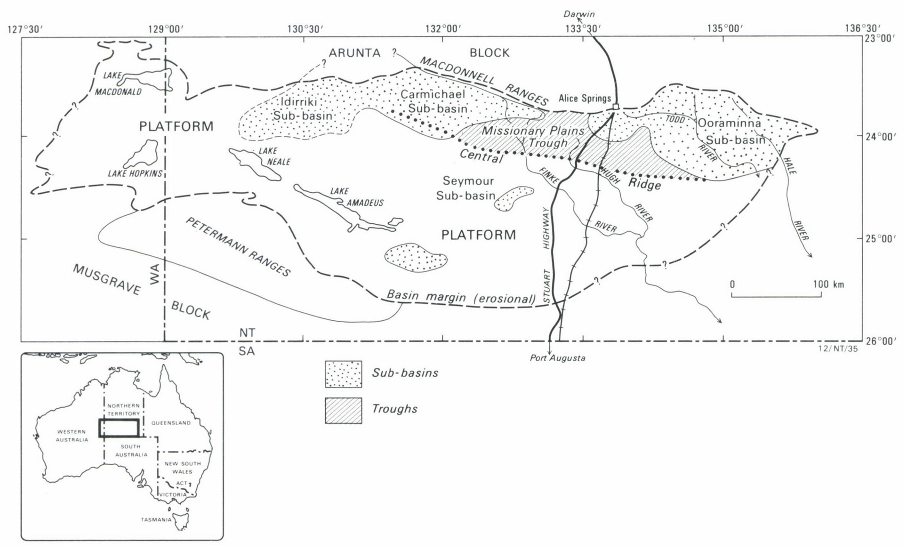


Fig. 11. The Amadeus Basin and its main morphologic features (sub-basins, trough, platforms, and topographic highs and ridges). The Petermann Ranges, which form part of the Musgrave Block, were an active source of sediment during the Early Cambrian.

Other interior basins

In the Late Proterozoic a number of broad shallow intracratonic depressions appeared across a large part of central Australia (Georgina, Officer, Ngalia, Ord, Wiso, and Warburton basins). Analysis of their fill by means of tectonic subsidence curves has allowed a direct comparison with the Amadeus Basin, and the results suggest that all are the product of the same two episodes of crustal extension (at 900 Ma and 600 Ma). These episodes were probably the result of failed rifting that all but fragmented the Australian continent during the Late Proterozoic. The 600 Ma phase was probably related to major continental rifting elsewhere (e.g. North America).

For further information, contact Dr Russell Korsch or Dr John Lindsay at BMR (Division of Continental Geology).

BOOK REVIEW: *RECENT ADVANCES IN UNDERSTANDING PRECAMBRIAN GOLD DEPOSITS*, edited by S E HO & D I GROVES, 1987, 368 pp. Publication No. 11, Geology Department and University Extension, University of Western Australia

At a time when industrial and economic interest is focused almost entirely on gold, the conceptual framework relating to controls on gold mineralisation becomes central to the development of exploration strategies and the eventual success of ore search. Research over the last eight years by the Gold Group at the Geology Department, University of Western Australia, in collaboration with other organisations around Australia and overseas, is continuing to provide some of the essential database for this growing framework of knowledge. The series of papers and reviews presented in this volume is therefore both timely and informative. The papers also represent a substantial contribution to the International Global Correlation Project (247) — *Precambrian Ore Deposits related to Tectonic Styles.*

The volume comprises 18 chapters relating to Archaean gold deposits in Western Australia, and a further six dealing with aspects of conglomerate-gold in southern Africa, a review of gold occurrences in China, and a chapter on the origin of the Boddington lateritic gold deposit. The volume is well produced, with few text errors, and is a credit to its editors, Sue Ho and David Groves, as well as, at $35.00 including postage within Australia, being an excellent example of the growing power of desktop publishing — based on a Mac system, no less.

The papers on Western Australian gold divide broadly into those dealing with particular mineral deposits and their regional environment, and those tackling specific structural or geochemical problems relating to the understanding of ore formation. Summary papers on the results of oxygen, hydrogen, carbon, and lead isotope analyses and fluid inclusion studies are particularly useful, whilst among the more provocative contributions is that of Nick Rock & others discussing the possibility that lamprophyres (with gold contents up to several hundred parts per billion compared to the 2 or 3 of average crust) may be the ultimate source of Archaean gold.

Unfortunately lacking from the volume is an overview of the different styles of mineralisation in the Archaean and of progress in the understanding of Precambrian gold. This would have provided a perspective to the many newcomers to Archaean gold research and exploration and highlighted the major advances which have occurred in understanding these important environments of mineralisation. In the genetic sense this is partly provided by the specific, and excellent, chapters on application of isotope and fluid inclusion techniques. However, it is important to emphasise that, less than two decades ago, prior to the advanced development of these techniques, ad hoc models which assumed almost statutory involvement of granites or rather questionable physical and chemical processes dominated the literature. These techniques have led firstly, in the 1970s, to the recognition of the close ties between mineralisation and metamorphism and are now pushing hard on the frontier of crust-mantle interactions as a major factor in ore genesis. Closure of the gap between geochemical understanding of ore genesis and related metamorphism and the structural evolution of the Archaean terranes is clearly the target for future research, and for the realisation of the potential of modern geoscience in mineral exploration and for the finding of the Golden 1.6 Kilometres of the future.

Recent Advances in Understanding Precambrian Gold Deposits is a substantial contribution to the literature on the Precambrian ore deposits and as such is an essential for all involved in gold research or exploration.

R.W. Henley

Chemical modelling of ore fluids: the CSIRO-SGTE THERMODATA programs established at BMR

Thermodynamic equilibrium calculations are a powerful tool for developing and testing ideas about the geochemical controls of ore deposition. The CSIRO–SGTE* THERMODATA program package has recently been established on BMR's Data General mainframe computer, and its thermodynamic database has been extended to a large number of compounds common in hydrothermal ore fluids. The programs can be used for ore-genesis and other geochemical research at BMR and in collaboration with guest investigators from universities and industry.

What is THERMODATA?

Equilibrium thermodynamics provides a theoretical framework to quantify the stability of a chemical compound with regard to external conditions such as temperature, pressure, and chemical environment. The CSIRO-SGTE THERMODATA is a general-purpose computer program package that can apply this theory to a wide variety of chemical problems. The package has been developed over the last ten years by A.G. Turnbull and M.W. Wadsley at CSIRO's Division of Mineral Chemistry in Port Melbourne. It was originally designed mainly for industrial-chemical investigations such as the optimisation of metallurgical processes. However, its generality and a number of recent extensions by CSIRO and BMR have made it equally valuable for ore genesis studies and other geochemical and petrological applications.

THERMODATA consists of two main parts:

(a) A *databank of basic stability data* for a large number of organic and inorganic solid, liquid, gaseous, and aqueous species. The databank includes several large international compilations (e.g. the JANAF tables), a critical compilation of literature data by CSIRO, and some data for ionic species in supercritical aqueous solutions from H.C. Helgeson (University of California, Berkeley). A data file for ions and complexes in subcritical aqueous solutions at elevated temperature has been added at BMR, based on experimental data from recent literature and a compilation by M.H. Reed (University of Oregon).

(b) *Eight programs to perform a wide range of functions* based on this and any additional data supplied by the user. Applications range from simple tabulations like the solubility constant for a mineral dissolution reaction, through plotting of stability diagrams (program SYSTEM), to the quantitative prediction of mass transfer during stepwise boiling or equilibration of a hydrothermal fluid with a rock (program CHEMIX).

The strength of THERMODATA is its generality, which allows a large variety of thermodynamic computations based on a single command structure and a common data set. Many thermodynamic problems of geochemical interest can also be solved more efficiently with the other, more specialised, programs available (e.g. calculation of isochores for $NaCl–CO_2–H_2O$ fluid inclusions, or construction of P–T–X phase diagrams for metamorphic reactions involving supercritical $CO_2–H_2O$ fluids). Programs for these calculations are available at BMR, and other specialised programs will be included as the need arises.

*Scientific Group Thermodata Europe.

Example: 'Efficiency' of metamorphic gold mineralising mechanisms

The formation of a gold orebody in a metamorphic environment depends on a coincidence of structural and geochemical controls. Suitable structures are required to focus enough fluid to the site, and thus primarily control the size of the deposit, whereas geochemical processes have an important influence on grade. THERMODATA can be used to investigate the 'chemical efficiency' of these ore-forming processes.

Accumulation of an economic grade requires (a) a fluid with a composition capable of transporting a sufficient gold concentration, and (b) a physical–chemical mechanism of gold precipitation that scavenges the maximum amount of gold from a relatively small amount of rock.

The *gold-transporting capacity of a fluid* can be easily portrayed with program SYSTEM, which calculates and plots phase diagrams with a variety of possible axes and for specific conditions determined from additional information such as fluid-inclusion data. The now well-known 'gold window' in Figure 13 shows that maximum gold solubilities as $Au(HS)_2^-$ occur in a sulphur-bearing fluid at redox and acidity conditions where the ligand component, sulphur, is present in similar concentrations of H_2S, HS^- and SO_4^{2-}.

The first chemical requirement for economic gold mineralisation, i.e. a fluid rich in gold, is intuitively clear, and quite straightforward to calculate by hand. Less obvious are the substantial differences that exist in the *efficiency of gold precipitation* between various possible processes, which are equally likely to influence grade. Gold precipitation during progressive reaction with wall rock can be quantitatively modelled with program CHEMIX, as shown by a simplified example in Figure 14. This was calculated in order to compare the changes in the composition of a gold-rich fluid (initially relatively oxidised near the triple point in Figure 13) upon stepwise reaction with a graphitic or magnetite-rich rock.

The fluid must react with a comparatively large amount of *graphite-bearing rock* (Fig. 14a, solid lines) before gold starts to precipitate, which in this case is due to a redox-change, as evidenced by the sharp decrease in SO_4^{2-} and an increase in the CH_4 concentration in the fluid. Although this mechanism could explain the formation of some metamorphic gold veins of the 'slate belt' type (e.g. SE Australia), the calculations suggest that less than half of the gold in solution is deposited, even after extensive equilibration of the fluid with the graphitic rock. More than half of the dissolved gold will be flushed through and out of the deposit unless some other chemical trap is encountered.

Fig. 13. Gold transport in low-salinity metamorphic fluid, shown in a pH vs. redox diagram calculated with program SYSTEM. The maximum stability of the gold bisulfide complex, with concentrations of $Au(HS)_2^-$ exceeding about 10 ppb inside the shaded 'solubility window' is controlled by the speciation of the ligand element, sulfur (dashed lines).

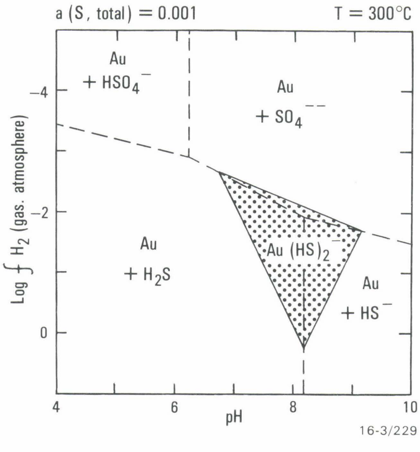
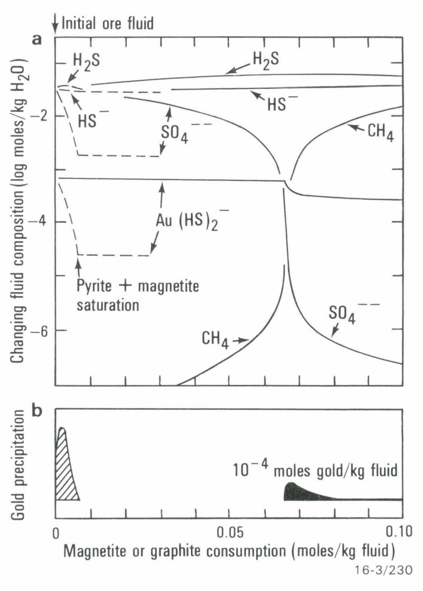


Fig. 14. (a) Changes in the composition of a gold-bearing fluid by progressive reaction with graphitic rock (solid lines) or magnetite-bearing rock (dashed lines), modelled by program CHEMIX. (b) Gold precipitation from the same fluid by progressive reaction with magnetite-bearing rock (hachured area) and graphitic rock (solid area). Note that desulphidation by reaction with magnetite to form pyrite is a particularly efficient precipitation mechanism for gold deposition. By contrast, after extensive reaction of the same fluid with graphite, more than 50% of the gold stays in solution and is lost.



By contrast, reaction of the same fluid with a *rock containing minor magnetite* will precipitate more than 99% of the dissolved gold after consumption of a much smaller amount of magnetite (Fig. 14a, dashed lines). The greater efficiency of the second process is due to reduction and desulfidation of the fluid, and replacement of the magnetite in the host rock by pyrite. Similar processes have probably contributed to the high gold grades of some Archaean greenstone belt deposits (see e.g. *Economic Geology*, 79/1, p. 162, 1984).

Limitations: an open question regarding metamorphic copper ores

The application of the THERMODATA programs is primarily limited by the *availability of experimental stability data* for species or chemical systems under the P-T conditions of interest. In some cases missing data can be estimated, and THERMODATA includes a program to estimate unavailable high-temperature data from experimental low-temperature data. This has been used in a semiquantitative investigation of the possible relation between arsenopyrite precipitation and ore grades of cassiterite in tin deposits (*Economic Geology*, 81/3, 511, 1986). In other cases stability data may be completely unavailable or else not accurate enough.

The *stability of iron chloride complexes* in hydrothermal brines is an example of critical importance to several ore deposit questions. One of them concerns the geochemical controls on the formation of Mount Isa style copper deposits.

The epigenetic Mount isa copper ores are located where a number of structural and potential chemical traps coincide:

(a) a zone of hydraulic brecciation originating from local extension

(b) a contact between altered mafic volcanics and dolomitic metasediments

(c) a closer localisation of the richest copper ores where the metasediments are rich in preexisting sedimentary pyrite and pyrrhotite which are partly incorporated in the replacive copper ores.

Exploration question: Is feature (c) a crucial ingredient in the formation of rich Mount Isa style ore through reaction of Cu-rich, but Fe- and/or S-deficient, fluids with the sedimentary iron sulfides? Or could similarly rich ore be formed in any other location where only conditions (a) and (b) are fulfilled? In the latter case the presence of the iron sulfides would be an accidental feature, unimportant for exploration.

Preliminary calculations, using various combinations of the published stability data for Fe, Cu, and S species in conjunction with fluid-inclusion data, suggest very low chalcopyrite solubilities if all ore components were carried in the same fluid. However, it has not been possible to define any thermodynamically consistent mechanism of ore deposition that leads to chalcopyrite precipitation without simultaneous precipitation of much larger amounts of magnetite. Magnetite is absent from the Mount Isa ore, and this discrepancy probably indicates that the published stoichiometry and stability data of either Fe or Cu complexes (or both) are not applicable and indeed are incapable of being used to assess the significance of the sedimentary pyrite.

New BMR-DSIR experimental study

Closer inspection of the published experiments on Fe species showed that their thermodynamic interpretation is highly questionable. BMR has therefore begun a new experimental study in collaboration with the New Zealand Department of Scientific & Industrial Research (DSIR). DSIR hosts the only laboratory worldwide where UV spectroscopy of high-temperature fluids has been used successfully to measure the thermodynamic stability of aqueous species. This technique is of unprecedented accuracy, and its successful application to iron chloride and possibly copper chloride solutions would make a major impact on several of BMR's projects on hydrothermal base metal and gold deposits.

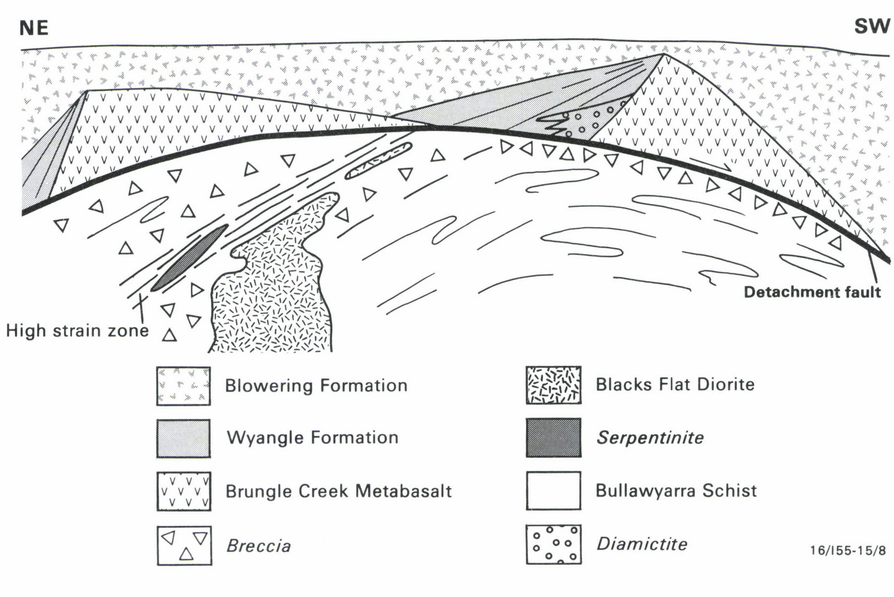
For further information contact Dr Chris Heinrich or Dr Subash Jaireth at BMR (Division of Petrology & Geochemistry).

Extensional tectonics in the Tumut Trough

Several large-tonnage, low-grade, gold and other mineral deposits are known to be associated with metamorphic core complexes and detachment terranes in the western USA. This association has not been recognised in Australia, partly because of the difficulty of recognising extensional tectonic environments that have undergone later compressive orogeny (see *BMR Research Newsletter* No. 2).

The Structural Studies Group at BMR in conjunction with the Geology Department, ANU, has been engaged in an attempt to assess the relevance of extensional tectonics to the development of the Lachlan Fold Belt. Recent work in the **Brungle area** of the Tumut Trough (which is a small Silurian basin 100 km southwest of Canberra) has established features consistent with an early extensional history. The rocks in this area form two distinct domains (Fig. 15): an Ordovician(?) basement (Bullawyarra Schist) and a Silurian sedimentary and volcanic cover sequence (Brungle Creek Metabasalt, Wyangle Formation, Blowering Formation). The two domains are separated by a sharp discontinuity marking an abrupt change in rock type, structure, metamorphic grade, and deformation style. Cover sequences have undergone only one major deformation during the Early Devonian, involving lower-greenschist-facies metamorphism and upright folding as a result of E–W shortening. By comparison, the basement underwent at least two previous deformations at upper-greenschist facies and has distinct high-strain zones subconcordant to the basement/cover contact. The high-strain zones, characterised by a ubiquitous NNW-trending mineral-elongation lineation, record a progressive, though discontinuous, history of ductile to brittle behaviour consistent with an extensional origin.

Fig. 15. Schematic cross-section showing rock relationships in the Tumut Trough in the Middle Silurian.



The structural and metamorphic discontinuity separating the basement from the Silurian cover is characterised by extensive cataclasis and alteration and is interpreted as a major detachment fault associated with extension and the development of the Tumut Trough in the Early to Middle Silurian. Serpentinite was emplaced in the high-strain zones prior to intrusion of the Blacks Flat Diorite into the basement (Bullawyarra Schist) during the main period of movement on the detachment. This preceded deposition of the Silurian trough sediments and volcanics which unconformably overlie and onlap older units.

The development of the Tumut Trough in the Brungle area bears many similarities to that of Cordilleran metamorphic core complexes. Such a model is consistent with the back-arc, marginal-sea environment suggested for the area by previous workers and may have a wider application to similar Silurian 'trough' sequences throughout the Lachlan Fold Belt.

For further information contact Mr Peter Stuart-Smith, at BMR (Division of Petrology & Geochemistry) (presently at Geology Department, Australian National University).

BMR completes study of hydrocarbon prospectivity of the Middle Proterozoic McArthur Basin

BMR has just completed a 3½ year NERDDC-sponsored study of the petroleum potential of the southern McArthur Basin. This study has considerably enhanced our view of the basin's petroleum potential, through the discovery of petroleum source rocks, potential reservoir rocks, and the world's oldest oil. The final report to NERDDC is available as *BMR Record* 1987/48.

The report includes a discussion of the geology, sedimentology, reservoir potential, source-rock potential, maturation, hydrocarbon composition, and potential plays. It incorporates the results of geochemical and organic petrographic analyses of 1100 samples from 55 locations and discusses an approach to source-rock assessment in the Proterozoic.

Good to excellent source rocks indicated

Five potential source rocks have been discovered (Fig. 16). They occur at various stages of thermal maturity in different parts of the basin. Two of these source rocks, the lacustrine Barney Creek Formation in the McArthur Group and the marine Velkerri Formation in the Roper Group, compare favourably in thickness and potential with rich, demonstrated source rocks in major petroleum-bearing provinces in the Phanerozoic. Organic carbon contents in the Barney Creek Formation range up to 7%, with organic-rich intervals up to 200 m thick; the organic matter is Type I to Type I/II and in marginally mature samples consists of fluorescent lamalginite. Organic carbon contents in the Velkerri Formation range up to 6.5%, with organic-rich intervals up to 80 m thick; the organic matter is Type II.

Extractable hydrocarbon yields from mature samples indicate that good to excellent source rocks are present. The potential of these Proterozoic source rocks was confirmed in no uncertain fashion by the discovery of 'live' oil in an interbedded mudstone and siltstone sequence in the Velkerri Formation in the BMR Urapunga No. 4 stratigraphic hole drilled during the study. The composition of the oil and of extractable hydrocarbons suggests that most of the organic matter was derived from prokaryotic organisms. The major classes of hydrocarbons identified were n-alkanes, monomethyl branched alkanes, cyclohexylalkanes, and acyclic isoprenoid alkanes. There were also low abundances of pentacyclic triterpanes, comprising hopanes and methylhopanes. The presence of low amounts of steranes in some samples indicates that eukaryotic organisms existed as far back as 1690 Ma.

Maturation level

A variety of techniques have been used to assess the maturation level of these Proterozoic sediments. Tmax measurements derived from Rock Eval analyses show the same relationship to hydrocarbon generation as found in Phanerozoic sediments. Methyl Phenanthrene Indices and reflectance measurements on lamalginite and bitumen have also been used to determine maturation levels. The Methyl Phenanthrene Index has been recalibrated against vitrinite reflectance for the purposes of this study. As might be expected from reflectance measurements of hydrogen-rich organic matter in Phanerozoic samples, reflectance values of Proterozoic lamalginite and bitumen are lower than the vitrinite reflectance levels calculated from the Methyl Phenanthrene Indices for the same samples. Nevertheless, systematic depth changes in reflectance do occur and with adequate calibration can be used to assess maturity of Proterozoic sediments.

McArthur Group and Nathan Group potential

The sediments of the McArthur and Nathan Groups consist mainly of evaporitic and stromatolitic cherty dolostones interbedded with dolomitic siltstone and shale with some thin sandstones. They were deposited in a complex interfingering set of environments including marginal-marine, lacustrine, and fluvial. Source beds are located in the Barney Creek, Yalco, and Lynott Formations. Potential reservoir beds are vuggy carbonates or breccias associated with penecontemporaneous faulting. Both source and reservoir distributions are likely to be complex and difficult to locate and predict. The maturation levels of McArthur Group sediments are also very variable, ranging from marginally mature to mature in the Glyde Sub-basin and on the eastern margin of the Batten Trough, to late mature to overmature in the central and northern parts of the Batten Trough. Maturation levels can also vary rapidly on a local scale; this may be associated with movement of hydrothermal fluids along faults. Considerations of burial history suggest that hydrocarbon generation occurred during deposition of the McArthur and Nathan Groups, and was followed by erosion prior to the deposition of the Roper Group. Thus, preservation of hydrocarbons in these older sediments represents a significant risk for petroleum exploration.

Roper Group potential

In contrast, the sediments of the younger Roper Group consist of quartz arenite, siltstone, and shale, which are characterised by more uniform facies deposited in a stable marine setting. Source beds are located in the Velkerri and laterally equivalent 'Lansen Creek Shale' and McMinn Formations. Potential reservoirs consist of thick shelf sandstones. Both source and reservoir facies are laterally extensive (over 200 km). Maturation levels in the Velkerri Formation and 'Lansen Creek Shale' fall within the oil window throughout the study area, but the McMinn Formation is marginally mature where sampled. Porosity and permeability measurements of potential sandstone reservoirs are generally low because of extensive quartz cementation. The burial history suggests that hydrocarbons were generated during deposition of the Roper Group. There is a real possibility that hydrocarbon accumulation may have largely pre-dated the cementation and inhibited it in the accumulation zone. The critical question is whether any hydrocarbon accumulations have been preserved until the present day. However, discovery of 'live' oil at relatively shallow depth in the Velkerri Formation in the BMR Urapunga No. 4 stratigraphic hole and the possibility of accumulation occurring prior to reservoir cementation provide encouragement that commercial hydrocarbons may be preserved in protected Roper Group reservoirs.

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

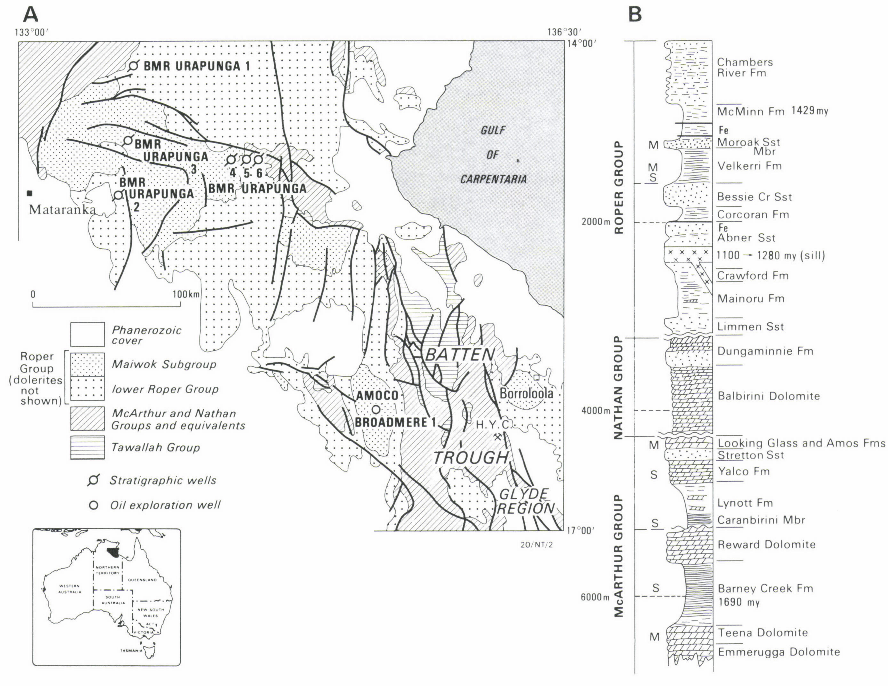


Fig. 16. Locations of some stratigraphic and petroleum exploration wells, southern McArthur Basin, together with generalised stratigraphy showing potential source horizons (S), migrated hydrocarbons (M), and geological ages.

McArthur Basin Bulletin released

GEOLOGY OF THE SOUTHERN McARTHUR BASIN, NORTHERN TERRITORY, by M.J. Jackson, M.D. Muir & K.A. Plumb, 1987. *Bureau of Mineral Resources, Australia, Bulletin* 220, 173 pp, 7 tables, 172 figs., 3 microfiche appendixes, 1 plate (1:100 000 scale geological map, Abner Range Region). Price: $36.15. Available from Publication Sales, BMR, GPO Box 378, Canberra, ACT, 2601.

This long-awaited Bulletin was released in July 1987. It presents the results of detailed stratigraphic and sedimentologic studies of this mid-Proterozoic basin carried out between 1977 and 1982, dealing with that part of the basin lying between the Roper River and the Queensland–Northern Territory border.

Mineral and petroleum potential

The Bulletin includes descriptions of the region occupied by the very large HYC (McArthur) lead–

zinc–silver deposit. The accompanying map covers some 6000 km^2 west and southwest of the HYC deposit, and delineates the major formations of the Tawallah, McArthur, Nathan, and Roper Groups in and around the Abner Range. This area contains most of the critical outcrops on which understanding of the evolution of the Batten Trough, a mid-Proterozoic rift system and the major structural feature of the region, is based.

Detailed studies of the Roper Group were undertaken between 1983 and 1986, following completion of the work reported in the Bulletin, and resulted in the discovery of live oil in a core obtained from a stratigraphic drillhole, BMR Urapunga 4, in 1985 — see article in this number, 'BMR completes study of hydrocarbon prospectivity of the Middle Proterozoic McArthur Basin'.

The studies reported in the Bulletin have led to important advances in knowledge of the evolution of Proterozoic sedimentary environments and their microfloras and stromatolites, the genesis of evaporitic carbonate sequences, and the role of such sequences in the formation of base-metal sulphide deposits. A marine or lacustrine environment for the carbonates? This has been a controversial topic, and is not completely resolved, although the weight of evidence favours a lacustrine influence for many of the McArthur Group formations.

For further information contact Mr Jim Jackson at BMR (Division of Continental Geology).

Seismic survey provides new information on eastern margin of Surat Basin, Qld

BMR's Explosion Seismology Section field-tested its new Sercel SN368 seismic telemetry system near Millmerran on the eastern margin of the Surat Basin in 1986. Anticlines in the Jurassic, directly overlying the ?Permian, are considered to indicate new petroleum prospects.

The survey acquired 27 km of 5-fold data along an E–W line in the Boondandilla State Forest 50 km east of the Moonie oil field. Parts of this line had been shot in the early 1960s (single-fold coverage) and early 1980s. The western end of the processed section shows a ?Lower Permian sequence subcropping beneath the Jurassic–Cretaceous Surat Basin. Fig. 17 shows the westernmost 5 km of the section. The ?Lower Permian sequence is terminated to the east by a major fault (just off the figure).

The data processing included first-break statics, gain recovery, dynamic mute, dynamic corrections, and a deconvolution filter before stack. A new technique was developed to calculate static corrections using all available information from the first breaks. The technique involves calculating travel times in the weathered layer from all combinations of forward and reverse shots and averaging at each geophone station. The weathering times are then combined with elevations, uphole times, and velocities to produce static corrections. The deconvolution filter was developed by the Explosion Seismology Section and was found to be very effective for processing records obtained using explosives in this area. The combination of the new statics and deconvolution filter has produced a high-quality section.

The section shows the Jurassic to Cretaceous strata in fine detail, and the eastern edge of the ?Lower Permian basin is represented by the subcropping Permian in the section. The section shows several anticlines in the Lower Jurassic at the expected level of the Evergreen and Precipice Formations (projected from Tinker Creek No. 1 well, about 7 km north of the section line). These anticlines are broadly similar in dimensions and geological relationships to the one in which oil

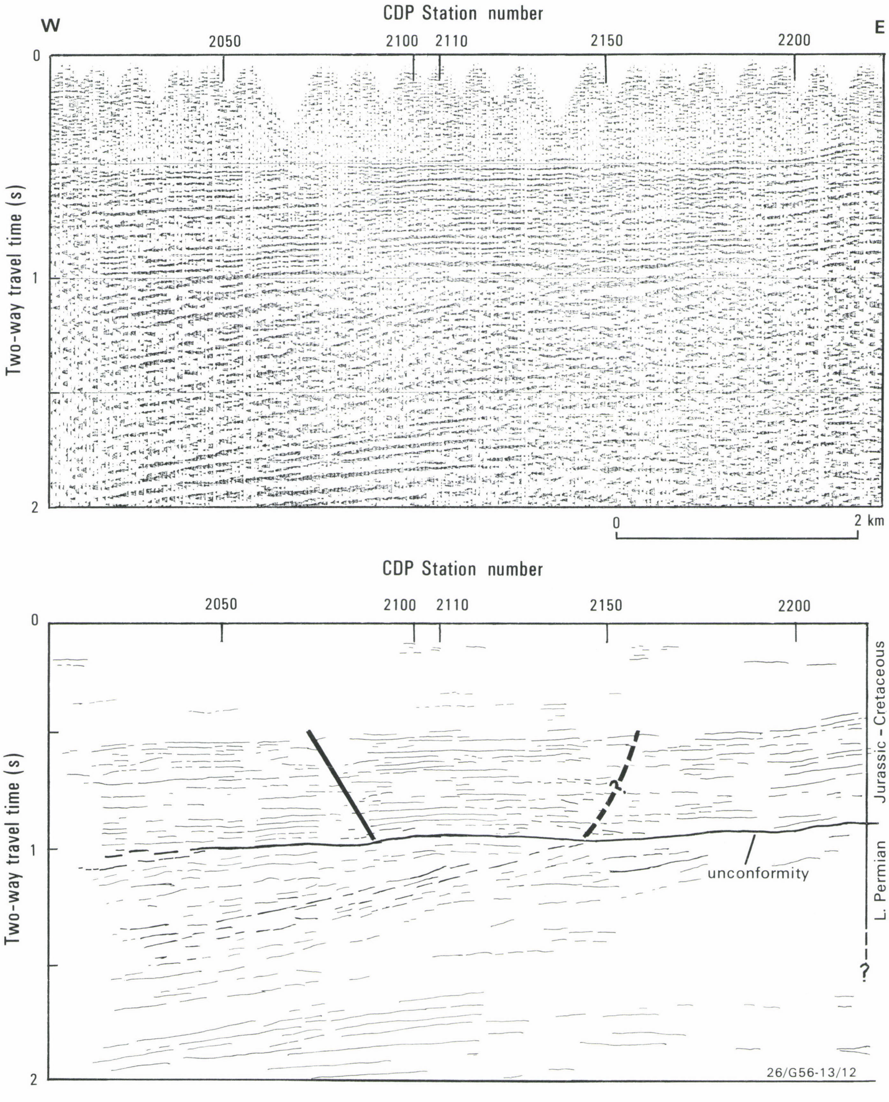


Fig. 17 Seismic section and interpreted line drawing from the 1986 BMR Milmerran traverse (V/H is approximately 1 between the ground surface and 1 sec. 2-way travel time).

was found at Moonie 50 km to the west. One is apparent in Fig. 17 at CDP station 2110.

The above interpretation, taken together with the presence of reservoir sands in nearby wells, indicates the area should be considered prospective for petroleum. Further work, particularly N-S lines, should be considered in order to check for closure. Existing data from other E-W lines covering the eastern margin of the Surat Basin are being processed by the same techniques, to look for similar structures. The base (i.e. eastern limit) of the subcropping ?Lower Permian occurs also on the BMR 1984 line at the Kumbarilla Ridge, farther north. It also extends farther southwest of the Millmerran line in Figure 17 and hence the possible prospective area may extend at least 60 km along strike.

For further information contact Mr F.J. Taylor at BMR (Division of Petrology & Geochemistry).

Palaeogeographic Maps project: drawing to a close as a successor waits in the wings

The Palaeogeographic Maps project has been under way in the Division of Continental Geology for the past three years. Its aim has been to produce a series of palaeogeographic maps of Australia during the Phanerozoic, to be used in exploration, for generating new play concepts in frontier areas, for assessing undiscovered resources, and as a regional framework for more detailed basin studies. The project has been jointly funded by BMR and APIRA (Australian Petroleum Industry Research Association), representing thirteen sponsoring companies.

The success of the project can be gauged by its extensive output, the interaction it has encouraged with industry, and the initiatives it has stimulated. It has achieved its primary aim by producing over 160 maps and charts that capture the changing mosaic of environments on the continent through 70 time-slices over the past 600 million years. The maps show hydrocarbon occurrences and are supplemented by source-rock overlays annotating source type and quality; thus the correlation between petroleum occurrence and palaeoenvironment can be assessed and predictions made about untested potential. The maps also show mineral occurrences.

Phanerozoic History of Australia project

The most notable ancillary benefit has been the creation of a comprehensive database of stratigraphic, lithological, palaeoenvironmental, palaeontological, thickness, and structural information for all of Australia's Phanerozoic basins. This mammoth data set has been the impetus for the development of a new project, the Phanerozoic History of Australia project.

This successor to the Palaeogeographic Maps project will update and consolidate the database, and extend it to include regions adjacent to Australia now and in the past, including Papua New

Guinea and Antarctica. A new series of palinspastically reconstructed maps will be produced using BMR's Intergraph graphics system; the maps will be supplemented by regional cross-sections developed from seismic, well, and outcrop information. Other spin-offs of the first project will include revision of the biostratigraphy of each time period, development of a Phanerozoic inundation curve for Australia, and the construction of subsidence curves for selected basins.

The Phanerozoic History of Australia Project will commence in late 1987–early 1988, depending on the support of a few more company sponsors. Companies not among the sponsors for the first project will be welcome to join the new project. The results of both projects are confidential to sponsors for one year prior to general release.

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

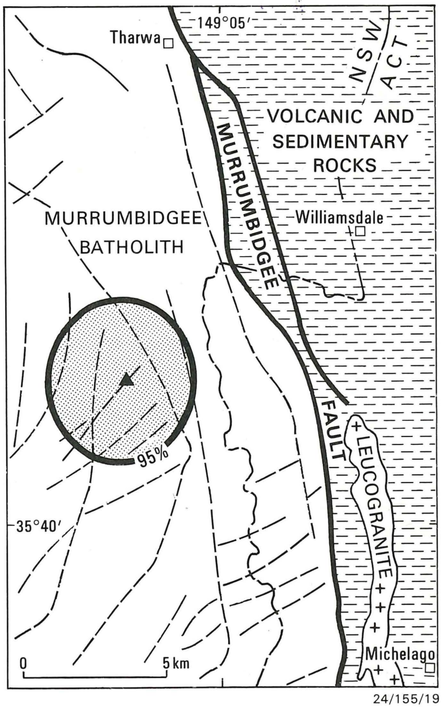


Fig. 18. U. Naas Valley earthquake of 4 April 1987: regional geology and epicentral location, with 95% confidence ellipse.

Googong Dam and the Upper Naas Valley earthquake of 4 April 1987

On 4 April 1987 a small earthquake (ML 2.6) south of Canberra triggered a newly installed accelerograph on the inlet tower of Googong Dam, on the Queanbeyan River. The recording provided the natural frequency and damping coefficient of the structure — essential in determining its capacity to resist earthquakes.

Local residents in the epicentral region reported effects consistent with an intensity of MM III, although the earthquake was not felt at the nearest townships 11–14 km from the epicentre.

From the analogue output, and applying the crustal model of Finlayson & McCracken (1981: *Journal of the Geological Society of Australia*, 28, 177–190), a depth of 8.0 ($\pm$ 0.3) km can be estimated, i.e. quite consistent with the felt effects.

The epicentre is in the fault-bounded, early Palaeozoic Murrumbidgee Batholith, in an area occupied by a conjugate set of generally northeasterly trending lineaments.

The crustal model used to obtain the fault-plane solution was derived from a BMR crustal survey that used quarry blasts from the Googong Dam construction site as seismic sources. The mechanism has a strong thrust component, with some right-lateral strike-slip motion on the nodal plane striking at N 32°E. This nodal plane is roughly parallel to the trend of the lineaments near the epicentre. The principal stress is almost horizontal, striking at N 330°E.

Free vibration of the tower is very clear on both horizontal records comprising the accelerogram at Googong Dam. The apparent damping coefficient of the tower was computed to be in the range 0.01 to 0.035, depending on the method of computation.

Even in areas of low seismicity such as Australia, earthquake loading must be considered in the design of structures, especially where damage or loss could threaten populated areas. By measuring the vibration of structures under dynamic load, two of the fundamental parameters required for earthquake-resistant design — natural frequency and damping — can be determined. Additional instruments are being installed in selected structures in the Canberra region, to monitor their response to earthquakes.

For further information, contact Mr Kevin McCue at BMR (Australian Seismological Centre).

Cadoux earthquake, 7 March 1987

An earthquake of Richter magnitude (ML) 4.5 occurred 4 km west-southwest of Cadoux, WA, on 7 March 1987. It was felt at a ground intensity of up to MM VI near the epicentre. The average radii of the MM V and MM IV isoseismals were 21 km and 100 km respectively, and the earthquake was felt (MM III) in the outer suburbs of Perth, 170 km away. The greatest ground acceleration yet measured in Western Australia was recorded near the epicentre, and the event triggered newly-installed accelerographs in the dam wall at Canning Dam.

Near the epicentre the geology greatly influenced the ground period but not the peak acceleration. Figure 19 shows how the peak ground acceleration and velocity became attenuated with hypocentral distance (these are important relations used in earthquake risk studies).

The water level in a well 5 km from the epicentre rose by about 10 mm (corrected for air pressure) over a six-hour period before the earthquake. In another well, 2 km from the epicentre, the water rose to 4 m from the surface, the highest ever noticed by the farmer, 2–3 months beforehand, despite the previous extremely dry summer; two days afterwards it had dropped to 6 m from the surface.

The earthquake's focus (hypocentre) was computed to be at a depth of 5 $\pm$ 1 km and the dip of the fault 45 degrees to the west.

For further information contact Mr Brian Gaull, Mr Peter Gregson, or Mr Edward Paull at BMR (Mundaring Geophysical Observatory, Mundaring, WA).

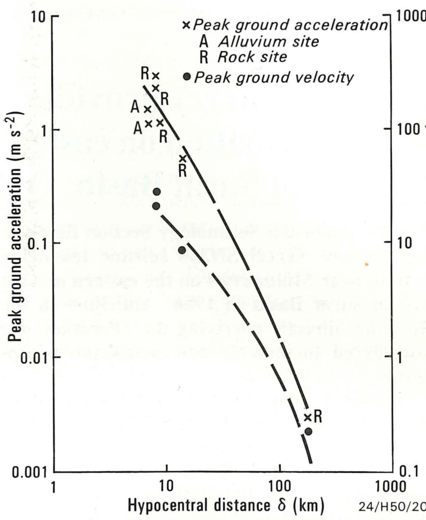


Fig. 19. Attenuation of peak ground acceleration, Cadoux earthquake of 7 March 1987.

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

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