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Epithermal gold potential in the northern Coen Inlier

Reconnaissance whole-rock oxygen-isotope data for Permo-Carboniferous volcanic rocks that extend from north of 14°S in Cape York Peninsula to Torres Strait indicate an extensive area of ^{18}O depletion in the northern Coen Inlier (Fig. 1A). This is similar to regional whole-rock ^{18}O depletion observed in the northern Drummond Basin — an area known since 1984 for its epithermal gold potential. Isotopic data, and As, Sb, Au, and Ag anomalies revealed by a regional stream-sediment survey carried out in 1990, suggest that high-level igneous rocks in the northern Coen Inlier have a similar but poorly understood potential for epithermal gold mineralisation.

Unaltered primary igneous rocks typically have a narrow range of $\delta^{18}O$ values between about +5.5 and +10 per mil relative to Standard Mean Ocean Water (SMOW). However, there is a growing realisation that some volcanic and plutonic rocks are regionally ^{18}O-depleted relative to 'normal' igneous values. Interaction between low-^{18}O meteoric fluids and rocks at high temperatures is the only plausible means of producing this depletion, because other fluid sources (e.g., magmatic or metamorphic) will either increase or only slightly decrease 'normal' whole-rock igneous values. This meteoric-water–rock interaction could have occurred at the magmatic stage (through magma interacting directly with the meteoric fluids or assimilating rock already depleted in $\delta^{18}O$) or at the subsolidus stage during cooling.

A coincidence between areas of igneous whole-rock ^{18}O depletion and epithermal districts was reported first by O'Neil & Silberman (1974: *Economic Geology*, 69, 902–909). Tertiary epithermal gold deposits in the USA (e.g., Round Mountain, Comstock Lode, and Goldfield) are associated with igneous rocks regionally depleted in oxygen isotopes. However, the application of regional ^{18}O-depletion patterns as a tool for discriminating areas prospective for epithermal deposits is not apparent from the literature. The discovery of epithermal gold in the northern part of the Palaeozoic Drummond Basin (economic deposits at Pajingo and Wirralie, and numerous prospects) was followed by the recent recognition of ^{18}O depletion of the associated volcanic rocks over at least 1500 km^2 (*BMR Research Newsletter* 14, 1–2). An association between epithermal mineralisation and regional ^{18}O depletion might be expected: low-sulphidation epithermal systems almost invariably involve meteoric water, and hydrothermal systems dominated by meteoric water could be anticipated in volcanic terrains during the waning stages of igneous activity.

Reconnaissance-scale whole-rock oxygen-isotope data are being compiled by AGSO for Palaeozoic igneous rocks in north Queensland. One area being assessed is Cape York Peninsula, where volcanic rocks extend from the northern Coen Inlier to Torres Strait. Miezitis & Bain (1991: *BMR Record* 1991/74) drew attention to the moderate to high potential for gold in the Cape York–Oriomo and Coen Inliers, which have regional geological features similar to the northeast Queensland felsic volcanic province (Georgetown/Townsville area).

Fifteen samples of rhyolitic to andesitic tuffs and lavas from the Permo-Carboniferous Janet Ranges, Kangaroo River, and Cape Grenville Volcanics in the northern Coen Inlier and the Carboniferous? Torres Strait Volcanics were analysed. The sampling was biased towards volcanic rocks because past experience in the northern Drummond Basin had shown that they are more consistently and intensely ^{18}O-depleted than intrusive

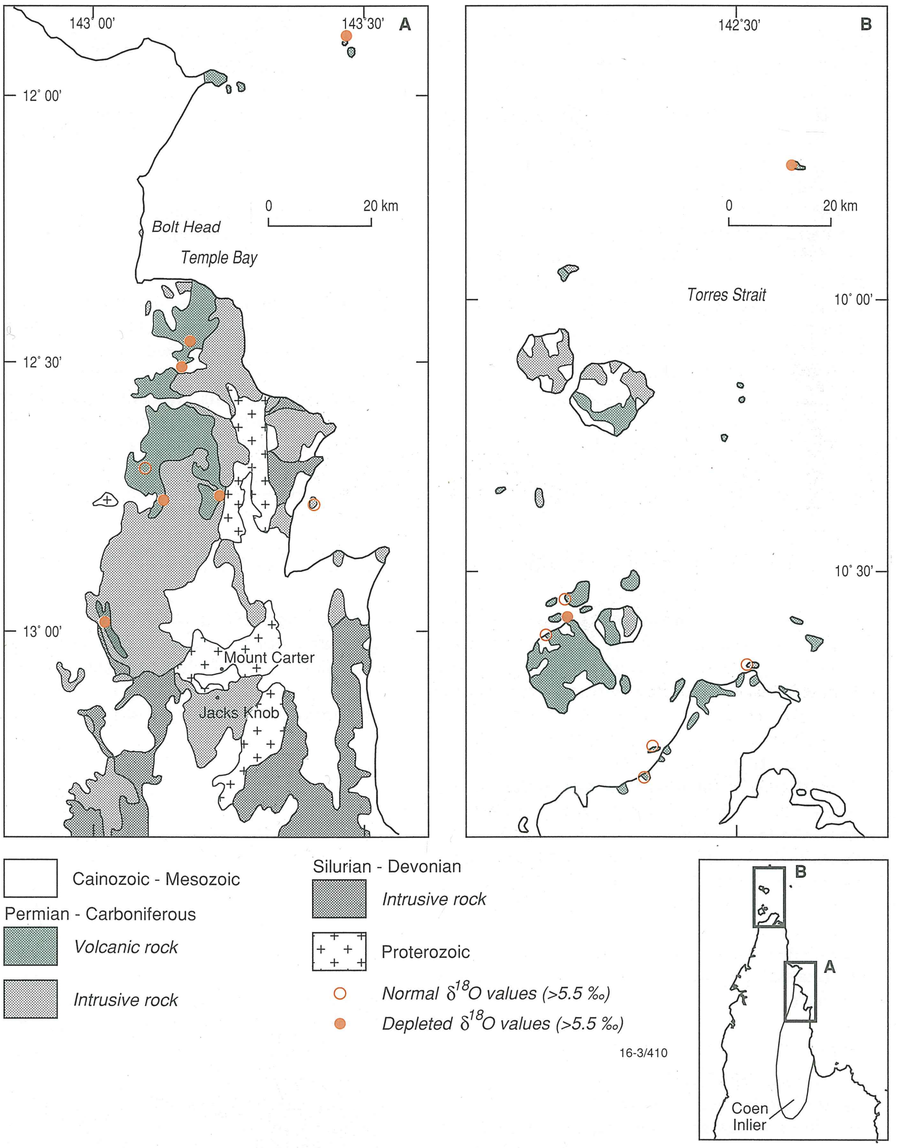

Fig. 1. Simplified geology and measured $\delta^{18}O$ values for volcanic rocks in the northern Coen Inlier (A) and Torres Strait region (B).

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rocks. Weathered rocks were avoided because low-temperature processes cause ^{18}O enrichment and obscure any ^{18}O depletion.

The isotopic data indicate that two of the Torres Strait samples are ^{18}O-depleted (Fig. 1B). Of greater interest is a zone of consistent ^{18}O depletion in the northern Coen Inlier, where six out of eight samples have low $\delta^{18}O$ values (+1.3 to –2.7 per mil; Fig. 1A).

The results for part of a regional stream-sediment survey (one sample per 10–15 km^2) in the Coen Inlier north of 14°S are plotted for Au and a multi-element index of pathfinder elements characteristic of epithermal gold deposits (Fig. 2). The index is the sum of standardised values for the five elements, and was calculated according to the equation:

$$\text{Index} = \sum_{e=1}^{e=5} [X_e - \overline{X}_e]/S_e$$

where X_e is the element value for a sample, $\overline{X}_e$ is the population mean for that element, and S_e is its standard deviation. High Au values relate to known Au mineralisation at Iron Range and Wenlock. However, the multi-element index indicates a highly anomalous region immediately south of Temple Bay that broadly coincides with the area of regional ^{18}O depletion north of the Pascoe River and south of Temple Bay. No stable-isotope data are available for an area about 80 km due south near Mount Carter and Jacks Knob, where the multi-element values are moderately high; this area broadly corresponds with the southernmost outcrop of the Early Permian Weymouth Granite.

The results of an examination of enhanced Landsat Thematic Mapper imagery in the region south of Temple Bay, for evidence of clay and silica alteration normally associated with epithermal systems, were inconclusive, largely owing to the masking effects of vegetation.

A compilation of previous mineral exploration activity (Culpeper & others, 1992: *Queensland Resource Industries, Record* 1992/10) reveals that parts of the ^{18}O-depleted area have been covered for short periods since 1951 by Authorities to Prospect and Exploration Permits for Cu, U, Au, Sn, and W. Notable among these were three Authorities (AP 3815M, AP 4329M, and AP 5019M) held between 1984 and 1988 over parts of the Kangaroo River Volcanics in the Temple Bay area. Although these Authorities were relinquished, evidence of epithermal mineralisation was apparent to the companies that had held them. These companies established from rock-chip and stream-sediment samples that anomalous Hg, As, Sb, and Au (elements typically concentrated in epithermal deposits) were present: most attention was focussed on prospects around the margins of Temple Bay (Bolt Head, Lake Anomaly and Glennie Inlet). However, the regional oxygen-isotope and stream-sediment data suggest that the area with epithermal mineralisation potential may be larger, and that a more systematic and thorough evaluation of the area could be warranted.

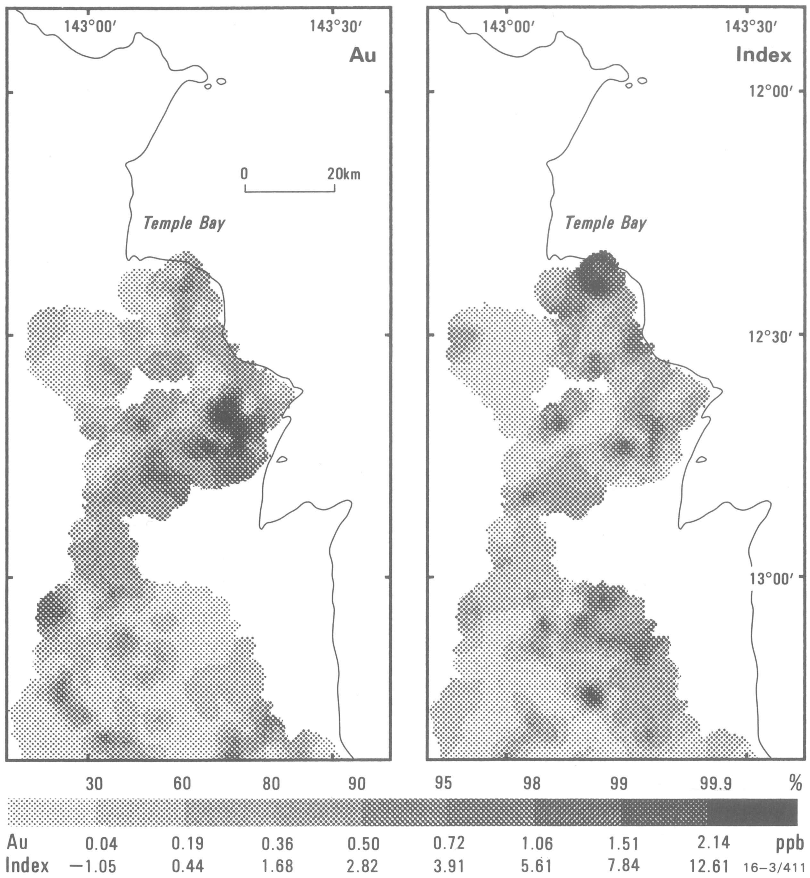

Fig. 2. Geochemical images of Au and a multi-element index derived from Ag, As, Au, Sb, and Tl. The randomly spaced element or index values were interpolated to a square grid and imaged as shown.

For more information, contact Dr Greg Ewers (stable isotopes) or Dr Bruce Cruikshank (stream-sediment geochemistry) at AGSO (Minerals & Land Use Program).

The Australian groundwater quality assessment project

Groundwater is an important resource in rural and urban Australia, where it is extracted for drinking, industrial, and agricultural purposes. About 20 per cent (but considerably more in the arid interior) of the nation's water requirements are presently met by groundwater. The already apparent degradation in the quality of our surface water resources emphasises the need to manage our groundwater resources so as to ensure the sustainability of ecosystems and economic activities which depend on them. After two years of reconnaissance studies, AGSO has received additional funds for three years (1993–96) to commence an assessment of groundwater quality in key areas of national priority.

What is groundwater quality?

Groundwater quality is determined by both natural and human activities. In addition to pollution from human activities, many naturally occurring substances can make groundwater from demonstrably pristine aquifers unsafe or unsuitable for a variety of uses. The acceptability of groundwater for use or disposal can be assessed when we know what is in the extracted water, and just how much is present.

One of the most familiar indicators used to assess groundwater quality is its salinity; increasing salinity has a serious impact on agricultural sustainability. Other factors can make groundwater of otherwise acceptable quality unsuitable for human consumption or for agricultural and industrial uses — especially high concentrations of fertilisers, pesticides and other toxic organic contaminants, heavy metals and other elements, and micro-organisms of faecal origin.

A disquieting lack of information about the

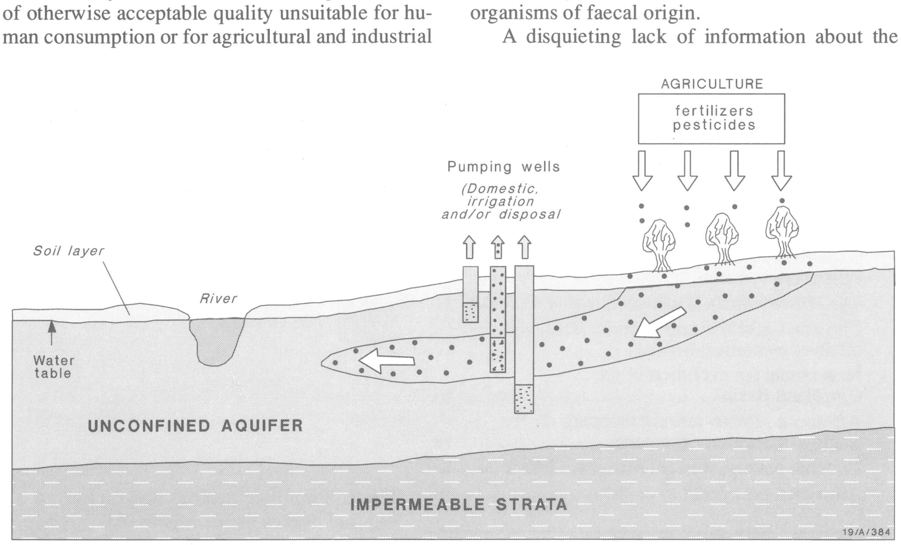

Fig. 3. Interaction between the application of agrichemicals, the movement of groundwater to adjacent surface water, and the withdrawal of underlying groundwater for domestic, irrigation, and other uses.

Fig. 4. Irrigation areas investigated during the reconnaissance phase of AGSO's Australian groundwater quality assessment project: 1, Shepparton East; 2, Berriquin–Denimein; 3, Padthaway; 4, Burdekin Delta.

quality of Australia's groundwater resources is of growing concern to water managers in all States. Agrichemicals (e.g., insecticides, herbicides, fungicides, and fertilisers) continue to be applied extensively in key areas of irrigated agricultural production throughout the nation. Groundwater resources underlying these areas are commonly exploited for domestic and town-water supplies too, and pumped to adjacent surface waters for disposal (Fig. 3). The impact of these activities is both poorly documented and poorly understood, yet has potentially far-reaching health, environmental, and economic significance for natural-resource management.

Objectives, activities, and outcomes

Knowledge of the present status of groundwater quality, and a clear understanding of the biogeochemical processes which determine this, are prerequisites to managing one of our nation's essential natural resources. AGSO's *Australian groundwater quality assessment project* will ascertain baseline conditions in key groundwater-resource areas, and monitor them for subsequent changes using best-practice sampling and analytical techniques. Monitoring them will enable us to assess the performance of natural-resource management practices, which will depend on the integration of the monitoring data with a clear understanding of the hydrogeological and biogeochemical processes occurring within and adjacent to the monitored area. Interpretation of the accumulating groundwater-quality data will identify specific processes for detailed investigation. These may include the hydrogeological controls on microbial denitrification (conversion of nitrate to nitrogenous gases) within contrasting aquifer systems, and the geochemical constraints on pesticide degradation in aquifer environments.

Study areas will be selected in consultation with State water agencies and the Murray–Darling Basin Commission. Whereas early priority may be given to catchments where groundwater is used for both agriculture and town supply, relatively pristine areas and those from which groundwater is disposed to adjacent surface water are likely to be selected for study in the longer term.

The project is expected to make major contributions to, firstly, the initiation and establishment of a national groundwater quality database (NGQDB) and, secondly, the scientific knowledge base required for rational implementation of the National Water Quality Management Strategy, which includes National Guidelines for Groundwater Protection. An NGQDB would be a powerful resource for management decision-making and policy formulation from a national perspective. While it is envisaged that an NGQDB would operate within a GIS environment, and that data would be shared and exchanged with State agencies, the final form will be determined after consultation with interested State and Commonwealth agencies.

A taste of AGSO groundwater quality data

AGSO's reconnaissance studies have concentrated on areas of irrigated agriculture, principally in the Murray Basin of southeast Australia (Fig. 4). These areas were selected because groundwater resources underneath irrigated agricultural land are likely to be at greatest risk of contamination. Groundwater quality was assessed by measuring a plethora of parameters, including both dissolved and particulate indicators of accession to the water-table. Data sets for two classes of substances of concern provide an interesting and instructive contrast.

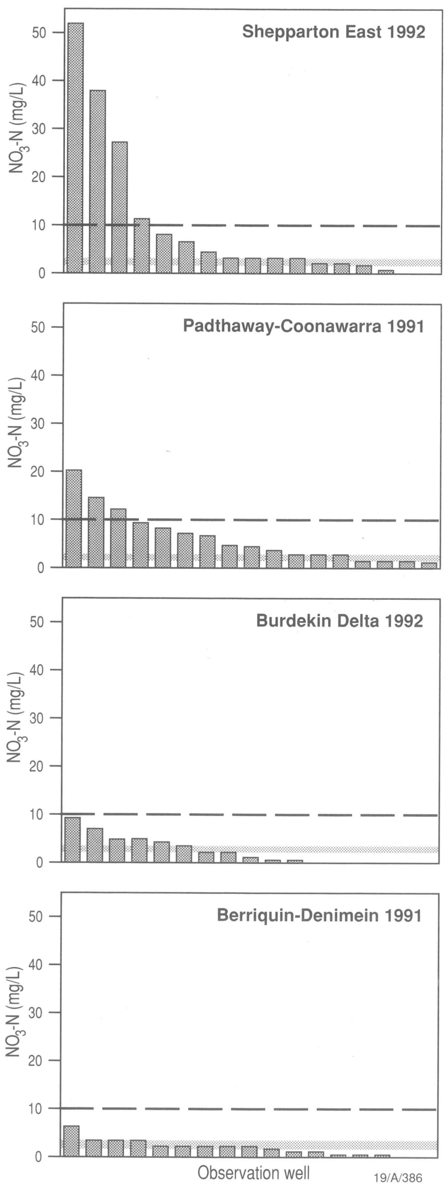

Fig. 5. Nitrate concentrations in groundwater from unconfined aquifers underlying irrigated agricultural areas with contrasting hydrogeological characteristics and agricultural activities (see Fig. 4 for locations). For each area, the WHO drinking-water recommended maximum limit of 10 mg L^{-1} NO_3-N and the usual boundary between pristine and contaminated groundwater (2–3 mg L^{-1} NO_3-N) are indicated.

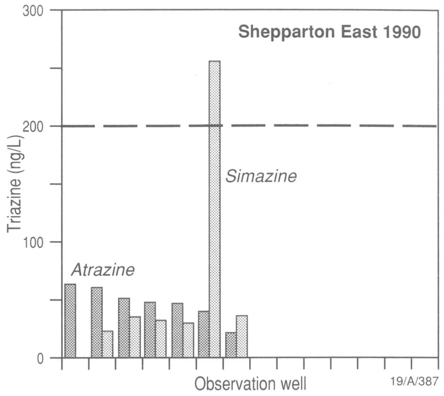

Fig. 6. Triazine herbicide concentrations in groundwater underlying irrigated agriculture in the Shepparton East area. The dashed line indicates the NH&MRC proposed draft standard (200 ng L^{-1}) for simazine.

Nitrate is both naturally present in water and soil and applied to agricultural land as a fertiliser component. Nitrate concentrations in groundwater samples underlying forest or grassland are reported to be generally less than 2 mg L^{-1} NO_3-N, while concentrations greater than 3 mg L^{-1} are considered to be indicative of contamination by human activities (though high concentrations occasionally arise as a consequence of natural processes). The World Health Organization (WHO) has defined an upper limit of 10 mg L^{-1} NO_3-N for drinking water.

NO_3-N concentrations in groundwater that AGSO sampled from four unconfined aquifers (Fig. 5) show substantial variation. Only in the Padthaway and Shepparton East areas did samples exceed the WHO limit (ca 20% of samples for both), yet all four areas yielded samples which exceeded the 3 mg L^{-1} level. The proportion of samples exceeding this level varied from one area to another (Padthaway–Coonawarra ca 60%, Shepparton East ca 40%, Burdekin ca 30%, Berriquin–Denimein ca 10%), which presumably reflects the sum of differences in variables such as fertiliser application, irrigation practice, hydrogeological properties of subsurface environments, and relative rates of bacterial denitrification.

Atrazine and simazine are members of a class of herbicides called triazines. Limits for drinking water vary worldwide but, in Australia, the National Health and Medical Research Council (NH&MRC) has proposed draft standard limits of 500 and 200 ng L^{-1} respectively for atrazine and simazine. One or more triazine herbicides were detected in 50% of groundwater samples taken from observation wells in the Shepparton East area (Fig. 6), though in only one sample were the draft standards (for simazine) exceeded.

Our data show that nitrate and triazines have reached the groundwater underlying at least some irrigated agricultural areas, and emphasise the need for a systematic nationwide assessment of groundwater quality commencing with those key areas regarded as high priority because of their probable vulnerability.

For further information, contact Dr John Bauld (Environmental Geoscience & Groundwater Program, AGSO).

Connecting the Riverina and Waroonga Gneisses, Eastern Goldfields

The Waroonga Gneiss west of the Agnew anticline, and Riverina Gneiss 160 km to the south, are shown to be parts of a continuous gneiss domain which crops out sporadically through central western LEONORA*. East of the Agnew anticline, the Perseverance Gneiss has a magnetic signature similar to that of the gneiss domain. These observations, coupled with structural and lithological relations, reinforce the view that the gneisses are uplifted rocks that represent basement to the greenstones in the area.

Gneiss cropping out in small areas on the western margin of the Eastern Goldfields Province (Fig. 7) is represented, in particular, by the Riverina Gneiss in MENZIES, and the Waroonga Gneiss and Perseverance Gneiss in LEONORA and SIR SAMUEL. Mapping the distribution of these units, however, has been hindered by poorly exposed granitoids, particularly in LEONORA. As part of the National Geoscience Mapping Accord, AGSO acquired complete aeromagnetic coverage of LEONORA along lines 400 m apart, and has accordingly been able to map the extent of the gneisses there. Detailed geochemical, isotopic, and petrographic studies, combined with an interpretation of the aeromagnetic images, are currently under way.

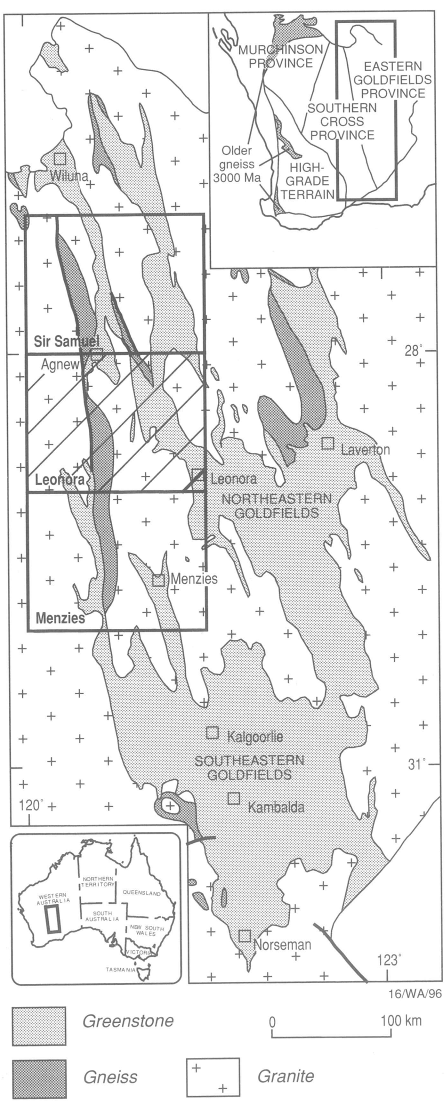

Fig. 7. Distribution of gneiss in the Eastern Goldfields Province (after Myers & Hocking, 1988: 'Geological map of Western Australia', *GSWA*).

An interpretation of the new aeromagnetic data shows seven structurally distinct domains (Fig. 8).

The central gneiss domain

The central gneiss domain comprises complexly deformed banded felsic gneiss with migmatite patches and abundant felsic intrusions. The gneiss varies from moderately homogeneous to strongly banded, and locally migmatitic, at scales of millimetres to tens of metres; the banding is defined by compositional and grainsize differences.

The gneiss comprises plagioclase, biotite, quartz, and alkali feldspar; compositions range from biotite-rich granodiorite and tonalite to leucogranodiorite and adamellite. Accessory minerals include opaques, zircon, apatite ± garnet, sphene, and allanite?; secondary minerals are sericite, muscovite ± epidote, calcite, titanite, and chlorite. Deformational and metamorphic effects are evident from the foliation, lepidoblastic and granoblastic textures, common tartan twinning, variable perthite development in alkali feldspar, and common occurrence of myrmekite. Original igneous features are locally evident in oscillatory-zoned plagioclase.

Variably deformed veins of aplite, pegmatite, syenite, and microgranite cut the gneiss, both parallel and oblique to the gneissic foliation. Cross-cutting veins are commonly folded and contain only the regional upright foliation as the axial fabric. These relationships suggest that there were several episodes of vein emplacement.

Mafic amphibolite lenses form a small but significant component of the gneiss. They have the assemblage hornblende (brownish green), clinopyroxene, plagioclase, quartz, titanite ± garnet, epidote, and ilmenite. The amphibolite locally contains irregular felsic patches which appear to be derived by partial melting of the amphibolite. Rare pelitic lenses consist of muscovite–biotite–chlorite schist containing relict kyanite. These assemblages are appropriate to the upper amphibolite facies. They contrast with the distinctly lower metamorphic grades of the adjacent greenstone domains, which contain greenschist or, at most, lower-amphibolite-facies assemblages.

On the aeromagnetic images, the gneiss has prominent, laterally persistent bands which are truncated in places by subparallel faults. Faults also define a number of lenses in the gneissic layering, which suggests that primary layer-parallel extensional or thrust-faulting was important in the structural development of the gneiss.

Large granitoid bodies intrude the gneiss, which must have existed as an earlier felsic component. The asymmetric lens shape of the larger intrusions within the gneiss (Fig. 8) suggests that they may be syntectonic in a dextral simple shear environment. However, the intrusions are composite and internally undeformed. They do not contain a significant component of late dykes or enclaves, and so also probably postdate the intrusion of those components in the gneiss.

Across the north central part of LEONORA, the central gneiss domain is about 60 km wide. Along its eastern margin, it has complex tectonic relations with the adjacent greenstone. The pattern of deformation in the north-northwest-trending greenstone, into which the large north-trending structures in the gneiss domain swing, indicates major regional sinistral shear parallel to the greenstone. This shearing has severely disrupted the margin of the gneiss domain, in which narrow north-trending bands of gneiss are interleaved with thin sheets of greenstone. Structures are parallel to the bedding in the greenstone and layering in the gneiss, which suggests that the original deforma-

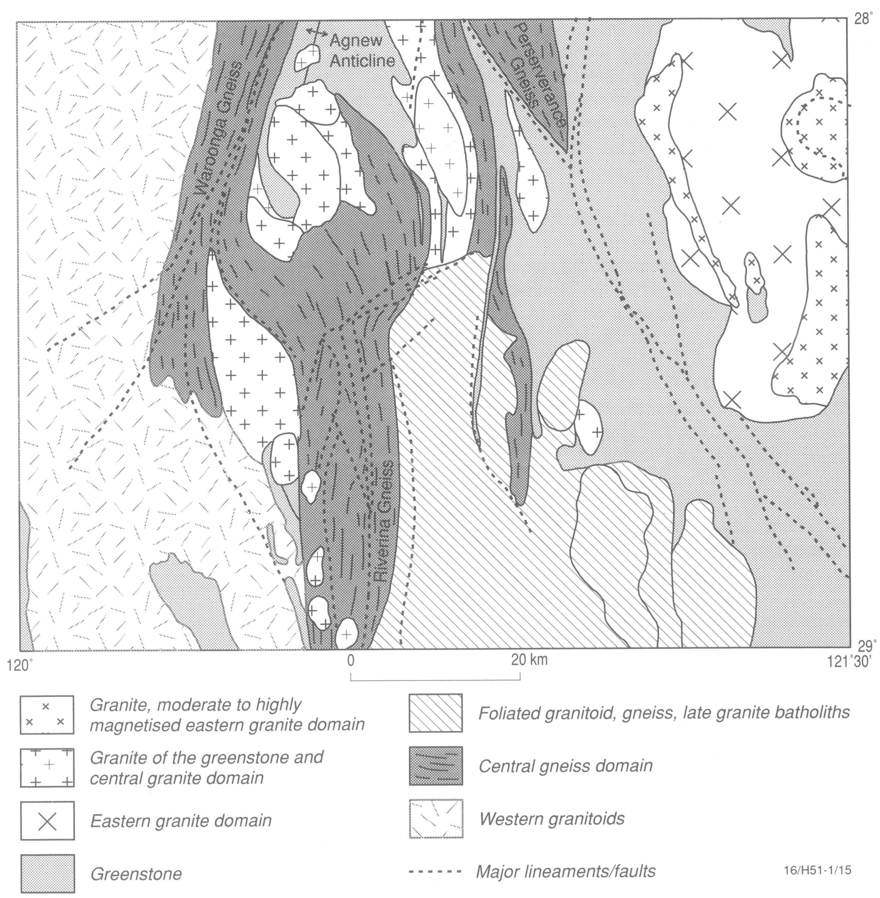

Fig. 8. Generalised geology of LEONORA based on interpretation of the recently acquired aeromagnetic data.

* Names of 1:250 000 Sheet areas are printed in capitals.

tion was related to uplift of the gneiss. Without the early layer-parallel deformation, an excessive amount of strike-slip displacement and flattening would have been needed to produce the outcrop pattern. However, the overprint of northerly trending regional upright folds and later strike-slip faults in the greenstone (including that in the Agnew anticline) has severely disrupted the original relationship between the gneiss and greenstone.

Conclusion and regional significance

The aeromagnetic images show that gneiss constitutes a north-trending domain extending across LEONORA, connecting the Waroonga and Riverina Gneisses and linking the geology of two previously disparate areas. The Perseverance Gneiss, which is magnetically similar to both units, forms an outlier of the central gneiss domain.

The presence of a continuous thick sequence of upper-amphibolite-facies gneissic and migmatitic rocks along the western margin of the Eastern Goldfields Province mirrors that along the eastern margin (C.Swager, GSWA personal communication 1992), suggesting that the Province has a regional symmetry. The presence of regional extensional shear zones bounding the greenstone at Leonora (*BMR Research Newsletter* 12, 8–9), and the recent recognition of the regional significance of the internal gneiss domes and the steep regional metamorphic gradients (Williams & Whitaker, 1993: *Ore Geology Reviews*, 8, 1–22), suggest that the gneiss domains on either side of the Province might be metamorphic core complexes uplifted during regional extension. However, they could equally well represent uplifted rift-margin rocks associated with a later graben-forming event. Both marginal gneiss domains have been extensively intruded by later granitoids, suggesting that high heat flow and crustal recycling were an integral part of the tectonic environment in which gneiss emplacement occurred.

For more information, contact Dr Peter Williams, Dr Morrie Duggan, Mr Alan Whitaker, or Dr David Champion (Minerals & Land Use Program, AGSO).

Extension of the Woodroffe Thrust, Musgrave Block, into Western Australia

The Woodroffe Thrust in the Musgrave Block, central Australia, is part of a major system of south-dipping thrust-faults that penetrate the continental crust on the southern margin of the Amadeus Basin (Fig. 9). Detailed mapping by AGSO in the Western Australian segment of the Musgrave Block, as part of the National Geoscience Mapping Accord (NGMA), has shown that the Woodroffe Thrust extends 200 km farther west than its previously known exposure.

The Musgrave Block (Fig. 9) consists chiefly of metavolcanics and metasediments intruded by layered mafic intrusions (Giles Complex), granites, and mafic dykes. Metamorphic facies ranges from amphibolite to granulite. The parent volcanics and sediments accumulated between about 1550 and 1330 Ma, and were metamorphosed at about 1200 Ma (e.g., Sun & Sheraton, 1992: *AGSO Research Newsletter* 17, 9–11). Renewed tectonism formed major east-striking thrust-faults ranging from low to high-angle, including the Woodroffe Thrust, at about 550 Ma (e.g., Maboko & others, 1992: *Australian Journal of Earth Sciences*, 39, 457–471). These thrusts formed in response to north–south compression of the Australian plate, which transmitted stress from the plate margins to the continental interior (Shaw, 1991: *Bureau of Mineral Resources, Australia, Bulletin* 236, 429–461).

The Woodroffe Thrust dips south at 20–30°, and separates high-grade metamorphic rocks in the south from moderate-grade metamorphics in the north. It has been interpreted as the root zone of the Petermann Ranges Nappe at the southwest margin of the Amadeus Basin (Fig. 9). In the Amata (SA) and Kulgera (NT) areas, northward movement on the thrust is well documented (Collerson & others, 1972: *Journal of the Geological Society of Australia*, 18, 379–393; Edgoose & others, in press: Kulgera 1:250 000 Geological Map and Explanatory Notes, SG53-5 [second edition], *Northern Territory Department of Mines & Energy*).

Before the recent NGMA mapping, the most westerly known exposure of the Woodroffe Thrust had been about 30 km west of Amata (Fig. 9). The thrust was inferred from aeromagnetic contour data to exist farther west (Forman, 1972: Petermann Ranges 1:250 000 Geological Sheet and Explanatory Notes, SG52-7 *BMR*; Forman & Shaw, 1973: *BMR Bulletin* 144; D'Addario & others, 1976: 'Geology of the Northern Territory', 1:2 500 000 geological map, *BMR*). Pharaoh (1990: *BMR Record* 1990/5, pl. 2) interpreted from reprocessed aeromagnetic data an extension of the thrust into Western Australia, but no field exposures of it were known there.

The considerable tectonic significance of the Woodroffe Thrust, and the question of its existence in Western Australia, prompted AGSO to conduct detailed mapping in the Bates 1:100 000 Sheet area (Fig. 9) as part of the Musgrave NGMA project in 1991. The results included the discovery and delineation of a major east-striking mylonite zone precisely at the predicted position of the Woodroffe Thrust.

The mylonite zone is about 1 km wide (Fig. 10). It separates granulite-facies garnet–hornblende granite patchily recrystallised to eclogite (Clarke & others, 1993: *AGSO Research Newsletter*, this number, pp. 6–7) that was thrust over amphibolite-facies granitic gneiss to the north.

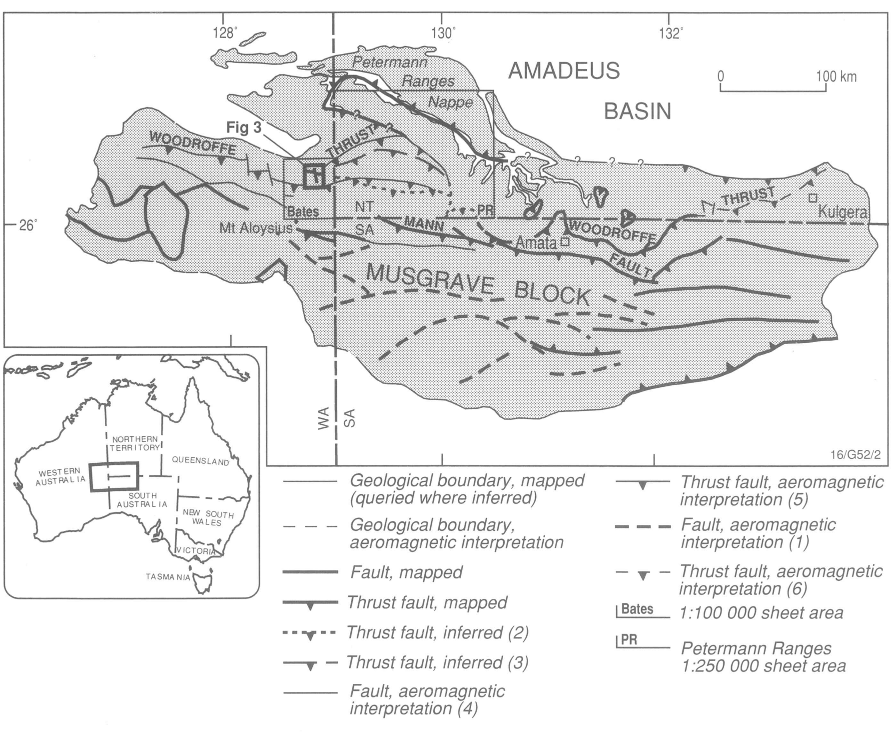

Fig. 9. Structure of the Musgrave Block. [1]A.J. Stewart (AGSO; unpublished data); [2]Forman (1972); [3]D'Addario & others (1976); [4,5]Pharaoh (1990); [6]Edgoose & others (in press); see text for abbreviated bibliographic references.

Deformational effects near the mylonite zone

Garnet–hornblende granite south of the mylonite zone has patchily recrystallised to a fine grainsize enclosing relics of K-feldspar. In the east, 1 km south of the mylonite zone (Fig. 10), the granite is cut by seams of mylonite up to about 1 m thick.

The granitic gneiss north of the mylonite zone is more widely affected by the faulting than the garnet–hornblende granite south of the mylonite. The gneiss is generally mylonitic and cut by mylonite seams; in places, however, it is recrystallised to a fine-grained mosaic. Four kilometres north of the mylonite zone, recrystallised blows of generally massive fine-grained vein quartz occur throughout a northwest-trending belt 5 km long (Fig. 10).

Mylonite zone

The mylonite zone is derived from the granitic gneiss, and displays a transition in rock type, as follows:

- along the northern and southern margins of the zone, the gneiss is sliced by numerous anastomosing mylonite shear bands; these are a few centimetres thick and 10–20 cm apart in the north, a few metres thick and several metres apart in the south;
- near the centre of the zone, fine-grained schistose friable mylonite with small feldspar augen is intensely foliated and lineated; and
- in the centre of the mylonite zone, the most intensely deformed rock comprises thin gently south-dipping alternating layers of black aphanitic ultramylonite and pale mylonitic granitic gneiss; steeply dipping extensional shear bands of mylonite cross-cut the gently dipping mylonite and gneiss.

All the granitic mylonitic rocks consist, in various proportions, of angular bent clasts of K-feldspar, sericitised plagioclase, and hornblende (in some samples), and a streaky groundmass of ribbon quartz and microcrystalline K-feldspar and uniformly oriented biotite aggregates. A mafic dyke with altered garnet relics in the mylonite zone is metamorphosed to actinolite, bleached biotite, and sericitised plagioclase.

The mylonite zone is cut by a north-striking cross or tear-fault which also has mylonite along it similar in grade to that along the east–west fault, implying that the two faults formed at the same time.

Structure

Foliation trends throughout the southern granite and northern gneiss terranes are at large angles, and hence are unrelated, to the east–west mylonite zone (Fig. 10). The lineation in the mylonite zone is almost everywhere subhorizontal to gently west-plunging, and indicates an east–west movement direction. Kinematic indicators were observed at only four locations (Fig. 10): two indicate movement of the top block to the west, and two indicate movement of the top block to the northeast. The scarcity of shear indicators suggests that the fabric is not markedly asymmetrical, because large strain produced almost parallel shearing and flattening planes.

Tectonic significance

The east–west lineation and hence movement direction in the mylonite zone are nearly parallel to the general strike of the mylonite zone, and differ from the northward overthrusting recorded on the Woodroffe Thrust in the Amata and Kulgera areas. Neverthless, the low dip of the Bates mylonite zone, and the thickness of the mylonite exposures, resemble features of the Woodroffe Thrust, and support the interpretation that the thrust extends into Western Australia. Mapping of the hitherto unmapped isolated exposures north of the Mann Range in the southwest Petermann Ranges 1:250 000 Sheet area should locate the Woodroffe Thrust there also.

For further information, contact Dr Alastair Stewart (Minerals & Land Use Program, AGSO), or Dr Geoff Clarke (Department of Geology & Geophysics, University of Sydney).

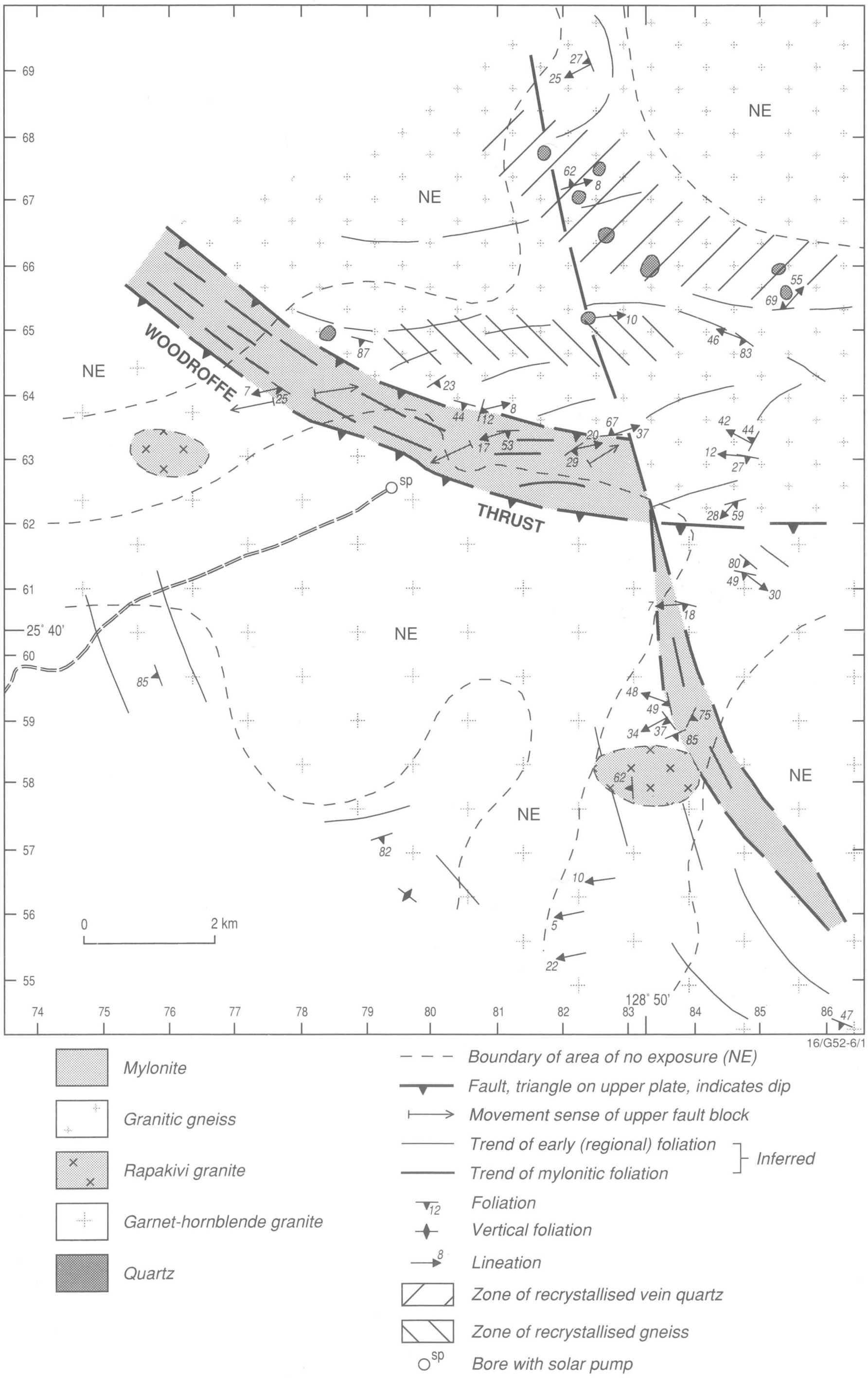

Fig. 10. Geological map of the mylonite zone, Bates 1:100 000 Sheet area (WA). Numbered ticks are 1 km intervals of the Australian Map Grid, Zone 52.

High-pressure granulite to eclogite-facies metamorphism in the western Musgrave Block, central Australia

Recent studies of the central Australian Precambrian crust in the western Musgrave Block have revealed assemblages representing the transition from garnet–mafic granulite to the eclogite facies. These assemblages reflect two stages of pressure increase from about 400 to above 1000 MPa: (1) garnet–hornblende assemblages of felsic gneisses formed under high-pressure granulite-facies conditions of ca 1100 MPa (T = 650°C), postdating 1185-Ma granites and coinciding with penetrative mylonitic D3 deformation; (2) garnet–clinopyroxene assemblages that developed under subsequent eclogite-facies conditions of ca 1300 MPa (T = 700–750°C) pervade mylonites and form coronas around orthopyroxene in post-D3 mafic dykes south of the Woodroffe Thrust. The older event may reflect crustal thickening following the emplacement of thick (>5 km) mafic–ultramafic sills of the Giles Complex. Isotopic dating will have to be applied to establish the relationship between the younger event and the Late Proterozoic to Cambrian Woodroffe Thrust.

Mineralogical studies of the layered mafic/ultramafic Giles Complex and associated felsic granulites and granites of the western Musgrave Block provide an insight to the pressure–temperature–temporal (PTt) evolution of the Musgrave Block. Goode & Moore (1975: *Contributions to Mineralogy & Petrology*, 51, 77–97) recorded P in the range of 1000–1200 MPa from mineral assemblages in some of the Giles Complex intrusions (e.g., Ewarara, Kalka, and Gosse Pile). These pressures were calculated from subsolidus reactions between (1) olivine (ol) + plagioclase (plg) to produce orthopyroxene (opx), clinopyroxene (cpx), spinel (sp), and Ca-poor plg; (2) opx + plg to produce garnet (gnt); and (3) sp + opx to produce gnt. Also, Ballhaus & Berry (1991: *Contributions to Mineralogy & Petrology*, 32, 1–28) have shown that the Wingellina Hills gabbronorite–pyroxenite body cooled isobarically from T = 1150 to 750°C under pressures of ca 650–620 MPa, based on the reaction of ol + plg to produce symplectites of opx–cpx–sp, ol–sp, and cpx–sp.

Recent thermobarometric measurements of mineral assemblages from samples collected as part of the National Geoscience Mapping Accord project in the Musgrave Block have produced the results documented below.

(1) Gnt–opx-bearing granulites from Mount Aloysius (Fig. 9) preserve coarse-grained mineral assemblages formed under moderately low pressures of ca 400 MPa (T = 750°C). An Rb–Sr isochron age of 1200 Ma for the granulite metamorphism (Gray, 1978: *Journal of the Geological Society of Australia*, 25, 403–414) is correlated with D1 and D2 deformation (Clarke & others (1992: *AGSO Research Newsletter*, 17, 6–8). Core-to-rim zonation of garnet reflects subsequent cooling.

(2) Porphyritic hornblende (hbl)–biotite (bi) granitoids in the Tomkinson Ranges (western Musgrave Block) represent an 1185-Ma intrusive event (Sun & Sheraton, 1992: *AGSO Research Newsletter*, 17, 9–11) which either accompanied or closely followed emplacement of the Giles Complex. These rocks recrystallised to gnt–hbl gneisses during the development of a mylonitic D3 foliation. These assemblages were formed at ca 1100 MPa (T = 650°C) — more than twice the pressure of the D1–2 granulite metamorphism.

(3) Coarse-grained gnt and opx in Mount Aloysius felsic granulites are surrounded by syn-

D3 to post-D3 gnt–opx–plg symplectites, indicating decompression to ca 450 MPa. This decompression is correlated with the formation of spinel–cordierite coronas surrounding gnt in pelitic gneisses at Cohn Hill, about 90 km west of Mount Aloysius (Clarke & Powell, 1991: *Journal of Metamorphic Geology*, 9, 440–451).

(4) Gnt–cpx assemblages occur within ultramylonite zones which cut the granulite-facies hanging block south of the south-dipping Woodroffe Thrust (see previous article). These assemblages may predate, or are contemporary with, the Woodroffe Thrust, which contains hydrous upper-greenschist to upper-amphibolite-facies (biotite–sericite ± amphibole) assemblages. The overlying thrust-sheet also contains post-D3 mafic dykes that recrystallised to gnt–cpx–hbl–plg–rutile–quartz assemblages, and preserve mineral coronas of metamorphic gnt–cpx-bearing symplectites around magmatic opx and cpx grains (Fig. 11).

Thermobarometric measurements applied to the recrystallised mafic dykes yields pressure estimates of up to 1300 MPa (T = 700–750°C). These PT estimates overlap the range between the uppermost garnet–mafic granulite and the lowermost eclogite fields (e.g., Holland, 1983: *Contributions to Mineralogy & Petrology*, 82, 214–220), as reflected by the mole fraction of albite in plg (<0.7), the jadeite content of cpx (<0.12), and the grossular content of gnt (<0.3). The gradational relation between these components as end-members of solid solution in cpx and gnt complicates the definition of the above metamorphic fields. However, the occurrence of rutile and scapolite in the post-D3 dykes, which contrasts with the occurrence of hematite in the syn-D3 granulites, is correlated with group C eclogite-facies rocks elsewhere (Coleman & others, 1965: *Bulletin of the Geological Society of America*, 76, 483–508). Further, the mineral assemblages and PT estimates correlate with retrograde kyanite-bearing eclogite-facies shear zones near Amata (Fig. 9), where P and T were estimated as 1200 MPa and 850–900°C (Ellis & Maboko, 1992: *Precambrian Research*, 55, 491–506).

The foregoing and earlier studies suggest that the PT history of the western Musgrave Block (Fig. 12) reflects (1) an increase in pressure from the ca 1200-Ma D1–2 metamorphism to the post-1185-Ma D3 deformation; (2) late to post-D3 decompression; and (3) a sharp increase in pressure after both D3 and the intrusion of mafic dykes. The significant crustal thickening represented by the late-D3 PT values, which correspond to lithostatic

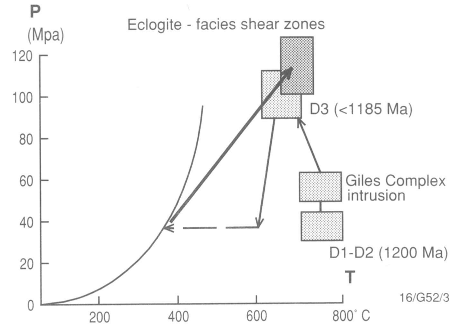

Fig. 12. Pressure–temperature relations for events in the Tomkinson Ranges. Boxes represent PT events, and the curve represents the continental geotherm.

pressures at depths of about 30 km, may be closely related to the emplacement of the thick (>5 km) dense mafic–ultramafic sills of the Giles Complex. The post-D3 sharp increase in pressure may reflect either: (1) that the granulites and mylonites south of the Woodroffe Thrust represent basal structural levels of the overlying south-dipping thrust-sheet, and originated in the crust at a depth of 30–40 km, or (2) that the eclogite-facies assemblages were developed in conjunction with Late Proterozoic to Cambrian movements along the thrust.

The results of this investigation accord with the observations of Goode & Moore (1975). Further work is needed to determine the significance, throughout the granulite-facies terrane, of PT variations suggested by others — for example, the decrease in pressures south of the Hinckley Fault (Nesbitt & others, 1970: *Geological Society of South Africa, Special Publication* 1, 547–564) and in possibly shallower crustal levels of the Blackstone, Cavanagh, and Jameson gabbroic intrusions to the west (Daniels, 1974: *Geological Survey of Western Australia, Bulletin* 123; Ballhaus, 1992: *AGSO Research Newsletter*, 16, 6–8).

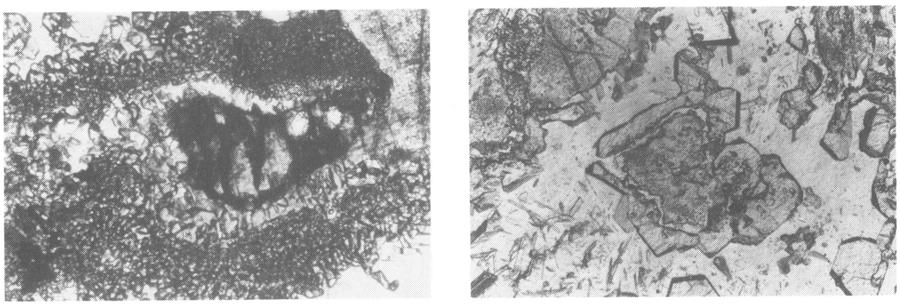

Fig. 11. Photomicrograph of an ophitic metadolerite dyke from south of the Woodroffe Thrust (see Fig. 9). *(left)* Structured corona around magmatic orthopyroxene. The lighter inner part of the corona is a symplectite of metamorphic clinopyroxene, plagioclase, and minor hornblende. The outer part of the corona is garnet–plagioclase symplectite. Base of photo = 1.5 mm. *(right)* A grain of magmatic clinopyroxene surrounded by a corona comprising an inner clear zone of metamorphic plagioclase–clinopyroxene symplectite, and an outer zone of well crystallised garnet and embayed plagioclase grains that preserve the subophitic texture of the dolerite. The chemistry of the metamorphic clinopyroxene and that of the magmatic grain are distinct. Base of photo = 3 mm.

For further information, contact Dr Geoff Clarke (Department of Geology & Geophysics, University of Sydney), Dr Alastair Stewart, or Dr Andrew Glikson (Minerals & Land Use Program, AGSO).

The Australian palaeoclimatic record
The key to future climate-change modelling

Predicted changes of climate in the immediate future, and their impact on human activities, are causing widespread concern at government and community level. The nature of future climate changes, however, needs to be set in the context of naturally occurring climatic cycles, and the geological record provides a key source of information on natural cycles on a variety of timescales. The role of palaeoclimatic information is threefold: it provides the broad context of naturally occurring change; it can be used to test global-climate models; and, with acknowledged qualification, it can provide analogues for the predicted enhanced greenhouse conditions of the future.

To fulfil these functions, information from the recent geological past needs to be accessible in formats suitable for manipulation in model tests. A considerable body of proxy climatic data is available for the Australian Quaternary — on lake and sea levels, vegetation patterns, sea and land temperatures, and hydrologic regimes. It is, however, currently widely scattered among individuals and institutions.

AGSO's Environmental Geoscience & Groundwater Program and Information Systems Branch are collaborating in the design of a database to store and manipulate information about climate in Australia during the Quaternary, which covers the last 2 million years. The database will run on the corporate Oracle relational-database-management system.

The climatic information is being extracted from the published literature, which shows that the Australian Quaternary mean annual temperatures varied from a few degrees warmer to 8–10°C colder than at present. Because climatic information is extracted from a wide variety of disciplines, the range of the database is correspondingly broad. A bibliography (*BMR Record* 1991/104), already published (in hard-copy and digital forms), serves as the source of the relevant information; at present it holds 1300 references.

Besides aiming to centralise information from widespread sources, the database will serve to make the data more uniform, and thus facilitate manipulation. Another objective is to produce a series of palaeoclimatic maps of Australia for different time-slices especially during the last glacial cycle. These will be of great use in understanding how the Australian region reacts to global changes in climatic conditions.

The embryonic database has a tripartite structure. The first part holds the 'sites' table, containing information about the location and current environment of study sites. The second part holds authors' results of investigations, expressed as a series of tables — each relating to a different branch of research: geochronology, geochemistry, palaeontology, palaeobotany, geomorphology, and palaeomagnetism. The third part contains the 'conclusions' table, storing climatic inferences.

The database design is expected to benefit from a small pilot scheme set up on Oracle. Data are being entered into the four tables so far erected — viz, 'sites', 'geochronology', 'geochemistry', and 'conclusions'. The 'conclusions' table structure is very general; at present, it will allow entry of all conclusions so as to gauge the types of fields necessary in the final structure. Tables for 'palaeobotany' and 'palaeontology' are being developed in collaboration with staff and students from the Department of Geology, Australian National University.

We are keen for more interaction with the Quaternary scientific community about the database design and what information should be stored in it. In the future it should become a place where new research information is entered and unpublished work stored. With ready external access it could become a key resource for those national and international researchers interested in the climatic environment of the Australian Quaternary.

For further information, contact Geoff Hunt or Dr Elizabeth Truswell (Environmental Geoscience & Groundwater Program, AGSO).

Prospective layered mafic–ultramafic intrusions in the East Kimberley

Recent field mapping by AGSO and the Geological Survey of Western Australia as part of the National Geoscience Mapping Accord Kimberley–Arunta project has re-evaluated the geological setting and economic potential of several of the Early Proterozoic layered mafic–ultramafic intrusions in the Halls Creek Orogen, East Kimberley. Within the orogen, the Lamboo Complex was produced by Early Proterozoic (1910–1830-Ma) sedimentation, deformation, metamorphism, and voluminous mafic and felsic volcanic and plutonic igneous activity and is situated between the Kimberley Basin and the Sturt Block of northwestern Australia. It contains one of Australia's largest concentrations of mafic–ultramafic intrusions prospective for different styles of stratiform and hydrothermal–remobilised platinum-group element (PGE), nickel, chromium, gold, titanium, and vanadium deposits.

New geological mapping in the McIntosh 1:100 000 Sheet area (Fig. 13) has redefined the distribution and differentiated the structural–metamorphic histories of the layered mafic–ultramafic intrusions previously mapped as the Alice Downs Ultrabasics and McIntosh Gabbro (Dow & Gemuts, 1969: *BMR Bulletin* 106; Gemuts, 1971: *BMR Bulletin* 107). The intrusions can be divided into three groups (Table 1) based on their relative age of emplacement, contact relations with country rocks, degree of fractionation, style and intensity of deformation, and types of mineralisation.

Geological setting and economic potential

Group 1 intrusions (1 to 9 in Fig. 13; Table 1) consist of rhythmically layered mafic–ultramafic bodies restricted to the area between the Halls Creek and Springvale Faults. They were intruded into the Tickalara Metamorphics, a complex sequence of sedimentary and igneous rocks that had previously undergone two periods of deformation and metamorphism (D1–M1 and D2–M2). They crystallised in situ, and evince chilled and contaminated contacts (e.g., poikilitic orthopyroxene related to silica contamination developed along basal contacts), narrow contact aureoles in which sillimanite locally crystallised, and thin comagmatic satellite intrusions in the country rocks adjacent to the main intrusion.

The group 1 intrusions were deformed by tight upright northwesterly trending folds, and metamorphosed under lower-amphibolite-facies conditions (D3–M3). They form steeply dipping bodies 0.2 to 2 km thick, and contain the highest ratio of ultramafic to mafic cumulates. A cyclic distribution of the rock types, and repeated occurrences of olivine-rich cumulates throughout the stratigraphy, indicate open-system fractionation that involved multiple injections of primitive magma pulses into the magma chambers. Chromitite layers (0.1 to 1.5 m thick) are associated with these more primitive pulses, and occur near the basal contacts of the ultramafic zones and in the middle of the mafic zones; these layers have greatest economic significance in an interval 5–150 m wide below the ultramafic–mafic-zone contacts.

Companies have generally focussed on the chromitite layers in the ultramafic zones, and have not thoroughly explored the higher stratigraphic levels of these bodies for different styles of stratiform and hydrothermal PGE–Au deposits. Group 1 intrusions are considered to be prospective for laterally extensive chromitite or sulphide-bearing pegmatoidal layers enriched in PGEs, Cu, Ni, and Au near the ultramafic–mafic-zone contacts, and for hydrothermal concentrations of PGEs and Au.

The Halls Creek Orogen is a province characterised by numerous occurrences of PGEs, multiple phases of igneous intrusion and metamorphism, and intensive faulting that has occurred over a prolonged period of time — all important parameters for the formation of hydrothermal–remobilised styles of precious-metal deposits. Shear zones traversing thick sequences of serpentinised olivine-rich cumulates and regions with widespread alteration features in the mafic zones should be a focus in the search for such deposits.

Group 2 intrusions (all mafic — e.g., West Panton and Wild Dog Creek; 10 and 11 in Fig. 13; Table 1) appear to intrude group 1 bodies east of the Springvale Fault. They are unaffected by D3–M3 and are metamorphically similar to group 3 intrusions. Their recessive sheet-like forms and more homogeneous compositions distinguish them from the group 3 intrusions. Lack of layering and cyclicity, and the high degrees of fractionation (as indicated by the abundant Fe–Ti oxides associated with dark red–brown soils), indicate that the group 2 intrusions have limited potential for base- or precious-metal resources.

Group 3 intrusions (12 to 22 in Fig. 13; Table 1) cross-cut the group 2 intrusions, and are the youngest and most common of the known layered bodies in the McIntosh Sheet area. They intrude the Tickalara Metamorphics east of the Springvale Fault, and occur within the Bow Granite batholith west of the fault. They are not tectonically dismembered fragments of a single large intrusive body, and typically form large basinal (e.g., Toby) and funnel-shaped (McIntosh) bodies with shallow to steep inward dips, or smaller fault-blocks (Togo) and troctolite plugs (Black Hills Yard). They are also unaffected by D3–M3, but predate late-orogenic dextral strike-slip movements on the Springvale and Halls Creek Faults (D4).

In-situ crystallisation of group 3 intrusions is evinced by chilled and contaminated contacts, and the development of sillimanite–K-feldspar–cordierite–garnet-bearing pelitic migmatites in narrow (50-m) contact aureoles. The larger, more tabular bodies have stratigraphic thicknesses of up to 7 km, and their discordant contacts with the country rocks indicate that the previously used term of sill for these bodies is incorrect. Minor (up to 15%) ultramafic cumulate components are commonly associated with the layered mafic rocks.

Group 3 intrusions are believed to be prospective for Au–PGE–Cu–Ni and/or Ti–V where magnetite is a cumulus phase in the upper parts of the

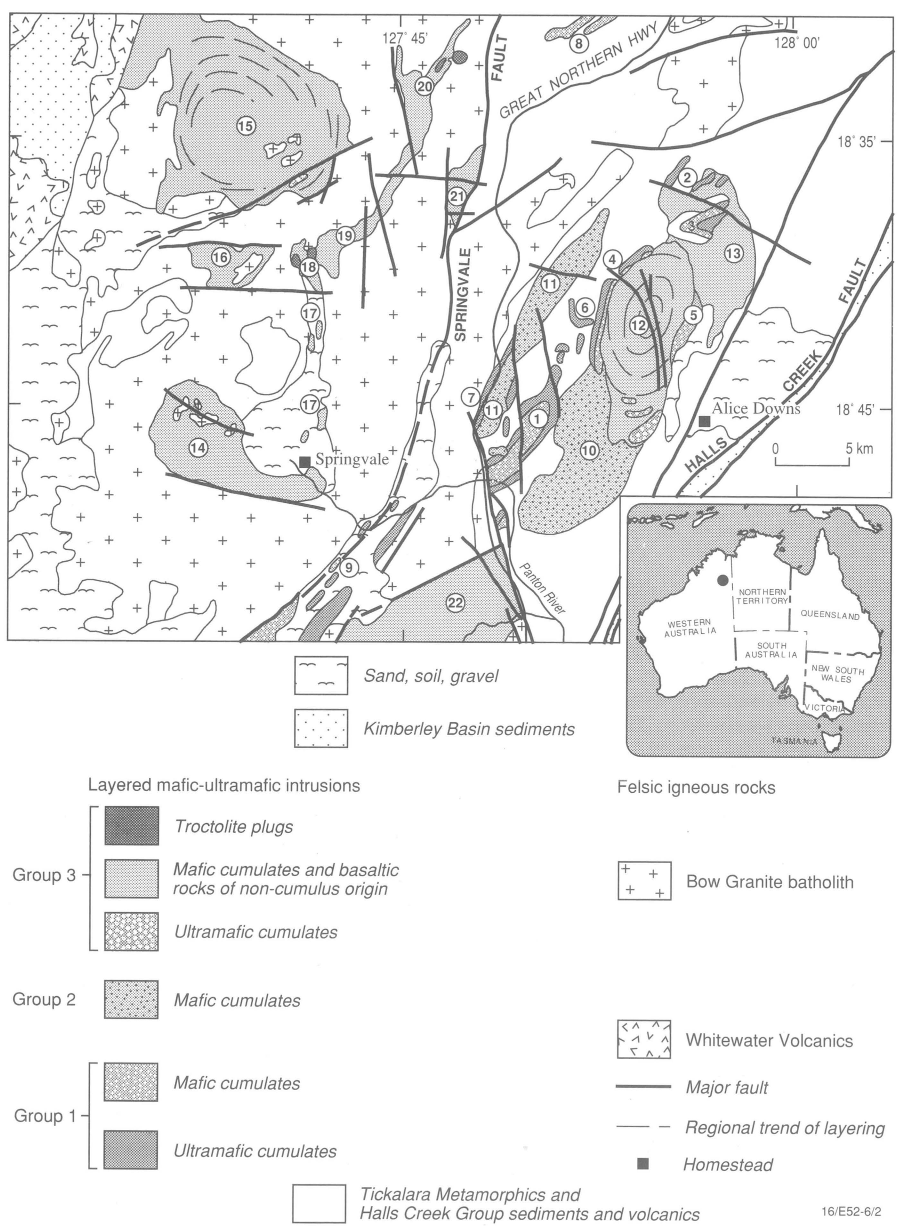

Fig. 13. Distribution of layered mafic–ultramafic intrusions in part of the McIntosh 1:100 000 Sheet area. Numbers refer to the names of intrusions listed in Table 1. Geology modified after Dow & Gemuts (1967: Dixon Range, WA, 1:250 000 Geological Sheet, SE52–6, *BMR*).

Table 1. Layered mafic–ultramafic intrusions investigated in the McIntosh 1:100 000 Sheet area, East Kimberley

Intrusion	Areal extent (km)	Approximate thickness (km)	Form	Surrounding rocks	Major rock types	Mineralisation documented
Group 1						
(1) Panton	3 x 12	1.6	Plunging syncline	Pelite, psammite, amphibolite, granite	Du, Ha, Cr, Tr-An, Gab, Gabn, N, AnG, An, Fg	Cr, PGEs, Cu, Ni, Au
(2) Melon Patch	3 x 3	?1	Steeply dipping sheets	Metavolcanic, calcsilicate, amphibolite, granite	Du, Cr, Amph, Tr-An, Gab, An, N	Cr
(3) South Melon Patch	2 x 4	1.5	Plunging anticline	Granite, amphibolite	Du, Cr, Ha, Amph, Tr-An, Gab, Gabn, N, AnG, An	Cr, PGEs
(4) West McIntosh	0.5 x 10	0.5	Steeply dipping sheets	Pelite, psammite, calcsilicate	Du, Cr, Amph, Tr-An, Gab, Gabn, N, An	Cr, PGEs
(5) East McIntosh	1 x 5	0.3	Steeply dipping sheet	Gabbro (McIntosh intrusion)	Amph, Gab, N, An, Du	
(6) Mini	0.3 x 3	0.2	Steeply dipping folded sheet	Pelite, psammite, granite	Du, Cr, Amph, Tr-An, Gab, N	Cr, PGEs
(7) Highway	0.3 x 10	0.2	Steeply dipping sheets	Pelite, psammite, granite, gabbro (West Panton intrusion)	Du, Cr, Amph, Tr-An, An	Cr, PGEs
(8) Ord River	0.5 x 3	?0.3	Steeply dipping sheets	Pelite, psammite, granite, amphibolite	Amph, Tr-An, An, Gab	
(9) Three Sisters	?1 x 12	?0.5	Steeply dipping sheets	Bow Granite batholith	Amph, Tr-An, Gab, Cr	Ni, Cu, Cr
Group 2						
(10) Wild Dog Creek	6 x 10	?2	Gently dipping sheets	Metavolcanic, calcsilicate, granite	Mlgab, MtGab, BiotGab, Dior, Amph	
(11) West Panton	2 x 2	?1.5	Gently dipping sheets	Pelite, psammite, granite	Mlgab, MtGab, BiotGab, Dior, Amph	
Group 3						
(12) McIntosh	6 x 15	7	Gently to steeply dipping funnel	Gabbro (groups 1 & 2), calcsilicate, metavolcanic, granite	OGab, OGabn, Troc, MtGab, AnG, Lherz	
(13) Northeast McIntosh	5 x 6	?2	Sheets	Gabbro (McIntosh intrusion), calsilicate, metavolcanic, pelite, psammite, granite	BiotGab, Gab	
(14) Springvale	6 x 13	1.5	Moderately dipping sheet	Bow Granite batholith	Gab, OGab, Troc, AnG, An, non-cumulates	Cr, PGEs
(15) Toby	16 x 21	?3-5	Gently dipping basin & faulted blocks	Bow Granite batholith	OGab, BiotGab, Troc, Du, Cr, AnG, An, N, non-cumulates	Cr, PGEs, Ni
(16) Juries	4 x 7	?3	Folded & faulted sheets	Bow Granite batholith	Gab, OGab	Cu
(17) Paperbark–Sandys Dam	1 x 6	?0.5	Sheets	Bow Granite batholith	BiotGab, Gab, MtGab	
(18) Black Hills Yard	2 x 4	?0.3	Sheets & plugs	Bow Granite batholith	BiotGab, Gab, Troc, OGab, AnG	
(19) Billymac Yard	1 x 6	?0.5	Moderately dipping sheets	Bow Granite batholith	Troc, BiotGab	Cu, Ni, PGEs
(20) Sandy Creek	2 x 14	?1	Moderately dipping sheets & plugs	Bow Granite batholith	OGab, BiotGab, Troc, AnG, An	Cu, Ni, PGEs
(21) Togo	2 x 6	?0.5	Fault-bounded block	Bow Granite batholith	Gab, AnG, An	
(22) Panton River	6 x 12	?2	Sheets	Bow Granite batholith, metavolcanics	OGab, Gab	

Major rock types are arranged in order of decreasing abundance. Amph = amphibolite; Cr = chromitite; Du = dunite; Ha = harzburgite; Lherz = lherzolite; Tr-An = tremolite-anthophyllite peridotite; BiotGab = biotite gabbro; OGab = olivine gabbro; Gab = gabbro; OGabn = olivine gabbronorite; Gabn = gabbronorite; Mlgab = melagabbro; MtGab = magnetite gabbro; Troc = troctolite; N = norite; AnG = anorthositic gabbro; An = anorthosite; Fg = ferrogabbro; Dior = diorite.

thickest intrusions. The precious-metal potential of these intrusions is strengthened by the recent discovery of economically significant Au–Pd–Cu resources (Platinova Reef) in the oxide-rich mafic rocks of the Skaergaard intrusion, East Greenland (Bird & others, 1991: *Economic Geology*, 86, 1083–1092). In addition, the unusually high concentrations of Au (22 to 53 ppb, average of 34 ppb; Mathison & Hamlyn 1987: *Journal of Petrology*, 28, 211–234) in the McIntosh intrusion implies potential for laterally extensive Platinova Reef-type or more localised structurally controlled hydrothermal-type Au–PGE deposits.

Emplacement mechanisms

Hamlyn (1980: *American Journal of Science*, 280, 631–668) interpreted the Panton intrusion (group 1) as an exotic body showing mineralogical evidence of crystallisation at pressures of 8–9 kb (corresponding to depths of 25 to 30 km) and temperatures of 800–1100°C. Subsequent metamorphism during re-emplacement at higher crustal levels took place at pressures of 4–6 kb and temperatures of 550°C. Hamlyn's conclusions, and a regional structural analysis, led Hancock & Rutland (1984: *Journal of Geodynamics*, 1, 387–432) to suggest that both the Panton and McIntosh intrusions were tectonically emplaced into the upper crust. However, the evidence presented above indicates that the East Kimberley intrusions are not exotic but that they crystallised in situ. The crystallisation pressures deduced by Hamlyn (1980) for the Panton intrusion and by Mathison & Hamlyn (1987) for the McIntosh intrusion (<6 kb) are consistent with the different structural and metamorphic histories that the bodies have undergone. It appears that the older Panton intrusion was uplifted together with its country rock during D3, and was then metamorphosed at a crustal level similar to that at which the McIntosh intrusion was later emplaced. Uplift during D3 would have taken place along the Halls Creek and Springvale Faults.

For further information, contact Dr Dean Hoatson (Minerals & Land Use Program, AGSO) or Dr Ian Tyler (Geological Survey of Western Australia, Perth).

Regional evidence for Mount Isa-style copper ore systems

Detailed geological mapping has helped to explain the temporal evolution of deformation, metamorphism, and hydrothermal alteration of the Eastern Creek Volcanics near Mount Isa. In conjunction with laboratory-based fluid tracer studies, the results suggest that a particular type of fracture-controlled carbonate–magnetite(–hematite) alteration is a district-scale expression of the large hydrothermal system which formed the Mount Isa copper orebodies.

The scale of the Mount Isa copper system

Metasediment-hosted 'silica-dolomite' breccia at Mount Isa contained in excess of 20 Mt of copper metal within a rock volume of about half a cubic kilometre (Waring, 1990: 'Mount Isa Inlier geology conference', Abstracts, *Monash University*, 69–71). Variably altered metabasalts of the Eastern Creek Volcanics surrounding the deposit on four sides have generally been assumed to be the main copper source, partly because of the local occurrence of exhaustively copper-depleted, Mg-chlorite–rutile-altered metabasalts immediately below the orebodies (Smith & Walker, 1971: *BMR Bulletin* 131; Wyborn, 1987: *Geological Society (London), Special Publication* 33, 425–434). Three-dimensional geophysical modelling by Leaman (1991: *Australian Journal of Earth Sciences*, 38, 457–472) is consistent with the presence of 30–50 km^3 of Mg-chlorite–rutile-altered metabasalts beneath the deposit — the minimum volume of metabasalts required to source the quantity of copper extracted.

However, the low solubilities of quartz and chalcopyrite place constraints on the minimum quantity of fluid required to transport the components now enriched in the 'silica-dolomite', and new data on the Br/Cl ratio of ore-fluid inclusions suggest an ultimate source of the ore fluids in an evaporite sequence well above the present erosion level (Heinrich & others, in press: *Geochimica et Cosmochimica Acta*). This indicates that the entire hydrothermal system — i.e., the segment of crust enclosing the network of fluid transport paths that contributed to copper ore formation at Mount Isa — had dimensions that were 10–100 times larger than the minimum copper source volume. A hydrothermal system of this magnitude is likely to have left some observable geological evidence at the scale of kilometres to tens of kilometres away from the deposit.

One of the aims of this project was to identify any specific exploration indicators which could help detect similar large hydrothermal systems elsewhere.

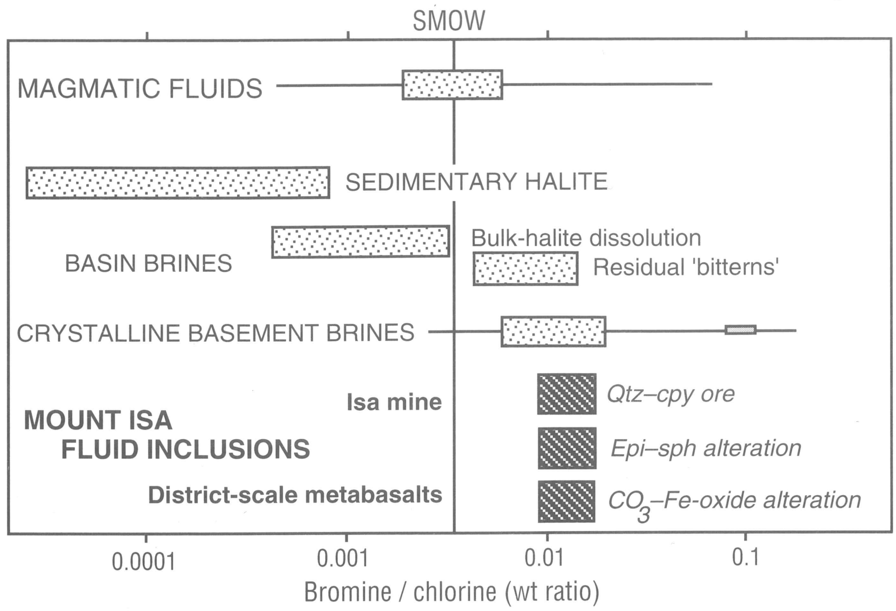

Fig. 15. The Br/Cl ratio of hydrothermal brines is one of several fluid tracers confirming the district-to-mine-scale correlation of hydrothermal events at Mount Isa. Comparison with modern crustal Cl reservoirs suggests that the copper-ore fluids might have originated by late metamorphic infiltration of residual bitterns from a halite-depositing evaporite sequence above the present erosion level.

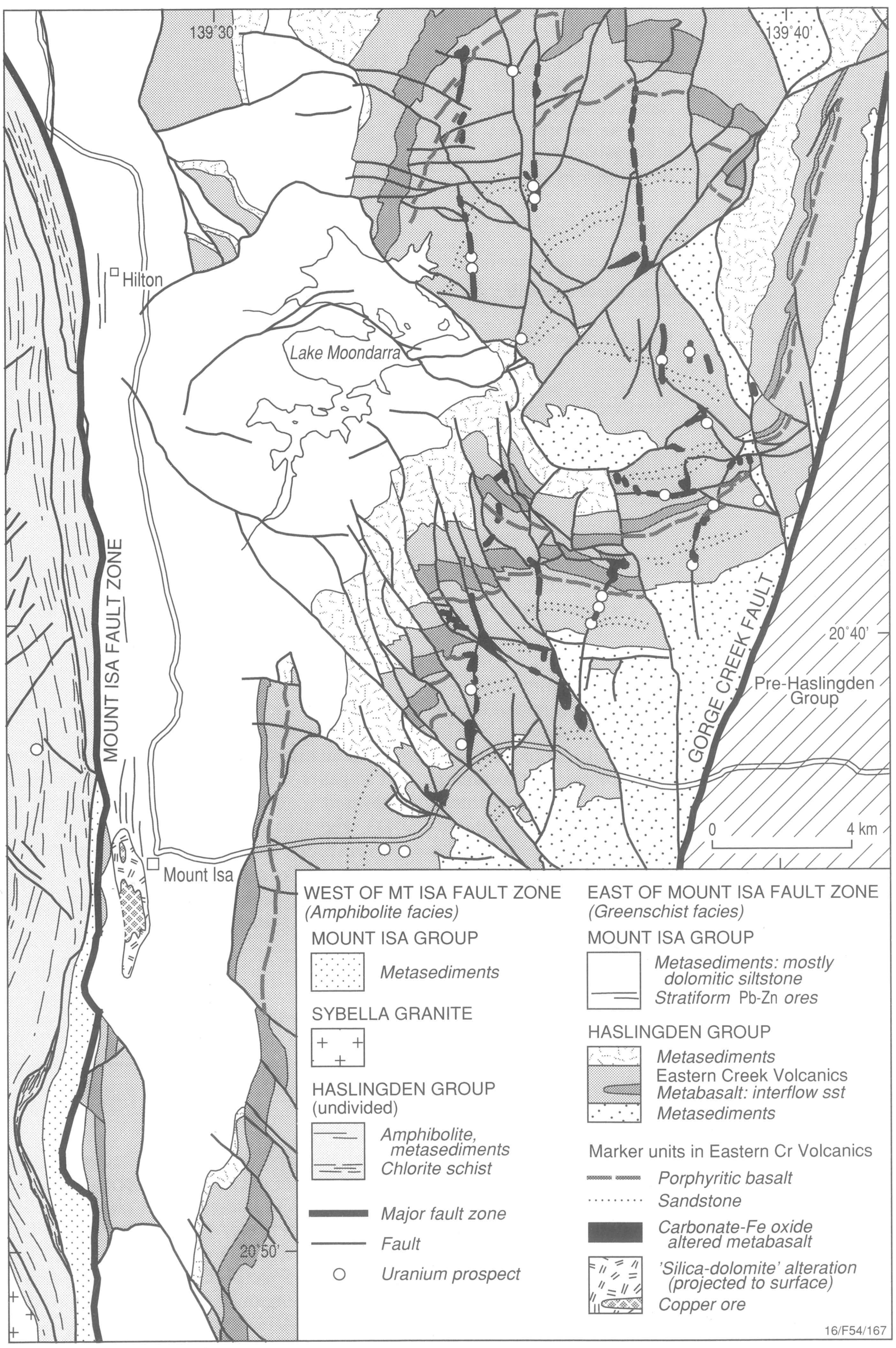

Fig. 14. Geological map of the Eastern Creek Volcanics around Mount Isa, based on 1:35 000 mapping by Bain & Henderson, and other maps referred to in *AGSO Bulletin* 243.

District-scale hydrothermal alteration near Mount Isa

Detailed field mapping combined with structural data was used to determine the time sequence of hydrothermal alteration, veining, and metamorphism. Peak regional greenschist-facies metamorphism, widespread epidote–sphene alteration of metabasalts, and minor chlorite alteration all overlapped in time with the development of a large D2 fold and a fan-like configuration of northwesterly directed faults (Fig. 14; Bain & others, 1992: in *AGSO Bulletin* 243). Irregular but generally north-striking fracture zones superimposed on this complex structure show little or no displacement, but are conspicuous in the field by the abundance of short millimetre-thick calcite veinlets that give weathered outcrops a hackly appearance. The rock matrix between the veins is altered to carbonate + iron oxides (magnetite + calcite + albite ± chlorite and biotite). In zones of most intense veining, the altered metabasalts are commonly red, reflecting additional hematite (Bain & others, 1992).

Fluid tracer studies

Veins and altered metabasalts showing clear chronological relations in the field were used for laboratory studies of whole-rock, mineral, stable-isotope, and fluid-inclusion geochemistry. The isotopic and chemical fluid tracers applied were those that are least-easily modified by interaction with wall rocks at the ore deposition site, and included the stable isotopes of O and H, the total salinity, the major cation ratios, and particularly the Br/Cl ratio of the fluids.

The results for these fluid tracers obtained from veins and carbonate–Fe-oxide-altered metabasalts associated with the north-striking fracture zones (Fig. 14) are all identical with corresponding tracer results obtained in earlier studies from the quartz–chalcopyrite (main ore deposition) stage in the evolution of the 'silica-dolomite' at the Mount Isa mine. They indicate a consistent fluid evolution and metasomatic history at the district-scale, which can be tentatively correlated with the fluid history previously determined for the Mount Isa mine (Fig. 15).

Tracer and mass-balance measurements indicate that the carbonate–Fe-oxide alteration marks zones of downward recharge of fluids which, after interaction with metabasalts and other rocks at depth, became focussed towards and up through the Mount Isa Fault Zone. By contrast, isotopic signatures of S and C in altered metabasalts of the district differ systematically from those of the copper ores; instead, these ore components were at least partly derived from the highly pyritic, carbonaceous, and dolomitic Mount Isa Group metasediments (Urquhart Shale). The components of this unit acted as a local chemical trap for extracting copper from a much larger hydrothermal system.

Conclusion

The establishment of a large-scale hydrothermal source and transport system, and the presence of an efficient structural and chemical trap for ore deposition, can occur independently of one another in the geological record. It is the temporal and spatial *coincidence* of the two 'ingredients' which leads to the formation of a world-class orebody like the Mount Isa copper deposit. Specialised host rocks and mine-scale alteration such as the 'silica-dolomite' and Mg-chlorite–rutile alteration at Mount Isa are well defined but relatively small exploration targets. Hydrothermal systems represent less easily definable but inherently larger targets, and may commonly be the only surface evidence for a world-class ore deposit. The recognition of these systems, and the correct interpretation of genetic and temporal links to ore-deposition processes, provide a major challenge for regional exploration and metallogenic research today. The characteristic carbonate–Fe-oxide alteration identified and studied at Mount Isa is an example of a specific indicator that could help to identify similar hydrothermal systems elsewhere.

For more information, contact Chris Heinrich or John Bain (Minerals & Land Use Program, AGSO), or Anita Andrew (CSIRO, North Ryde).

The *Murray Basin Hydrogeological Map Series*

Underpinning ecologically sustainable management strategies

Context

The Murray–Darling Basin covers about 1 000 000 km^2, or one-seventh of Australia. It hosts a range of significant natural resources whose economic value accounts for about one-third of the national output from rural industries. It is vital to Australia's balance of trade and to the existence of almost 3 million people who depend on its natural resources. It supports one-quarter of the nation's cattle and dairy farms, about one-half of its sheep, lambs, and cropland, and almost three-quarters of its irrigated land. The production derived is valued at $10 000 million annually.

Concern for the extent of land degradation, deteriorating water quality, rising groundwater levels, and loss of native flora and fauna is widespread throughout the Basin. Losses due to land degradation in cropping and irrigation areas were estimated in 1987 to exceed $220 million annually. Losses are also due to poor water quality (ca $35 million annually), and additional environmental degradation (unquantifiable), most of it attributable to groundwater processes.

The Murray–Darling Basin Ministerial Council (MDBMC) has embarked on an initiative to increase the effort directed at redressing the degradation. It has developed the Natural Resources Management Strategy, whose objective is to promote and coordinate effective planning and management for equitable, efficient, and sustainable use of the land, water, and other environmental resources of the Basin. One of the major areas of coordinated Government action, defined in the Strategy, is the management of groundwater both to combat degradation through salinisation and to promote sustainable land and water use. One of the expressions of this action is the *Murray Basin Hydrogeological Map Series.*

The hydrogeological map series

In 1987, MDBMC agreed to a program of hydrogeological mapping and database development for the Basin. The program has two components, of which one is the production of hydrogeological maps — 26 of them — of the entire Murray Basin at 1:250 000 scale (Fig. 16). Production of the maps, of which 10 so far have been published, is a collaborative effort between AGSO and the various water authorities of South Australia, Victoria, and New South Wales. The series is due for completion by mid-1994.

The **objectives** are:

- to generate a set of maps which will
  - — show the influence of groundwater on land salinisation and surface water salinity;
  - — delineate useable groundwater resources;
  - — highlight present and potential salinity hazards; and
  - — enhance community awareness and understanding of groundwater systems and processes; and
- to provide a groundwater database for the Basin in order to facilitate land and water-resource-management decisions.

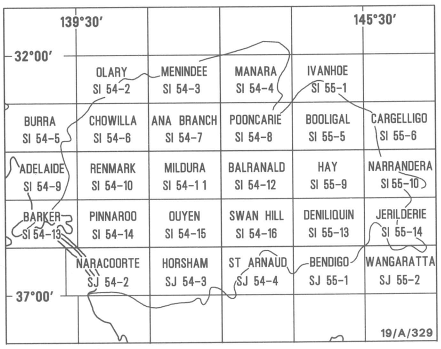

Fig. 16. Index map of the 1:250 000 Sheet areas that constitute the *Murray Basin Hydrogeological Map Series.*

Conceptual elements for portrayal on the map sheets were adopted from the Australian Water Resources Council's 1988 'Guidelines for the preparation of Australian hydrogeological maps'. These guidelines recommend that for mapping at scales of 1:250 000, a salinity/yield matrix should be used as the full-colour feature. This feature has been included because it will contribute to meeting the objectives of the mapping exercise.

Also portrayed on the map sheets are:

- the shallowest aquifer system (on the 1:250 000 map), showing
  - — salinity/yield categories;
  - — water-table contours (constructed using point-source heads — i.e., no density corrections);
  - — basic geology; and
  - — man-made water features (irrigation areas, channels, dams, locks, etc.);
- a salinity/yield matrix;
- two cross-sections;
- 1:1 000 000-scale inset maps for each significant deeper aquifer, showing
  - — potentiometric contours;
  - — salinity/yield; and
  - — structure contours, including bedrock surface and optional structural features (faults, blocks, etc.);
- 1:1 000 000-scale inset contour maps showing the difference in 'fresh water head' between each aquifer;
- 1:1 000 000-scale inset maps showing depths to water-table zones;
- a hydrogeological characteristics table detailing information on regional aquifer-hydraulic parameters;
- aquifer and rock relationship diagrams;
- hydrographs, including rainfall; and
- small isohyet and reliability maps.

Uses of the maps produced so far include:

- providing a hydrogeological framework for the Wimmera and Mallee Dryland Salinity Management Plans;
- providing a regional hydrogeological framework for Land and Water Management Planning in some New South Wales irrigation areas;
- helping Landcare groups make decisions about the importance of groundwater resources in their particular areas;
- contributing to Community Education, thereby assisting farmers and others to understand salinity processes;
- assessing groundwater-resource potential for farmers looking for new water supplies;
- identifying for irrigators and other community members the key recharge areas, and consequently the potential for altering recharge due to land management;
- identifying the regional water-table depth for a range of government departments, community groups, and individuals;
- helping to develop a hydrogeological understanding for input to the management of the South Australian/Victorian Border Groundwater Agreement;
- showing the extent of irrigation-induced water-table mounds to irrigators in the Riverland;
- assisting in the prediction of water-table levels over the next 20 years in both the Renmark irrigation area and the South Australian Mallee Dryland.
- assisting in the planning for the disposal of urban runoff by the Mildura Shire;
- assessing, on behalf of the Australian Workers Union, the potential effects, on workers, of groundwater which may be polluted by pesticides;
- understanding groundwater effects beneath intensive rural industries in the Narrandera area;
- assessing town water supply availability around Narrandera;
- helping to site a new landfill by the Shire of Kerang;
- assessing possible effects of groundwater inflow to wetlands;
- helping to site a new woodlot for the disposal of sewerage effluent by the Sunraysia Water Board in Mildura; and
- helping the review of applications for Transferable Water Entitlements adjacent to the Murray River.

For further information, contact Ray Evans (Environmental Geoscience & Groundwater Program, AGSO).

Christmas Island research cruise defines offshore resource potential

Christmas Island is an Australian territory in the Indian Ocean south of Java (Fig. 17). It comprises Cainozoic volcanics and limestone resting on oceanic crust of Late Cretaceous age; is moving northward at the rate of 7 cm y^{-1}; and is being raised as it climbs the bulge on the southern flank of the Java Trench. Australia has declared a 200-mile Fisheries Zone (AFZ) around the island, as a forerunner to an Exclusive Economic Zone. AGSO cruise 107 investigated this zone in early 1992. Previous geoscience cruises had provided several thousand kilometres of useful geophysical profiles and 17 bottom samples in the AFZ. Water depths in the AFZ are generally 5000–6000 m, but volcanic edifices rise above the abyssal plain in many places (Fig. 17).

Christmas Island is part of one of several north-easterly or easterly trending volcanic ridges. Oceanic crust around the island is overlain by 100–400 m of pelagic sediment which thickens northward toward the Java Trench. Foraminiferal ooze and marl give way to siliceous ooze and red clay below 5000 m. Volcanic ash from Indonesia is an additional component of the sediment.

Previous reconnaissance sampling had shown that manganese nodules are quite common in the deep sea in this area. In a similar geological setting to the west, India has pioneer investor status for a nodule mine site of 150 000 km^2 in the central Indian Ocean. At this site, the average grade of Cu+Ni+Co is about 2.55%, and nodule abundance is 5–7.5% of wet nodules per square metre, suggesting real economic potential.

The purpose of AGSO cruise 107 was to assess the seabed morphology, sediment thickness, and offshore mineral resources in the AFZ. This information will be of particular value to the Department of Foreign Affairs & Trade when Australia negotiates a Christmas Island seabed boundary with Indonesia, to the north.

About 2100 km of high-speed seismic profiles were recorded in the AFZ (Fig. 17), using a 24-channel seismic streamer 600 m long. The seismic profiles, along with results from Deep Sea Drilling Project site 211 in the west, confirm that the regional seismic reflectors of Veevers (1974: *Initial Reports of the Deep Sea Drilling Project*, 22, pp. 351–367) are present, and that the sequence can be divided as follows:

- **Ro–R1**: Quaternary to Miocene siliceous ooze and ash 50–200 m thick;
- **R1–R2**: Neogene turbidite and siliceous ooze 50–250 m thick; and
- **R2–R3**: Palaeogene turbidite and siliceous ooze; unfossiliferous clay; and Campanian–Maastrichtian nannofossil clay. R3 is the top of Cretaceous (Campanian) oceanic crust.

During the cruise, dredges, corers, and Benthos free-fall grabs successfully sampled the seabed (Fig. 17; Table 2).

Six rock types were dredged from the seamounts (Table 2), many of which lie on ridges. The seamounts often have the flat tops characteristic of guyots, suggesting that they were once exposed to wave erosion, and their peaks now lie in water 1200–3200 m deep. The volcanic pedestals consist of alkali basalt and trachyte, and are typical intraplate lavas. Mixed sediments consist of rounded hyaloclastic and volcaniclastic grains set in carbonate. Shallow-water carbonates contain red algae, larger foraminifera, and bryozoan, molluscan, and echinoderm debris. Deeper-water carbonates are largely chalks dominated by nannofossils and planktic foraminifera.

Isotopic dating of igneous rocks from DSDP site 211 and Christmas Island by other scientists has distinguished Late Cretaceous and Eocene–Oligocene volcanic episodes. Campanian, Maastrichtian, and Eocene sediments provide minimum ages for the seamounts from which they were dredged. The seamounts possibly formed over a hotspot as the crust moved slowly northeastward in Late Cretaceous and Palaeogene times. When fast spreading started in the Eocene, and the crust moved rapidly northward, the region would have been separated from the hotspot, and volcanism would have ceased. The shallow-water carbonate and volcaniclastic rocks accumulated around volcanic islands and on shallow seamounts until, as the underlying crust cooled and sank, they too sank well below the surface, and pelagic carbonates were deposited.

Most of the core attempts were on the tops of seamounts, where recovery was generally poor — probably because current action had winnowed the surface sediment to a fairly impenetrable foram sand. Seamount cores are Quaternary nanno-foram ooze containing well preserved microfossils ($CaCO_3$ = 75–90%). Two deep-water cores were also successfully recovered; they consist of nanno-foram ooze and siliceous ooze (G4 from 3665 m; $CaCO_3$ = 6–68%), and siliceous ooze (P5 from 4564 m; $CaCO_3$ = 3–39%). These cores conform with the regional picture of planktic carbonate decreasing with depth toward the calcite compensation depth (5000 m).

The free-fall grabs were deployed to investigate manganese nodule potential; most returned sediment and some returned nodules. Nodules were recovered at nine stations (in 22 out of 85 deployments), where their average abundance of 3.0 kg m^{-2} (maximum 12 kg m^{-2}) is below the generally accepted economic cut-off grade of 5 kg m^{-2}. The average nodule grade is Cu+Ni+Co = 1.13%, far lower than the cutoff grade of 2%. The results show that the Christmas Island offshore area has no potential for economic nodule fields.

Cobalt-rich manganese crusts, formed on the flanks of volcanic islands and seamounts, are considered to be deep-sea resources with long-term economic potential. Manganese crusts up to 20 cm thick recovered in the AFZ dredge hauls have an average cobalt content of 0.44%, somewhat less than the Pacific Ocean average of 0.63%. The results, though far from exhaustive, do not suggest that there are local Co-rich manganese crusts with economic potential.

Table 2. Summary of AGSO cruise 107 sampling stations

Equipment	*Depth range (m)*	*No. successful stations*	*Recovery*
Dredge	1600–3700	9 from 12	Basalt, trachyte, volcaniclastics, hyaloclastics, shallow and deep-water carbonates, Mn crusts
Piston core	453–5923	7 from 9	10.7 m: ooze, marl, clay
Gravity core	1993–3665	2 from 6	10.15 m: ooze, marl
Free-fall grab	4574–5929	28 (85*) from 28 (83*)	Clay, volcanic pebbles, Mn nodules (9 stations)

***Number of deployments.**

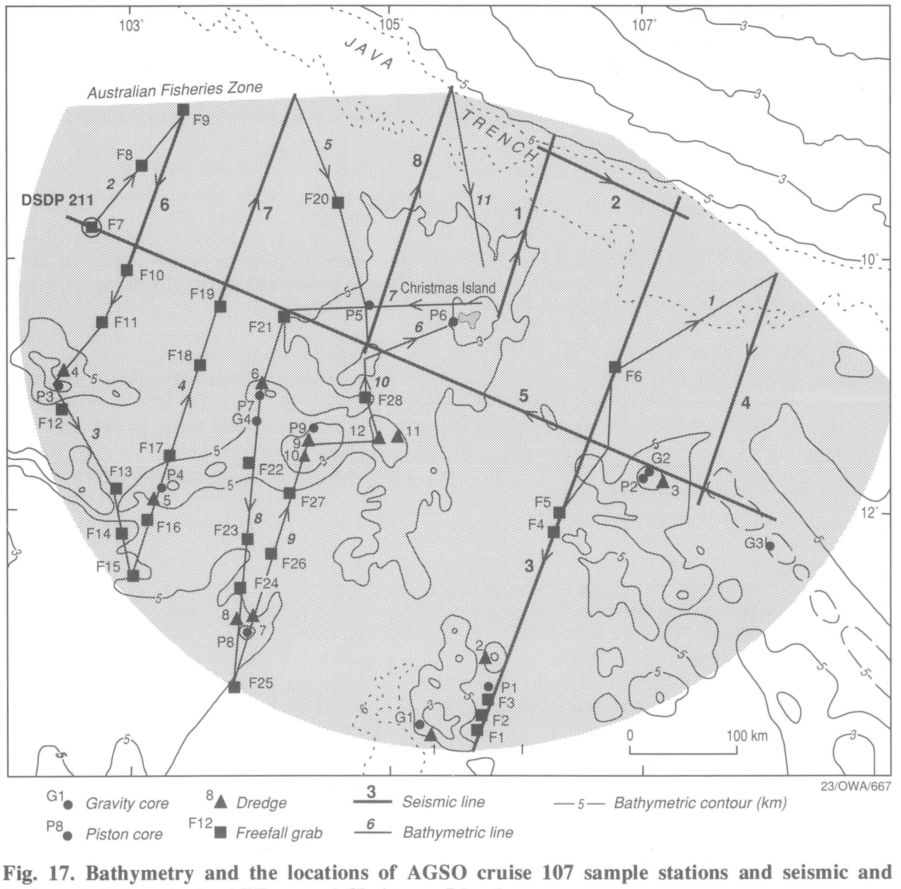

Fig. 17. Bathymetry and the locations of AGSO cruise 107 sample stations and seismic and bathymetric lines in the AFZ around Christmas Island.

For more information, contact Dr Neville Exon at AGSO (Marine Geoscience & Petroleum Geology Program).

New model for evolution of the Gippsland Basin

A unique set of deep (12–14-s) seismic data in the Gippsland Basin and elsewhere in Bass Strait, acquired aboard AGSO's RV *Rig Seismic*, suggests that the basins there were initiated by oblique extension, probably in the Late Jurassic. The basin-forming southeasterly directed extensional stress operated along the entire southern margin of Australia at that time. Strike-slip movements along the flanks of the Gippsland Basin, and wrenching within its sediment-fill, provided the potential for several phases of petroleum migration and entrapment. Possible traps exist within the deeper part of the Latrobe Group and the Golden Beach Group.

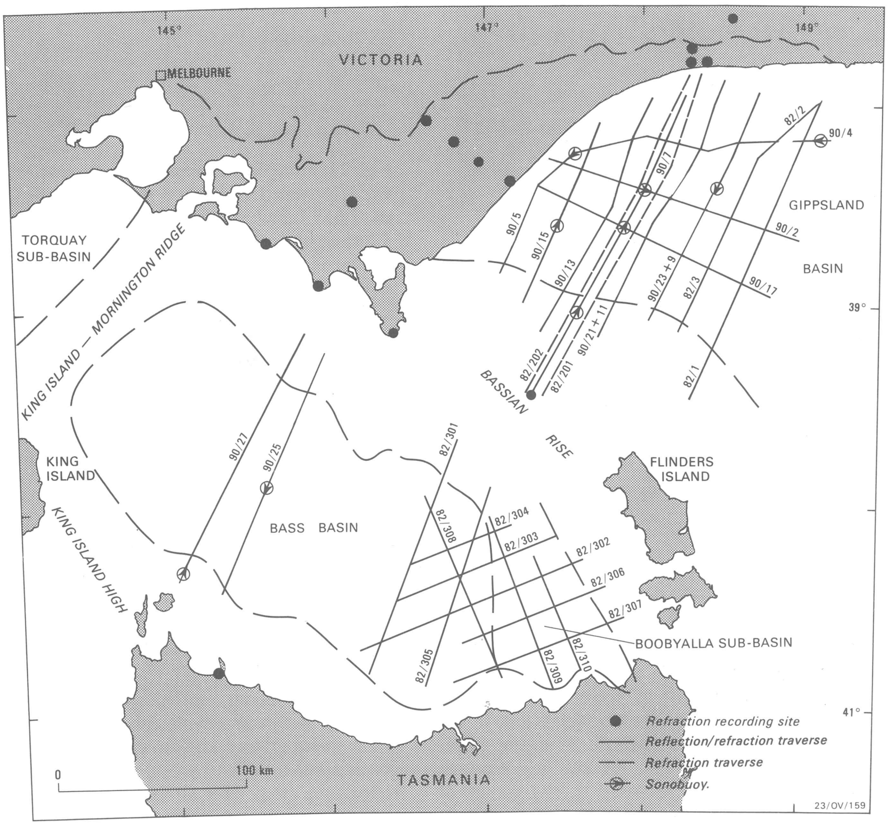

Fig. 18. Regional setting of AGSO's deep seismic lines in the Bass Strait region.

Even though the Gippsland Basin is one of Australia's most prolific and mature hydrocarbon provinces, its origins were largely unknown until AGSO recently acquired deep seismic data from it. Most exploration had concentrated on traps, and led to the development of petroleum fields, at the moderately shallow 'top Latrobe Group' level. Only with the decline in reserves, has the emphasis turned to deeper plays in the (Late Cretaceous) 'intra-Latrobe' and Golden Beach Formation. As a consequence of the early exploration strategy, the huge volume of industry seismic data collected in the basin largely comprises records with a 4–6-s time span. These records show little of the basin's architecture, except perhaps on the shallow northern and southern platforms. In contrast, AGSO's deep data reveal basin-forming structures, from which the basin's history can be interpreted and analogies drawn with less explored hydrocarbon-prospective provinces.

AGSO seismic data

The seismic reflection data set comprises 1650 km of 12–14-s records from a regional grid through the Gippsland Basin (Fig. 18). These data are tied to 35 exploration wells in the basin. In addition, and as part of the same acquisition program, two 14-s lines were recorded in the Bass Basin, and ten 10-s lines in the adjacent Boobyalla Sub-basin. Deep reflection events occur consistently in nearly all profiles from these basins.

The ship's reflection information is complemented by data recorded at onshore stations set up in conjunction with Monash University in Victoria, in Tasmania, and on Deal Island. Long-offset wide-angle reflections and refractions were obtained at these stations, by recording signals from the air-gun seismic source as the ship traversed the basin. The arrival energy was detected out to distances of over 200 km. The large number of shots recorded, up to 5000 per traverse, has enabled signal-enhancement techniques to be used. The correspondence of the deep refracting layers with events on the seismic reflection profiles provides convincing evidence of the efficacy of the technique.

Further, structural mapping in the Strzelecki Ranges (Vic.) has provided information on the trend, style, and age of faults in the early basin-fill (Strzelecki Group) and the younger section.

Deep structure

The basin contains 12–16 km of sediment in well defined sequences (Figs. 19, 20) which can be related to a ?Jurassic–Early Cretaceous southern-margin rift phase, a Campanian Tasman Basin rift phase, and a subsequent thermal sag phase. The basin formed over a detachment surface at about 8 s (16 km) under the depocentre. The Moho is present at 10 s, and depth conversion shows that it shallows from about 30 km regionally to about 25 km under the basin. The detachment forms an east-southeast-trending, south-dipping ramp under the basin's northern flank, and wraps around the basin's western (onshore) prolongation. It clearly extends as a subhorizontal surface under the Central Deep and Bassian Rise, and can be traced southwestwards beneath the other Bass Strait basins.

The basement blocks flooring the Gippsland Basin show no systematic increase in tilt towards its depocentre, except perhaps at its western end. The randomly distributed tilt of the basin-forming blocks, confined mainly to the northern part of the ramp, strongly suggests that basin formation was largely a result of oblique extension (transtension), probably on a southeasterly azimuth. Simple extension appears to have been confined to the basin's western end. Wrench-related movements influenced structuring of the main rift-fill (Strzelecki Group) throughout the Early Cretaceous.

The deep data show that structuring of the sediment-fill into prospective anticlines probably began as far back as the mid-Cretaceous. Some of the deep structures are not reflected at the commonly mapped top Latrobe level, and may provide additional plays for the future.

An integrated geological history for southern-margin basins

The recent study has led to the conclusion that the Gippsland Basin is unlikely to be a product of

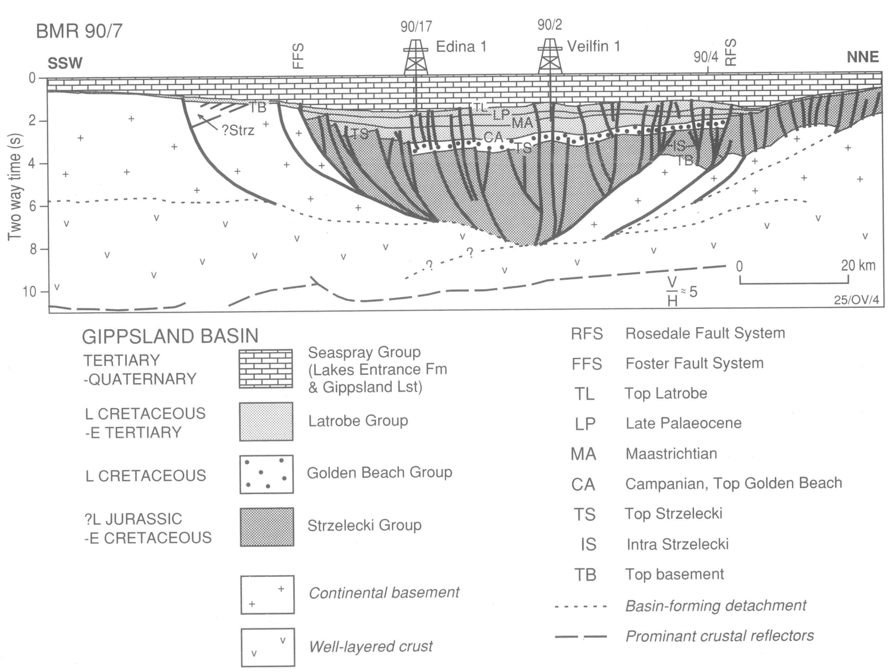

Fig. 19. Deep structure of the Gippsland Basin interpreted from seismic line 90/7.

south-southwesterly oriented extension, as proposed in some earlier interpretations based solely on the shallow industry data. Rather, it appears to have originated as a southeast-trending (i.e., subparallel to the basinal axis) left-lateral strike-slip to transtensional basin in the Late or pre-Late Jurassic (Fig. 21). Simple extensional tectonics are confined largely to the headwall area at the western end of the basin.

Similar geometry and age have been inferred for other southern-margin basins: for example, southeasterly extension in the Eyre Sub-basin and probably in the Ceduna Depocentre of the Great Australian Bight Basin; extension in the Robe Trough; and left-lateral transtension along the Otway Basin–Tasmania margin. This inference suggests that the Gippsland Basin is part of a linked system of basins which developed — probably from the interaction between several microplates (Fig. 21) — on a common detachment or detachment complex during the breakup of Gondwanaland. The Gippsland Basin sequences reflect the rifting and spreading of both the Southern Ocean and Tasman Sea. Continued adjustments and reactivation along the microplate boundaries from the mid-Cretaceous to Oligocene gave rise to the wrench-related and compressional structures which form the principal petroleum traps in the region.

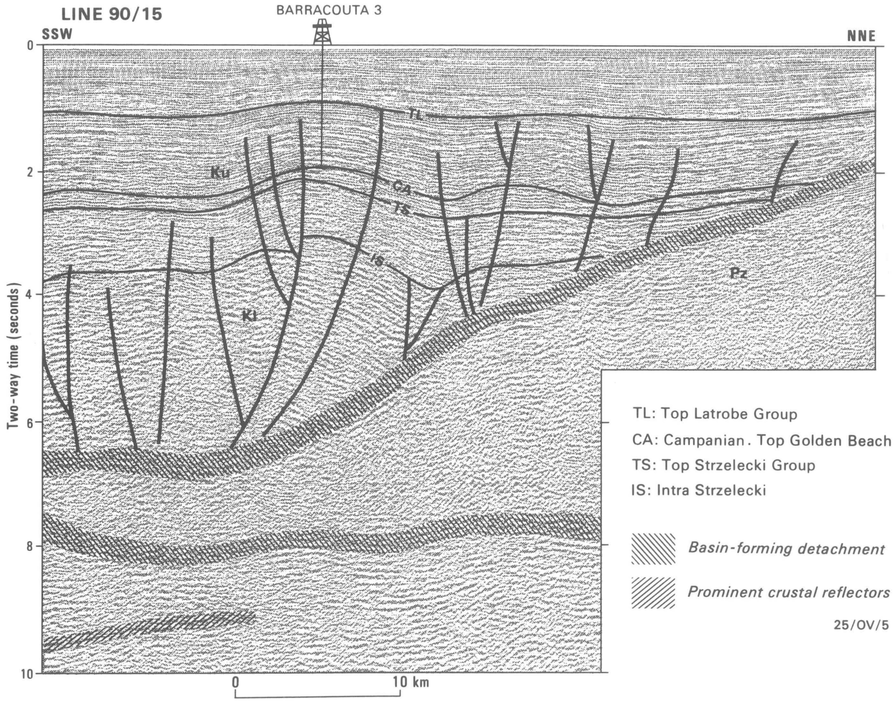

Fig. 20. Example of seismic data (line 90/15) through the Barracouta field.

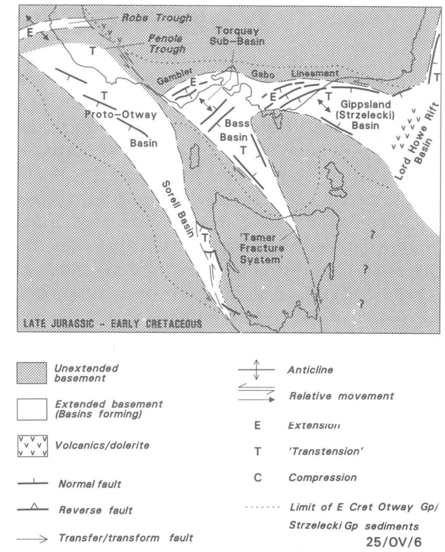

Fig. 21. Conceptual model for development of the Gippsland and other Bass Strait basins in the Late Jurassic–Early Cretaceous, as part of a linked, largely transtensional system.

For further information, contact Barry Willcox or Jim Colwell (Marine Geoscience & Petroleum Geology Program, AGSO).

Advanced remote-sensing mapping of shallow-marine environments

Remote sensing of reflected solar radiation can be used to study and map the shallow-marine environment, since reflected light from the bottom can be detected in clear water to a depth of about 35 m. Satellite scanners, such as Landsat, sense selected visible and infrared wavelengths of the electromagnetic spectrum, and provide a regional multispectral view of the Earth's surface. This can be a valuable data set, particularly where surface vegetation, soils, and rocks show wavelength variations in reflectance. In aquatic environments, solar radiation must transgress a water mass before the reflectance/absorption properties are recorded by the sensor. In visible light, the absorption coefficient of clear water is at its lowest, facilitating greatest penetration, in the range of Landsat Thematic Mapper (TM) waveband 1 (Fig. 22). As the wavelength increases beyond TM band 3, the depth of penetration is less than 10 m, and those bands are of little value for shallow-marine mapping.

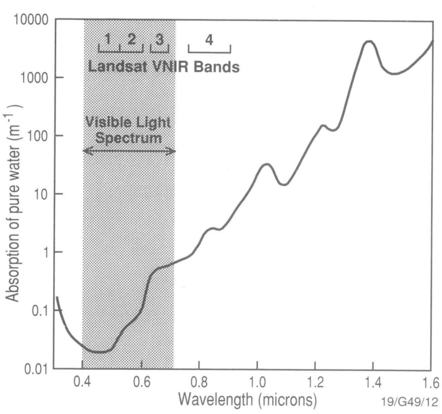

Fig. 22. Absorption coefficient for pure water in visible and near infrared wavelengths of the electromagnetic spectrum.

As part of AGSO's project investigating the geological environment and resources of the coastal zone, Landsat TM scenes have been used to study modern submarine sedimentary environments with particular emphasis on the distribution and structure of sediments, sea-grasses, reefs, and benthic algae. Like most applications of remote sensing, submarine data need to be extensively processed to extract the desired information. One of the main problems with interpreting the satellite data is that brightness variations due to water depth confuse the interpretation of substrate types. Since no previous research had been successful in separating water depth from bottom-reflectance effects, we attempted to design a processing algorithm to do this. If successful, bottom reflectances could be used to identify bottom materials, and water depths could be used for mapping structures and generating 3D models of the sea-floor.

As a base for the algorithm, we used the model from Jerlov (1976: 'Marine optics', Elsevier, Amsterdam) for light attenuation in a homogeneous medium:

$$R_i = R_{bi} e^{-2k_i z} \qquad i = 1,N. \qquad (1)$$

where R_i is the reflectance of the water mass (related to satellite image intensities) for wavelength i;
R_{bi} is the reflectance of the substrate;
z is the water depth; and
k_i is the coefficient of radiation attenuation.

The exponential term in (1) relates to the way light of a particular wavelength is attenuated with water depth. Using known values of k and by constraining the effective brightness of the bottom reflectance (R_{bi}) over all bands, we can derive useful estimates of the water depth (z) and bottom reflectances in each pixel. The algorithm is described in detail, with case studies, by Bierwirth & others (1993: *Photogrammetric Engineering & Remote Sensing,* LIX(3), 331–338.)

Examples of the developed method are shown in Figure 23. Landsat TM bands 1, 2, and 3 were analysed, mainly to show the distribution of sea-grasses in an environmentally sensitive area at Useless Inlet (Fig. 23a). Sea-grasses are generally dark but difficult to distinguish in the deeper water of their range. Applying the unmixing algorithm allows water depths to be removed from each pixel, and residuals representing the bottom reflectance in each band can be derived. The ratio Rb_2/Rb_1, determined from the known reflectance signatures of sea-grass, was applied to enhance the presence of chlorophyll (Fig. 23b).

Water-depth estimates derived from the algorithm can be used to generate 3D perspectives of the sea-floor. The image of an area at Honda Bay (Fig. 23c) was derived directly from the TM data without any addition of bathymetric information.

The remote-sensing methodology briefly outlined here is a good example of the usefulness and versatility of multispectral data when advanced processing algorithms are applied. Currently, this technique is being applied to satellite and aircraft multispectral data over parts of the Australian coastal zone by AGSO and other organisations.

For further information, contact Philip Bierwirth (Environmental Geoscience & Groundwater Program, AGSO).

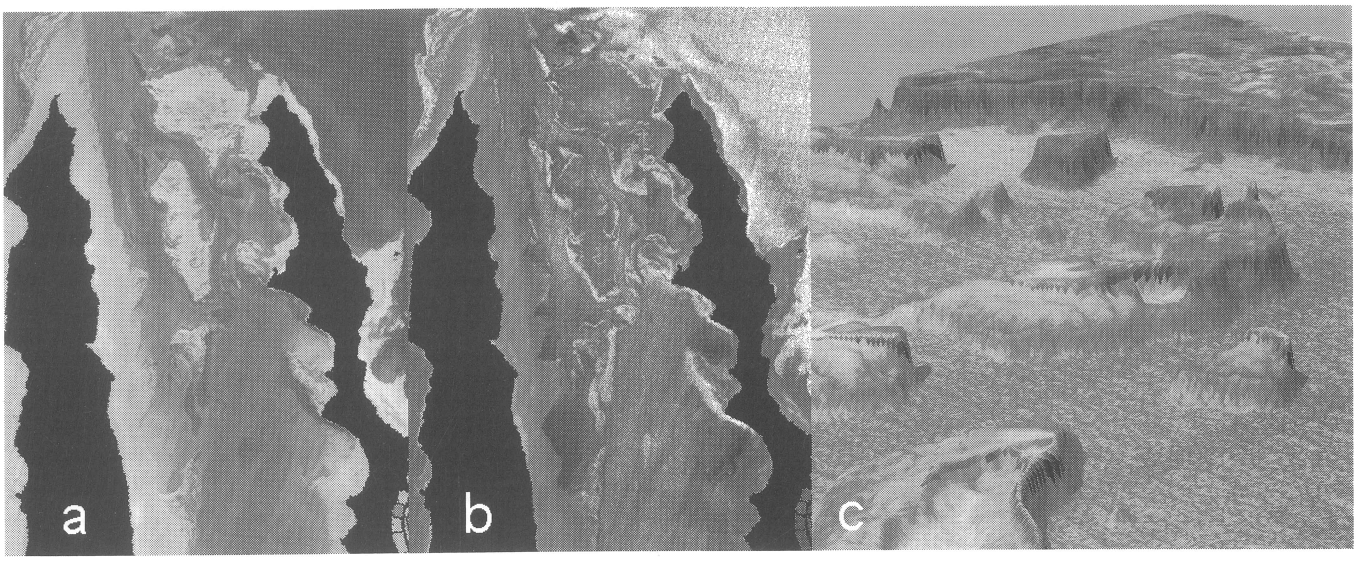

Fig. 23. (a) Landsat band 1 at Useless Inlet, Shark Bay, WA (area about 12 km^2). Land is blacked out. Dark areas are difficult to distinguish between deeper water and sea-grass. (b) Chlorophyll enhancement after the removal of water depth. Bright areas show the distribution of sea-grasses. (c) 3D perspective generated from Landsat-derived water depths showing island and reef topography, Honda Bay, Philippines.

Tectonic history of the Champ de Mars and westernmost Hinckley Range areas

The following table was omitted from the article 'Contact relationships and structure of the Hinckley Gabbro and environs, Giles Complex, western Musgrave Block, WA', published in *AGSO Research Newsletter* 18 (for October 1992, pp. 6–8).

Regional Events	*Age (Ma)*	*This record*		*Metamorphic conditions*	*Previous work*	
					Pharaoh (1990)	*Nesbitt & others (1970)*
D_7		retrograde shear zones	east-trending	musc+bt "crust" zones		
D_6	mid-Cambrian[2]	Petermann Orogeny	overthrusting to the north; ultramylonite+pseudo-tachylite			Hinckley Fault
D_5		ultramylonites	overthrusting to the southwest	greenschist facies		
D_4		ultramylonites	overthrusting to the southeast	amphibolite facies		
Mafic intrusion	<1000[3]	type C mafic dykes	aphanitic			type D mafic dykes
Tollu Volcanics and mafic intrusion	1080±140[1] 1054±14[4]	type B mafic dykes	coarse-grained plagioclase laths;? feeders of the Bentley Group			type C mafic dykes
D_3		upright tight to isoclinal F_3	SE-trending, steep S_3	granulite facies P~4-5 kbar, T>700°C	F_{2F}, F_{1M}	F_2
Mafic intrusion		type A mafic dykes				type A mafic dykes
Felsic intrusion	1185[3]	megacrystic granitoids, microgranite, rapakivi granite				
Mafic intrusion		Michael Hills, Hinckley gabbros		6±1 kbar	emplacement of Giles Complex	
D_2	1189±9[1]	reclined isoclinal F_2 folds	gently dipping S_2, pervasive L_{2i}	granulite facies	F_{1F}	F_1
Felsic intrusion		charnockite				
D_1		pervasive gneissosity in felsic/mafic granulites		granulite facies P~7kbar, T>750°C	?early gneissose fabric	?early fabric
Mafic intrusion		mafic granulites with igneous relics				
?Felsic intrusion		dominant pre-D_1 orthogneisses				
	1327±12[1] 1564±12[1]	protolith of paragneisses				felsic volcanic and sedimentary protoliths

[1] Rb-Sr whole rock, Gray (1971, 1977); [2] U-Pb on zircons, Maboko (1989); [3] U-Pb on zircons, S-S. Sun (pers. comm., 1992); [4] Rb-Sr whole rock, A. Camacho (pers. Comm. 1991).

Australian petroleum systems: framework for exploration

At recent workshops in Canberra and Melbourne, AGSO scientists Marita Bradshaw, Roger Summons, John Bradshaw, and Tom Loutit introduced to industry and government geoscientists the petroleum systems concept, and its application to Australasia. The response at the workshops was that the concept provides a simple and comprehensive framework for understanding and predicting hydrocarbon occurrence. Establishing a petroleum system framework stresses the linkages between coeval basins with similar palaeogeographic and tectonic setting; reservoir, seal and source facies; trap formation and maturation histories; and thus hydrocarbon prospectivity. In this way, basins in a petroleum system can be characterised, and knowledge of the more explored basins can be used predictively in the frontier basins.

A petroleum system is defined as a mature source rock and all its generated hydrocarbon accumulations (Magoon & Dow, 1991: *American Association of Petroleum Geologists, Bulletin* 75(3), 627). The system includes all geological factors necessary for the oil and gas fields to exist — that is, the source, reservoir, seal, trap, overburden required for maturation, and migration pathways. The petroleum system concept stresses the processes involved from source to trap and then the preservation of that accumulation. For the system to operate successfully, and hydrocarbons to accumulate, all the crucial elements must be in place in the correct sequence.

The time-slice palaeogeographic maps and regional cross-sections produced by AGSO's predecessor (BMR) jointly with the Petroleum Division of the Australian Mineral Industries Research Association provide a continent-wide database from which to delineate Australia's petroleum systems. Basins that share sequences of similar age, facies, and — in particular — source-rock type and structural history are linked together into broad petroleum systems. AGSO studies have distinguished six Phanerozoic petroleum systems: the Larapintine, Gondwanan, Westralian, Austral, Capricorn, and Murta systems. The hydrocarbon occurrences in the Middle Proterozoic McArthur Basin constitute a seventh — the Urapunga system.

The Larapintine system includes Upper Proterozoic to mid-Carboniferous sequences in basins in western, central, and eastern Australia (Fig. 24). During this time, Australia, as part of Gondwana, was located in low tropical latitudes, and sea levels were generally high across the continent. The influence of these two factors produced the characteristic Larapintine facies — carbonates, evaporites, and shallow-marine clastic sediments. Excellent marine source rocks were deposited during transgressions in the Late Proterozoic in the Officer Basin, the Middle Cambrian in the Georgina and Arafura Basins, the Early Ordovician in the Amadeus and Canning Basins, and the Late Devonian to Early Carboniferous in the Canning Basin.

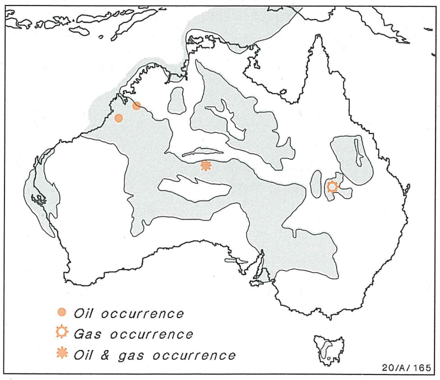

Fig. 24. Distribution of the Larapintine System.

The Gondwanan system includes Upper Carboniferous to Middle Triassic sequences in a widespread series of basins (Fig. 25). During this time, Australia was located in high southerly latitudes, and a major glaciation of the continent from Late Carboniferous to Early Permian time left its mark in the characteristic facies of the Gondwanan system — coarse glacigene clastic sediments followed by coal measures. In eastern Australia, the Gondwanan system source rocks are non-marine, and associated with the coal measures, as in the Cooper and Bowen Basins. Early Triassic marine shales are source and seal facies for the Gondwanan system on the western margin.

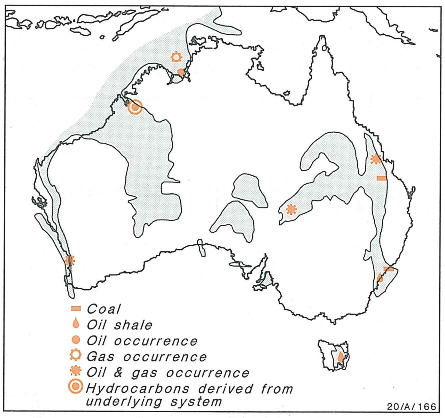

Fig. 25. Distribution of the Gondwanan system.

The basins along the North West Shelf and extending into Papua New Guinea are part of the Westralian system (Fig. 26). They share Triassic to Cretaceous reservoirs, Jurassic marine source rocks, and a Cretaceous regional seal.

The development of the southern margin as Australia and Antarctica separated has influenced the basins of the Austral system (Fig. 27). They have similar non-marine Mesozoic rift-valley sequences followed by marine Upper Cretaceous and Cainozoic sediments. The Capricorn system is related to the opening of the Coral Sea, and includes onshore Tertiary oil shale deposits and the offshore basins of northeast Australia (Fig. 27). The Mesozoic interior sag sequences of the Eromanga and associated basins are part of the Murta system (Fig. 27).

These Australian petroleum systems are much broader in scope than the original concept, as they extend through many basins and can encompass more than one source rock interval and several reservoir and seal combinations. They may be considered to be 'supersystems', analogous to 'superbasins'. No doubt as the petroleum system concept is developed in Australia the systems introduced here can be further refined and subdivided. However, response to this work at scientific meetings and workshops indicates that at this initial

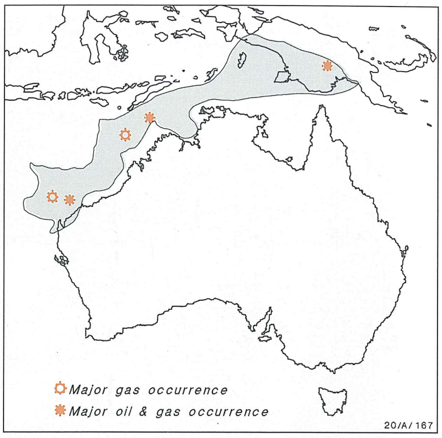

Fig. 26. Distribution of the Westralian system.

stage there is value in introducing these broad groupings of basins. They have proved to be an acceptable, simple, comprehensive framework for understanding hydrocarbon occurrences in Australia, and a stimulus to discussion and thought.

The Australian petroleum systems project will be analysing the operation of several of these systems. It is focussing initially on six basin module areas — five in the Westralian system: Dampier–Rankin, Browse, Barrow–Exmouth, Beagle–offshore Canning and Papuan; and one in the Gondwanan–Larapintine systems: Petrel (onshore/offshore). Major products include well correlations, maps, cross-sections, and computer databases of biostratigraphic and prospectivity information.

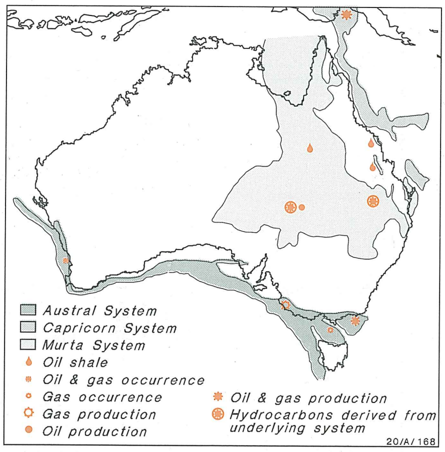

Fig. 27. Distribution of the Austral, Murta, and Capricorn systems.

This project is the latest and third in a series of cooperative research projects between AGSO and APIRA. It follows and is building on the successful outcomes of the two previous projects. It is currently sponsored by 15 companies, and sponsorship is available either for the full three years of the project at $24 500 per year or on a module-by-module basis.

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