agso RESEARCH NEWSLETTER

'Geoscience for Australia's Future'

Number 27 November 1997

Multibeam sonar reveals sea-bed structure and processes off east Tasmania and Gippsland

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AGSO recently mapped the topography and character of a large area of the sea-floor of the east Tasmanian continental margin and deep-water Gippsland Basin in unprecedented detail (Fig. 1). This region is of great petroleum and geological interest, and contains a major fishery.

For this purpose, AGSO chartered the 85-m RV *Melville* from the Scripps Institution of Oceanography in April 1997. The 8-day cruise (Fig. 2) was dedicated largely to swath-mapping, and to a lesser extent to magnetic and gravity profiling. About 3500 km of profile data were collected and 20 000 km^2 of the sea bed were mapped. The survey had the benefit of precise military P-code GPS navigation, which provides accuracy to better than 5 m.

The *Melville* carries a SeaBeam 2000 multibeam sonar system, a 12-kHz 121-beam echo-sounder that collects both swath-bathymetry and backscatter (sidescan) data. The system has a swath coverage of 120°, so it can map a strip of sea-floor ~3.4 times the water depth. Maximum swath-width is about 15 km. The bathymetric grid density is a function of water depth: the shallower the depth, the greater the density; in 2000 m of water, for example, the data spacing is about 50 m. The backscatter data provide additional information about the character of the sea bed. For example, hard surfaces such as exposed bedrock have a strong backscatter response, and appear dark in the imagery, whereas soft sediments (e.g., pelagic oozes) show very little backscatter and appear almost white.

The objectives of the cruise were:

- to determine the morphology and sea-bed character of selected areas;
- to map the structure of bedrock outcrop on the eastern margin of a north-trending, possible sedimentary basin that lies beneath the upper continental slope off the Freycinet Peninsula; the existence of this basin is inferred from the presence of a major elongate gravity low observed in ERS–1 satellite gravity imagery covering this offshore region, and from early-1970s seismic profiles;
- to provide data for tectonic, basin, and sedimentological studies (including survey of a jarosite dump site);
- to aid the fishing industry; and
- to provide critical information for future seismic profiling and geological sampling.

To maximise regional coverage, the survey was largely concentrated in water 2000–4200 m deep.

East Tasmania

In the past 20 years, Pasminco EZ, the owner

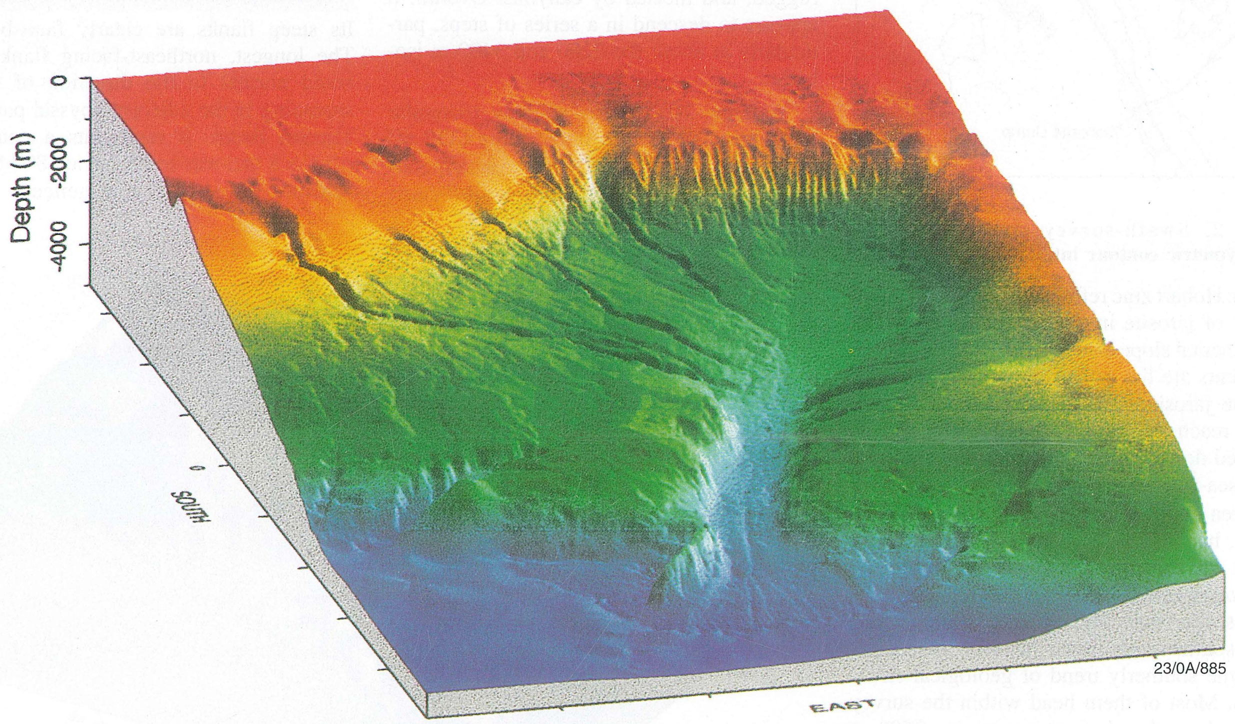

Fig. 1. Perspective view to the northwest of the Bass Canyon off Gippsland. Horizontal scale is indicated by the tick marks spaced at 20-km intervals. The image was generated from detailed AGSO SeaBeam 2000 swath-bathymetry, augmented at the edges by older trackline survey data.

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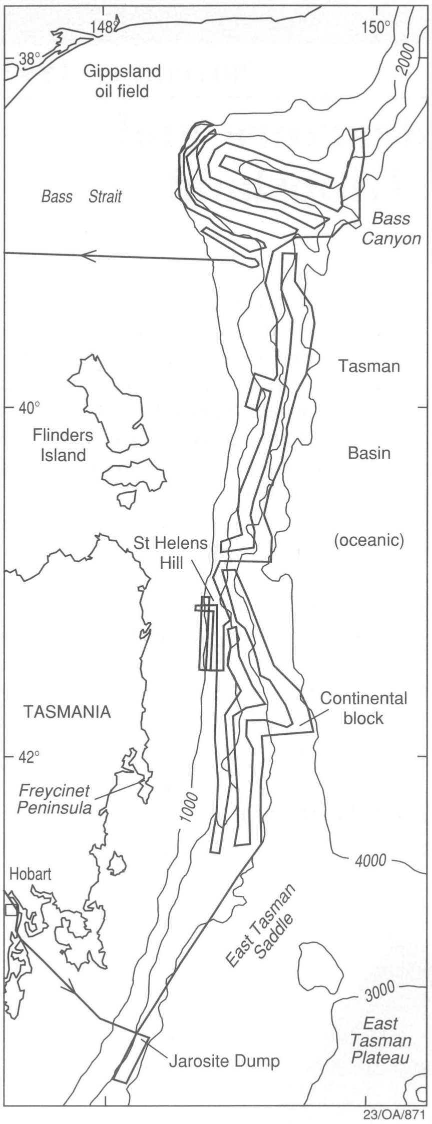

Fig. 2. Swath-survey track map. The bathymetric contour interval is 1000 m.

of the Hobart zinc refinery, has dumped about 4 Mt of jarosite in 2000 m of water on the continental slope southeast of Hobart (Fig. 2). Currents are thought likely to carry the bulk of the jarosite well to the south, but some may reach the bottom near the site and be carried down the slope by turbidity currents. The sea-floor at the dump site, surveyed over an area ~40 × 15 km in water 1800–3500 m deep, has a slope that increases from about 2° at the top to about 7° at the bottom. A few small canyons traverse the area; the deepest is less than 200 m deep. Some trend east-southeasterly down the slope; others follow the southerly trend of geological structures. Most of them head within the survey area where the slope steepens, at ~2500 m depth. These canyons could carry sediments as turbidites or gravity slides, and hence transport jarosite if it is present.

A transit line over the base of slope on the Tasmanian side of the East Tasman Saddle recorded the morphology of sea-floor sloping gently southeastwards from 2200–3400 m deep. The sea bed is mainly featureless and undulating; a previously postulated seamount does not exist there. The undulating topography may be due to late Cainozoic sedimentary sheets that have moved downslope and been reshaped by ocean currents, including minor erosion caused by turbidity flows originating at the shelf edge. A large downslope canyon about 250 m deep and 2 km wide is located at latitude 43°26′S, longitude 148°26′E. A 300-m-deep erosional embayment mapped between the canyon and the jarosite dump is further evidence that the lower slope in this area has been sculptured by erosional forces.

The margin off central east Tasmania was mapped by a series of five passes (Fig. 2), roughly oriented north–south, plus a more tightly spaced set of lines in the moderately shallow (~1000 m depth) fishery off St Helens. Satellite gravity images helped plan the route of the survey, which took in a major gravity ridge over the continental slope (~55 km offshore, between St Helens and Freycinet Peninsula) and a local gravity high 35 km farther east (on the inferred continent–ocean boundary, COB).

The survey of the margin off central east Tasmania extended from the flat-lying and sedimented abyssal plain at 4000 m depth, to about 800 m in the north (fisheries area) and to roughly 1600–2000 m towards the south. The topography in the central and southern parts is irregular, dominated by local highs, commonly with steep rugged flanks. In the north, the continental slope is steep, rugged, and incised by canyons. Overall, it appears to descend in a series of steps, particularly at about the 2200 and 3400-m isobaths.

A large, 20 × 10-km, roughly triangular block oriented northwesterly at the COB off central east Tasmania (Fig. 2) corresponds to the local gravity high ca 90 km offshore.

In this issue:

Its steep flanks are clearly fault-bounded. The longest, northeast-facing flank is oriented normal to the direction of seafloor spreading in the adjacent abyssal part of the Tasman Basin. It represents a continental rift block that was emplaced at ~80 Ma, when seafloor spreading commenced. Farther

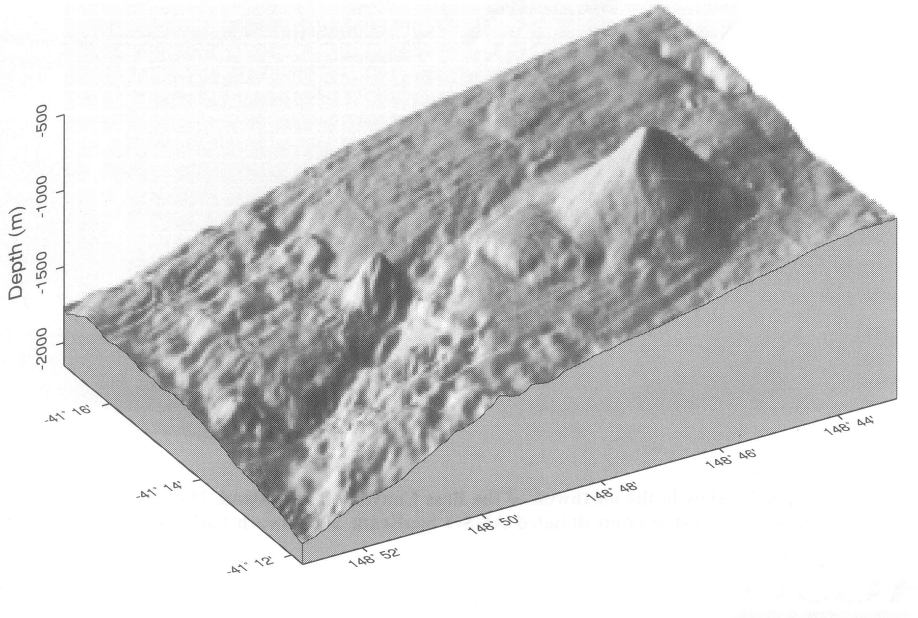

Fig. 3. View of the northeast face of St Helens Hill (Fig. 2) and adjacent upper continental slope off northeast Tasmania. Horizontal scale is indicated by the tick marks spaced at 2-minute intervals, about 3 km. The volcanic cone lies in 1050 m of water and rises to about 600 m below sea level. Orange roughy aggregate in dense shoals over the summit area during spawning runs in winter.

south, a basement ridge displays pronounced structural trends oriented northeasterly, parallel to the transform direction in the Tasman Basin, and north-northwesterly, roughly parallel to the spreading fabric and late rift direction. The sea-floor west of the ridge, over the possible sedimentary basin inferred from ERS–1 satellite gravity data, is smooth and slopes gently to the south. In the northern part of the area, a prominent northeasterly structural trend is also apparent on the southeast side of a broad basement high southeast of St Helens Hill. A number of shallow (50–100 m deep), but long (30 km or more) canyons cut downslope in this area. The longer ones trend east-northeast, but shorter sets show an east–west trend.

St Helens Hill, 450 m high (Fig. 3), is the only large volcanic cone mapped in the area. Apart from an embayment on its upper northwest side (?crater and/or slump) and steeper southern flank, the edifice is fairly symmetrical. A number of smaller cones (up to ~250 m high) were mapped on the continental slope to the east and northeast of St Helens Hill. The upper slope south of St Helens Hill (800–1400 m deep) is gullied, and has a scattering of pinnacles to ~30 m high, but overall is moderately flat. The imagery suggests that the slope is underlain

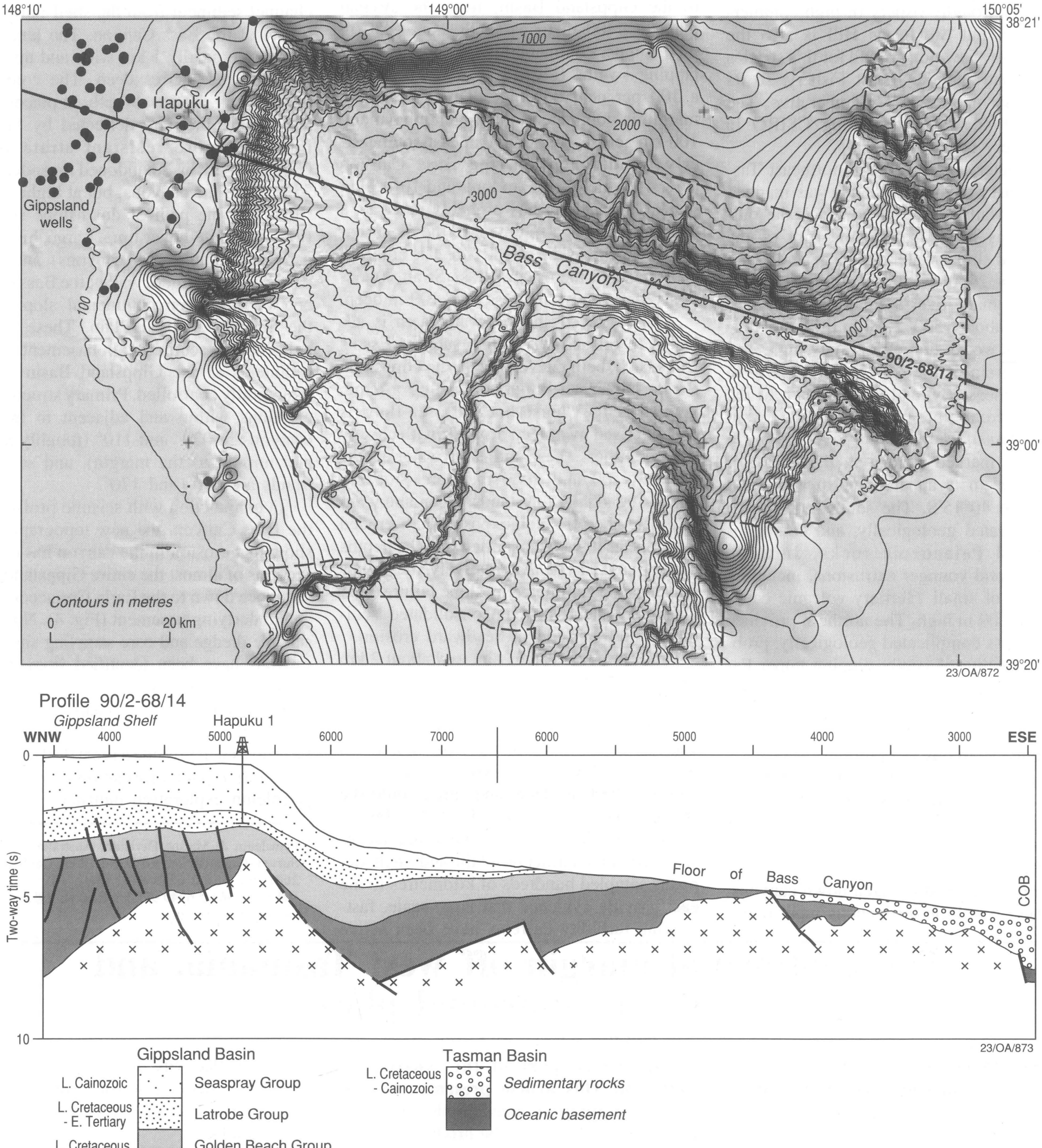

Fig. 4. Shaded contour map (100-m isobaths) of the Bass Canyon embayment (same area as Fig. 1). The dashed line bounds the extent of high-resolution multibeam survey coverage; note the great difference in detail. Three major tributary canyons, each several hundred metres deep, convey sediment into the entrance of the Bass Canyon from the continental shelf to the southwest. Profile 90/2–68/14, a longitudinal seismic cross-section through the Bass Canyon, shows extensive exposure of the Gippsland Basin sequence on the floor of the canyon. The interpreted section is after Willcox et al. (1992: *in* Gippsland Basin Symposium, Australasian Institute of Mining & Metallurgy, 93–109).

by shelf limestone that has subsided by margin sag. Early–Middle Miocene shelf limestone has been recovered from this area (Quilty & Telfer 1994: Papers and Proceedings of the Royal Society of Tasmania, 128, 41–56). As St Helens Hill penetrates the limestone, the volcanism that formed it is mid-Miocene or younger.

The AGSO survey provided the first detailed maps and images of the important deep-sea trawl fishery off St Helens. Not only is this orange roughy fishery of high commercial value, but St Helens Hill is also the only known spawning ground for this species in the Australian Southeast Fishery, so its sustainable management is imperative. The new swath data are benefiting CSIRO in their fishery research.

The outer margin off far northeast Tasmania (east of Flinders Island) was mapped as three swaths (Fig. 2), of which the outermost was located along the foot of the continental slope. Water depths generally are in the range 2000–4000 m. Additional swaths were also made over a small area in water depths of about 1500–2000 m over the morphological expression of a gravity high. The regional grain of the margin is northerly to north-northeasterly, and slopes down to the east vary from quite gentle to about 7°, but are expressed more steeply as scarps in places. A marked change in the character of the margin is apparent north and south of latitude 40°15′S. The southern province is complicated geologically, and comprises deformed Palaeozoic rocks, Jurassic dolerites, and younger extrusions, including a number of small ?Tertiary volcanic cones less than 200 m high. The northern province is much less complicated geologically, probably consisting of gently dipping upper Palaeozoic and Mesozoic sedimentary rocks. The margin is cut by faults trending 330° and 015–040°, which define two major embayments. Canyons are rare.

The east Tasmanian margin was probably uplifted before rifting during the Late Cretaceous, and sank beneath the ocean after break-up. It has been little sedimented since, probably because the early flood of eroded sediments bypassed the area down canyons, and there was little terrigenous input thereafter. The East Australian Current flows south along the margin now and prevents pelagic sedimentation. The result is that pre- rift, rift, and break-up structures and rocks are all exposed at the sea bed.

Deep-water Gippsland Basin and Bass Canyon

The AGSO survey swath-mapped 8000 km^2 of the continental margin on and adjacent to the Gippsland Basin, from the abyssal plain at 4400 m to as shallow as ~450 m on the upper continental slope; slightly overlapping swaths (Figs. 1, 2, and 4) ensured a 100 per cent coverage. This part of the margin is dominated by a large embayment, 100 km across, floored by an east-southeasterly trending chasm, the Bass Canyon (Fig. 4), which is 60 km long and 10–15 km wide. This canyon has probably acted as a conduit for clastic sediment to the deep seafloor since break-up at ~80 Ma. The adjacent shelf beneath the eastern Bass Strait is generally flat, sandy, and less than 100 m deep.

The surveyed shallow-water area is adjacent to oil and gas fields, such as Esso's Blackback, being developed in the Gippsland Basin, and is an important fishing ground, known as the 'horseshoe'. Its sea-floor is characterised by a steep drop-off with closely spaced gullies. These gullies, in water depths between 700 and 2000 m, were probably cut during glacial lowstands, when abundant sediment shed from an exposed shelf eroded the slope as it was transported into the depths of the Bass Canyon. Alternatively, the gullies may have been initiated by slope failure (also during lowstands) of unconsolidated sediments, and subsequent headward erosion.

The Bass Canyon has incised about 2 km into the margin, and is bounded to the north and south by steep inner walls 1000 m high. Its floor, 7–8 km wide, is moderately flat and has a gentle dip to the east. Sediments transported down the canyon debouch at its mouth, ~4000 m deep, and spread onto the abyssal plain via a network of distributary channels and levees with ~50 m relief. Deep-sea cores of continental-plain and shelf deposits sampled hundreds of kilometres to the east provide evidence that large-scale, fast-moving turbidity currents have been active in the past. Probably initiated by slope failure on the upper slope, these sediment-laden currents would have been funnelled through the Bass Canyon, depositing their sediment load on the abyssal plain.

Upslope at ~3200 m depth, the canyon opens into a broad semicircular amphitheatre, ~60 km across, extending to the shelf edge (Fig. 4). The surface of this amphitheatre is deeply incised by three large tributary canyons and a number of smaller ones. They channel sediment from the shelf into the entrance of the Bass Canyon. The larger canyons are typically 1 km wide and up to several hundred metres deep. The courses of the canyons change abruptly in places, probably where they are deflected by faults or intersect more resistant strata of the Gippsland Basin. Abandoned meander plains adjacent to the canyons, but at higher levels, show that the path of downslope sediment flow has shifted over time. Large, high-relief canyons (mainly box canyons) and ridges occur on the northern wall of the Bass Canyon and on the steep continental slope facing the Tasman Abyssal Plain. These features are probably sculptured in basement or older sediments of the Gippsland Basin and are structurally controlled. Primary structural orientations within and adjacent to the Bass Canyon are 020° and 110° (roughly parallel and normal to the margin), and secondary trends are 130° and 170°.

In conjunction with seismic profiles over the Bass Canyon, the new topographic data show that erosion in the canyon has exposed sections of almost the entire Gippsland Basin sequence down to the Early Cretaceous strata and underlying basement (Fig. 4). Numerous suitable dredge and core sampling sites in the canyons have been identified from the new maps and images for a geological sampling research cruise of RV *Franklin*, scheduled for 1998. The results from the *Melville* and *Franklin* cruises will provide a great deal of tectonic and stratigraphic information of value to the petroleum exploration industry.

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The continental margin off west Tasmania, and Tasmania's marginal plateaus

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An AGSO collaboration with other scientists has spawned a thematic issue of the *Australian Journal of Earth Sciences* (vol. 44 no. 5, for October 1997) which presents a wide-ranging review of the geology off Tasmania. Contributions include a tectonic review, syntheses of the geology of the west Tasmanian margin and the two offshore plateaus, three papers on igneous and metamorphic rocks, two on biostratigraphy, two on Quaternary sediments, and one on manganese nodules and crusts. They add greatly to the geological understanding of a potentially resource-rich part of the Australian continent. This article presents some of the major findings aired in the thematic issue, particularly for the offshore basins.

In 1994, AGSO surveyed an area south and west of Tasmania including the South Tasman Rise (STR) and the East Tasman Plateau (ETP; Fig. 5) aboard RV *L'Atalante*. A multibeam sonar system on the vessel returned a broad swath of bathymetric and acoustic data from the sea bed. Merging of the data from parallel tracks provided continuous coverage of about 200 000 km^2 of the sea bed, and superb bathymetric and acoustic reflectivity maps were produced. In addition, reflection seismic, magnetic, and gravity profiles were recorded along the ship's tracks.

In 1995, an AGSO follow-up sampling cruise aboard RV *Rig Seismic* used the *L'Atalante* maps and all seismic profiles to accurately target its dredges and corers. The work was constrained to the area mapped by *L'Atalante*. On this cruise, 53 deep-water dredge and 20 core stations provided physical information to facilitate interpretation of the remotely sensed data.

Regional setting

Tasmania was part of East Gondwana until late in the Cretaceous, when the Lord Howe Rise and Antarctica started to move away separately from it. Australia and Antarctica did not separate fully until the Oligocene, when Antarctica cleared the STR. Altogether, Tasmania has moved 2500 km northward relative to a fixed Antarctica.

The STR consists of western and eastern terranes: relative to Tasmania, the western terrane moved 450 km south in the Late Cretaceous and early Tertiary (95–65 Ma); the eastern terrane moved 150 km south in the Late Cretaceous (95–65 Ma). The ETP moved 130 km eastward relative to Tasmania in the Late Cretaceous (95–83 Ma).

Tasmania's complex geology is dominated by outcropping Jurassic and older rocks. The continental shelf and slope have large Cainozoic and Cretaceous depocentres north and west of Tasmania, in the Bass and Sorell Basins (Fig. 5), but are much less sedimented in the south and east, where basement outcrops are common. Two saddles, more than 3000 m deep and consisting of stretched continental crust, separate Tasmania from the STR and ETP. They constitute broad, moderately flat areas, and contain substantial sedimentary basins of Cretaceous and Cainozoic age. The STR and ETP drop off steeply to the abyssal plain at 4000–4500 m. The western margin of the STR is clearly controlled by the northern part of the Tasman Fracture Zone (Fig. 5), which extends southward to Antarctica.

West Tasmanian margin

The west Tasmanian margin is occupied by the Sorell Basin, which has a Cretaceous–Tertiary section at least 2 km thick* over more than 50 per cent of its almost 100 000 km^2 area and at least 6 km thick locally (Figs. 6 and 7). Northwesterly to north-northwesterly trending strike-slip faults control basin structure. Aeromagnetic modelling indicates that Late Cainozoic volcanics underlie parts of the continental shelf.

The Sorell Basin was initiated in the latest Jurassic to earliest Cretaceous, largely by northwesterly oriented wrench tectonics in the Southern Rift System between Australia and Antarctica. Late Cretaceous shallow-marine to fluvial detrital deposition was disrupted by major Maastrichtian to Early Paleocene tectonism associated with the Australia–Antarctica break-up. This was the last major structuring event in the Sorell Basin. It produced a basement high (Toogee Ridge in Fig. 5) adjacent to a transtensional plate boundary, and extensive faulting throughout the basin, including wrench reactivation of the depocentres now beneath the shelf (Fig. 6). The Toogee Ridge is block-faulted, and intruded by igneous rocks. As the spreading axis migrated southward relative to Australia, the margin subsided from north to

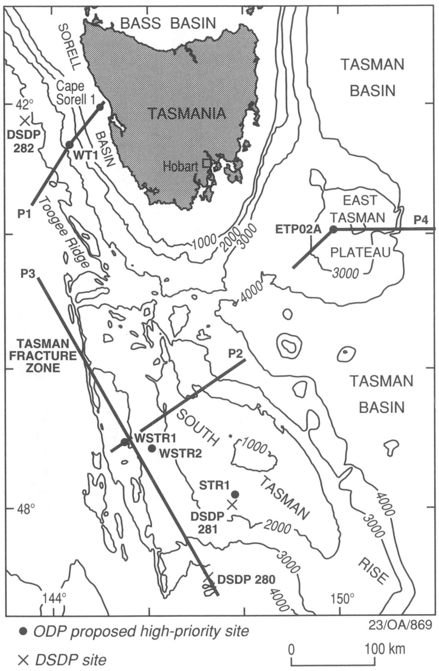

Fig. 5. Bathymetric map (contour interval = 1000 m) of the Tasmanian area, showing seismic profiles illustrated in Fig. 6, Cape Sorell 1 petroleum exploration well, and proposed Ocean Drilling Program sites.

south. Thick prograding deltaic sequences accumulated on it during the Paleocene in the north and Eocene farther south.

In the mid-Late Eocene, seafloor spreading in the Southern Ocean accelerated markedly and changed direction to north–south; associated transform movement along the western margin of the STR induced wrench deformation, mainly in the southern Sorell Basin. The west Tasmanian margin sagged rapidly as Antarctica departed after the Eocene. Starved of terrigenous sediments, it provided the setting for temperate carbonate sedimentation.

Free oil traces were found in Cape Sorell No.1 well, drilled in the Strahan Sub-basin off Macquarie Harbour. In addition, geochemical studies of surface-sediment cores indicate the occurrence of thermogenic hydrocarbons and mature source rocks at depth in the Strahan and Sandy Cape Sub-basins. Numerous structures in the Sorell Basin are favourable to the accumulation of petroleum, but not enough is known about basin lithologies to be sure that suitable reservoirs exist.

South Tasman Rise

The STR, a continental fragment of 200 000 km^2 with its culmination at roughly 800 m (Fig. 5), assumed its present configuration in the Palaeogene. It is surrounded on three sides by Late Cretaceous and Palaeogene oceanic crust. Its western side is dominated by the Tasman Escarpment, the northernmost part of the Tasman Fracture Zone. Linked to Tasmania by thinned continental crust, the STR consists of three north–south-oriented structural blocks that moved southward with Antarctica from Tasmania in the Late Cretaceous. All were affected by northwest–southeast strike-slip motion in the Late Cretaceous, and north–south extension and strike-slip motion in the Tertiary. The faults controlling the basins within the blocks accordingly trend northwesterly, northerly, or easterly (Fig. 7). The longest and most intense tectonism focused on the western block, which consists of large basement highs and the complex Ninene Basin.

Basins on all three blocks are fault-controlled, and are believed to contain Upper Cretaceous to Lower Oligocene detrital nonmarine and shallow-marine sedimentary rocks, and Upper Oligocene and younger bathyal to pelagic chalk and ooze (Fig. 6). The Ninene Basin sequence is more extensive and generally somewhat thicker (up to 5 km) than basin sequences on the other two blocks. Basins on all three blocks contain fault structures, and are prospective for petroleum in the long term, but only the central block is in water depths that are presently favourable to drilling. Geochemical studies of shallow cores indicate that thermogenic hydrocarbons were generated in the Ninene Basin and basins to the northeast, so mature source rocks must exist at depth. Little is known about pre-Eocene lithologies, so nothing can be said about potential reservoir rocks.

East Tasman Plateau

The East Tasman Plateau covers an area of 50 000 km^2 in water 2500–3000 m deep. Its continental affinity, implied by geophysical data, was confirmed by samples recovered from four stations on the bounding scarps of the ETP during AGSO's 1995 survey. These samples include orthogneiss of Late Proterozoic age, rhyolite, metasediments, metabasites, quartzite, quartz, quartzose sandstone, and ferricrete. Geophysical and petrological evidence suggest that the ETP was adjacent to the STR until it was transported east-northeastward during the Late Cretaceous early formation of the Tasman Basin. Stretching and seafloor spreading formed the 4000-m-deep L'Atalante Depression between the ETP and STR. Lord Howe Rise separated from the ETP at 75 Ma, as part of the Tasman Basin spreading, and the ETP thereafter remained fixed relative to Tasmania.

The plateau supports the Cascade Seamount, a Late Eocene guyot that rises to 650 m below sea level, and is part of the north–south trace of the Balleny mantle plume, which now lies beneath the Balleny Islands in the Ross Sea. The seamount consists of volcanic breccia, hyaloclastite, and alkali-olivine basalt. Seismic profiles (Fig. 6) suggest that the weight of the seamount might have caused subsidence of the central plateau area, where up to 1500 m of sediment fill a depression. Seismic profiles and some sedimentary evidence indicate that the depression is filled by 500–1000 m of Upper Eocene and Lower Oligocene volcaniclastic rocks, and 200–500 m of Upper Oligocene and younger calcareous ooze and chalk. These sequences are not thick enough to suggest that the ETP has any petroleum potential.

* 1 s TWT = ~1000 m of sedimentary section (cf. Figs. 6 and 7).

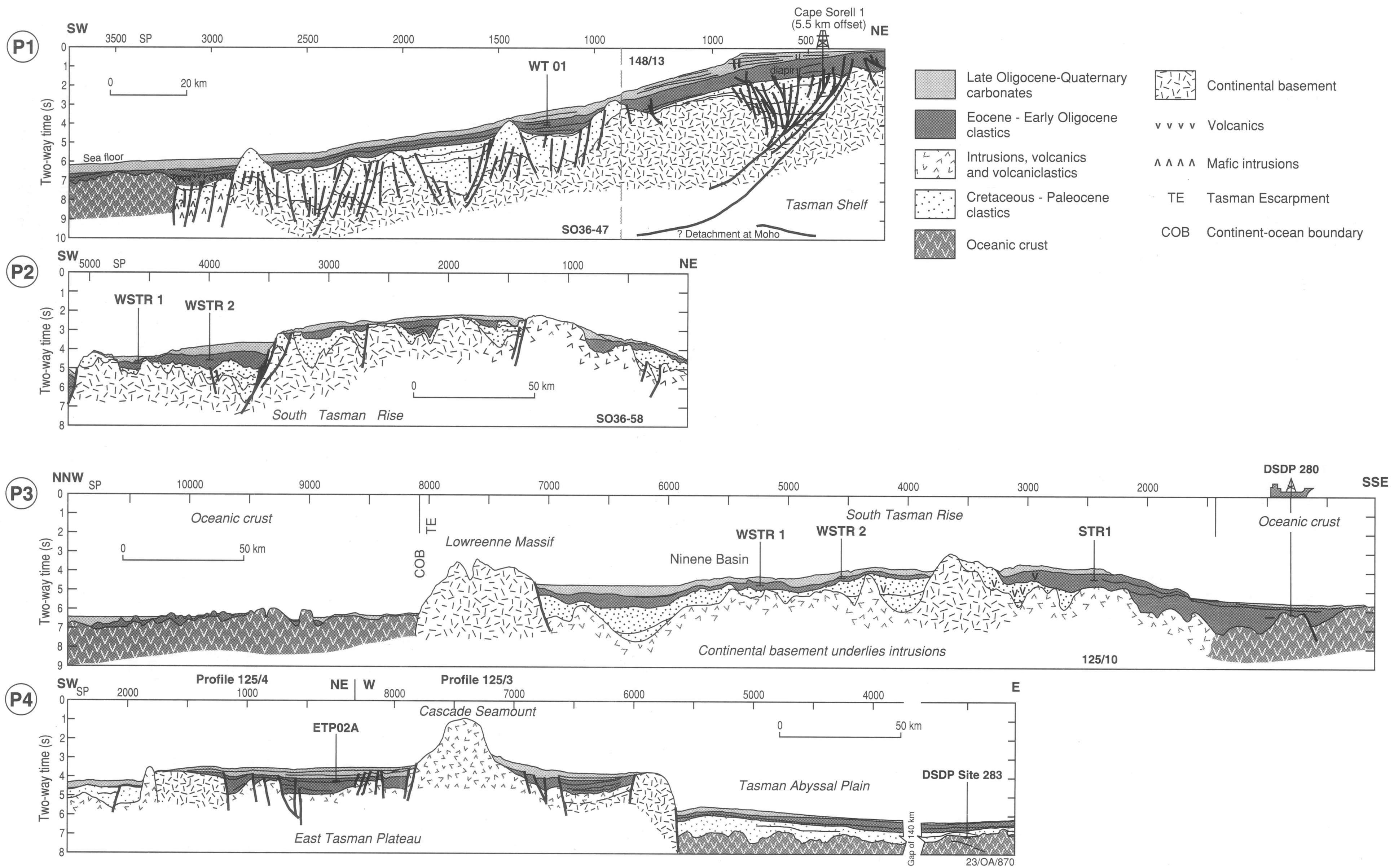

Fig. 6. Line drawings of seismic profiles across the west Tasmanian margin (P1), the South Tasman Rise (P2 and P3), and the East Tasman Plateau (P4). Locations in Fig. 5.

Fisheries and ferromanganese crusts

Areas south and west of Tasmania support the orange roughy, whose benthic habit induces fishermen to run their trawls just above the sea bed. Consequently, the high-quality bathymetric maps and images derived from the 1994 AGSO multibeam sonar survey over the southern fishing grounds generated a great deal of interest in the fishing industry. Declining stocks have raised questions of conservation not only about this fish but also about the unusual benthic assemblages growing on the seamounts, including corals, which provide cover for the orange roughy. A temporary Marine Protected Area established in 1995 over the newly discovered deeper

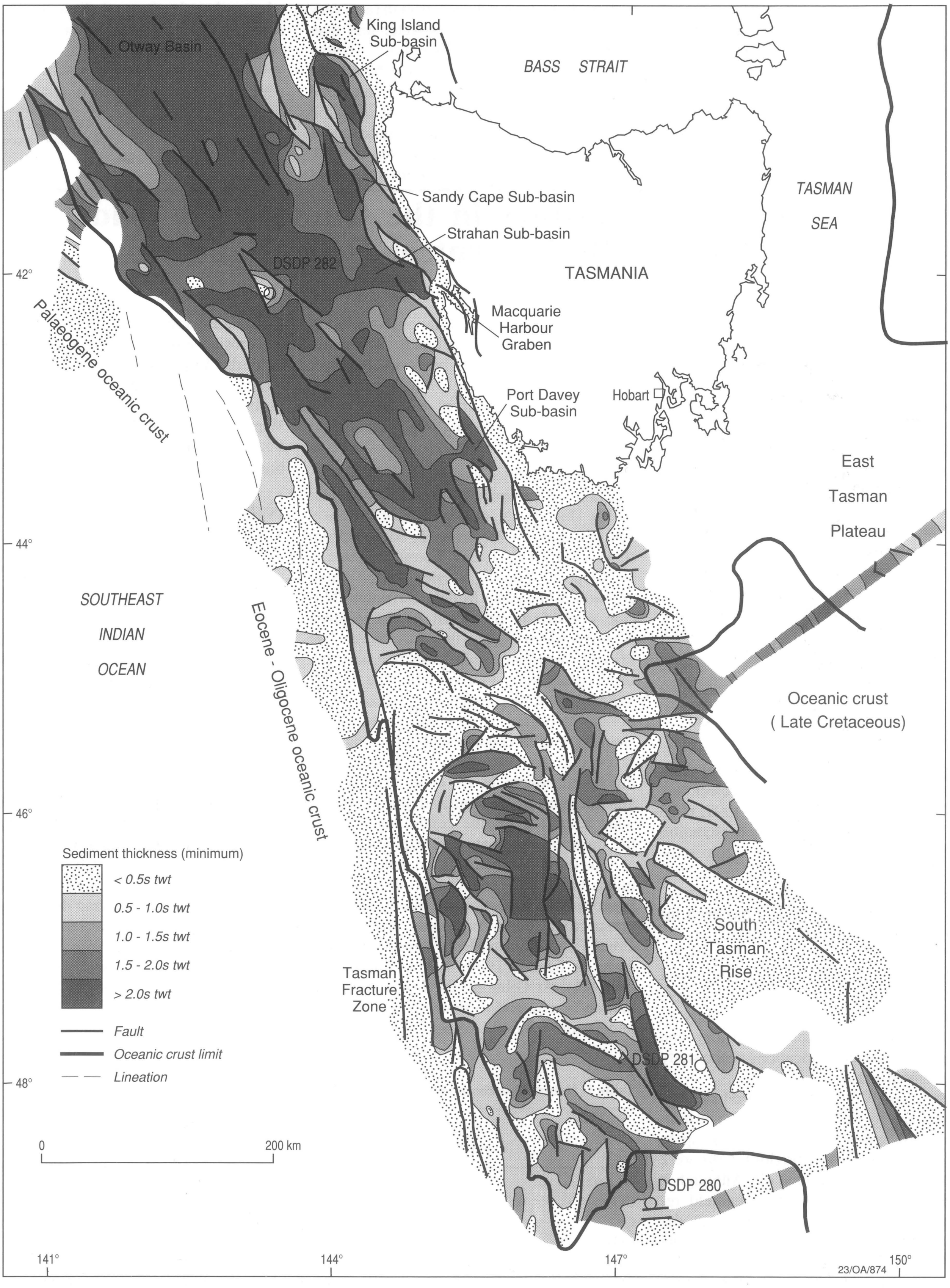

Fig. 7. Minimum sediment thicknesses according to seismic-profile interpretation on the west Tasmanian margin and South Tasman Rise. The depocentres are controlled by strike-slip faulting trending north-northwesterly in the north, and north-northwesterly and northerly farther south, depending on the tectonic regime.

seamounts south of Tasmania (volcanoes of Tertiary age) imposes a fishing moratorium while their natural resources are investigated.

Canyons in the upper continental slope west of Tasmania support a blue grenadier fishery, and the new multibeam sonar maps of that area are also of value to fishermen. In the light of the reaction to the maps, AGSO has established links with various parts of the fishing industry, and is actively promoting multibeam mapping to help define fishing potential for benthic species such as the orange roughy, blue grenadier, and Patagonian toothfish.

West of Tasmania and on the STR, rocky outcrops are commonly coated with unusually thick (up to 20 cm) ferromanganese crusts and exceptionally large ferromanganese nodules. Most crusts and nodules are of low grade, hydrogenetic, and mainly ferruginous vernadite and amorphous iron oxyhydroxide. Calculated crust growth rates vary from about 0.5 mm/m.y. in water less than 2000 m deep to about 20 mm/m.y. below 3000 m. Average grades (Cu + Ni + Co = 0.63%) in the nodules are of no commercial interest. The crusts average 0.08% Cu, 0.32% Ni, and 0.34% Co (total 0.74%), again grades of no commercial interest. However, six bulk analyses of crusts taken within the lower part of the oxygen minimum zone (1500–2000 m water depth), where Co grades are generally higher, average 0.79% Co. This grade is similar to that of high-grade crusts elsewhere, and suggests possible long-term economic potential. As is common elsewhere, though, these shallow-water crusts are only 2–4 cm thick, about the economic cut-off thickness.

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Multiple filling history in the Gilmore gas field, Adavale Basin, central Queensland

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Molecular and isotopic compositions in the Gilmore gas field (Adavale Basin, central Queensland) record the multiple filling history of this large dry gas reserve, which comprises deep-sourced methane and nitrogen mixed with wet gas and minor oil. Maturation indicators for the wet gas and associated oil are similar: both hydrocarbon phases have been generated at maturity levels past the conventional oil window (vitrinite reflectance >1.3%). The large input of deep dry gas to the reservoir (at a depth of about 3300 m) could have fractionally displaced condensable liquid, which accordingly might have migrated to shallower reservoirs if appropriate traps and seals have prevailed.

Gilmore gas drives first 'CAB' off the rank

AGSO's recently commenced 'Central Australian basins gas' ('CABGAS') project (see *AUS.GEO News 42*, for October 1997, p. 3) is designed to provide a better understanding of the development of the Palaeozoic sedimentary basins in the region, and to improve perceptions of gas prospectivity in them. A pilot component of this project has been investigating the origin of gas and oil in the Devonian Adavale Basin. Molecular and stable-carbon-isotope compositions of gas and oil in the Adavale's Gilmore gas field have provided the primary focus of a study to determine source and maturation history. The results and regional implications of the study are presented below.

The Gilmore field (Fig. 8) produces dry gas (methane 76–88%, ethane < 3%, and non-hydrocarbon gases such as nitrogen, up to 21%, and minor carbon dioxide). Gilmore 2 well contains non-economic oil. Although it was discovered in 1964, the gas field remained uneconomic for nearly 30 years, despite its large gas reserves (de Boer 1996: APEA Journal 36, 117–129), initially estimated to be up to 1.3 TCF (36.9E + 09 m^3). More recent estimates have reduced the recoverable reserves by an order of magnitude (Brand 1994: *in* 16th Annual Petroleum Symposium, Petroleum Exploration Society of Australia, Queensland Branch, Brisbane). Nevertheless, the gas is being used to fuel a gas turbine generating 37 MW of power. Even so, the gas reserves will have to be supplemented if electricity is to be generated continuously.

The Adavale Basin contains up to 4000 m of strata, and is entirely covered by younger basins (Fig. 9; cf. de Boer 1996: op. cit.). The gas and oil were probably sourced from shale in the Log Creek Formation, which was deposited during a brief marine transgression in the early Middle Devonian. Marine conditions prevailed in the eastern Adavale Basin during the start of the late Middle Devonian, when limestone accumulated extensively. Farther west, the Lissoy Sandstone was deposited over the Log Creek Formation during another marine transgression. As well as containing the principal reservoir unit, this formation is a potential hydrocarbon source in its upper part, where algal laminates accumulated during basin-wide restricted marine conditions marking the onset of evaporative precipitation.

The timing of hydrocarbon generation remains uncertain, though multiple phases of hydrocarbon generation are likely. The most prospective source-rock units are the Log Creek Formation and Bury Limestone (Passmore & Sexton 1984: APEA Journal 24, 393–411). At Gilmore, the Log Creek Formation is assumed to have entered the gas-generation window during Adavale Basin time (de Boer 1996: op. cit.). Regional uplift and erosion suppressed further gas generation until the Log Creek Formation was again buried deeply enough for it to resume — during deposition of the Late Cretaceous Winton Formation. Post-Cretaceous generation is also considered likely owing to the high nitrogen gas content (de Boer 1996).

Natural gas geochemistry

The molecular proportions of hydrocarbon and non-hydrocarbon gases in the Gilmore gas field wells (Table 1) are similar to those previously reported for the Adavale natural gases (de Boer 1996: op. cit.).

All gases can be considered dry (%C_1/C_1–C_4 hydrocarbon > 95%); the percentage of wet gas is low, and ranges from 2.7 to 3.5% for Phfarlet 2 and Gilmore 1 respectively. The carbon-isotope composition for methane ranges from –33.0 to –35.4‰, and has a consistent thermogenic character. The Log Creek Formation source rocks most likely contain type II kerogen, and for Palaeozoic organic matter would be expected to generate methane with $\delta^{13}C$ between –39.5 and –43.5‰ (Price 1995: Chemical Geology, 126, 335–349). The Gilmore field methane is more enriched in ^{13}C than this, suggesting that either it was not generated in association with the oil or it was altered isotopically by a post-generative process.

According to the genetic fields defined by Schoell (1983: American Association of Petroleum Geologists, Bulletin 67, 2225–

Table 1. Natural gas composiiton : Adavale Basin natural gases

	Gilmore 1 mole %	*Gilmore 3* mole %	*Gilmore 5* mole %	*Phfarlet 2* mole %
N_2 corr	8.88	19.54	14.30	15.88
CO_2	2.67	1.71	1.50	1.97
Ch_4	86.39	76.98	82.04	80.58
C_2H_6	1.56	1.51	1.81	1.38
C_3H_8	0.18	0.00	0.20	0.07
i-C_4	0.05	0.04	0.04	0.00
n-C_4	0.02	0.00	0.03	0.00
H_2	0.26	0.22	0.08	0.11

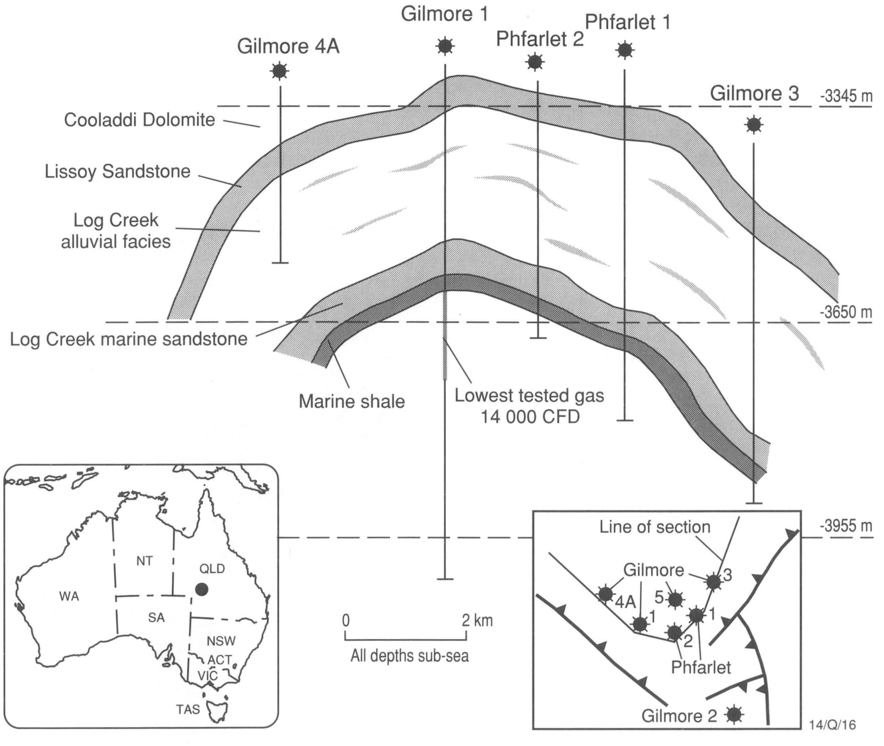

Fig. 8. Location of the Adavale Basin and Gilmore gas field (modified after Brand 1994).

2238), the Adavale Basin natural gases are of mixed origin and include a component from a 'deep' methane source (Fig. 10). If the deep source is completely dry (i.e., methane is the only hydrocarbon gas), the wet gas components will be unaffected isotopically, so the magnitude of the carbon-isotopic difference between wet gas components may be used as a measure of gas maturity (James 1983: American Association of Petroleum Geologists, Bulletin 67, 1176–1191). A wet-gas/deep-methane mixing ratio is calculated with an upper limit of 2.2 (Boreham et al.: submitted to the 1998 APPEA Journal).

This 'mixing' model (Jenden et al. 1993: American Association of Petroleum Geologists, Bulletin 77, 980–988) is preferred to a 'leakage' model (Prinzhofer & Huc 1995: Chemical Geology, 126, 281–290), which would result in the remaining gas becoming progressively wetter. Further, the leakage model would not readily account for the high non-hydrocarbon gas content. The mixing model also adequately explains the minor oil occurrence in Gilmore 2. Since the original gas was much wetter and found in association with a source from marine type II organic matter, it would be expected to be accompanied by an oil leg. Being a gas, the incoming deep-source methane can fractionally displace oil (as well as liquefied wet gas) through buoyancy (Gussow 1954: American Association of Petroleum Geologists, Bulletin 38, 816–853). The minor oil recovered in Gilmore 2 may represent a remnant of a much larger palaeoliquid reservoir. The expelled oil might have migrated to shallower depths, and been trapped in any younger reservoir rocks.

Boreham et al. (op. cit.) discuss the origin of the non-hydrocarbon gas components in more detail.

Oil geochemistry

The gas chromatography (GC) of the Gilmore 2 oil indicates that light hydrocarbons have been progressively lost from C_{15} to C_8, and that $< C_8$ are completely absent, resulting in an oil with moderate API gravity (38.6°).

The loss of the light hydrocarbons from the Gilmore oil is most likely explained within the basic concepts of migration–fractionation (Gussow 1954: op. cit.) and evaporative fractionation (Thompson 1987: Organic Geochemistry, 11, 573–590). These concepts have been cited to explain compositional changes in oil and gas during primary, secondary, and tertiary migration (Curiale & Bromley 1996: Organic Geochemistry, 24, 1097–1113; and references therein). In the Australian context, these oil modification processes have been largely overlooked by the geochemical fraternity. At Gilmore, deep-source methane entering the original oil reservoir could have displaced oil, leaving behind a residual oil lacking light-end components.

A presumed Devonian source for the oil would include the Gilmore 2 oil (Passmore & Sexton 1984: op. cit.; de Boer 1996: op. cit.) as a member of the Larapintine Petroleum Supersystem (Bradshaw 1993: PESA Journal 21, 43–53). Molecular and isotopic evidence facilitate a division of the Larapintine Supersystem into four systems in Western Australia, where the Larapintine 3 Petroleum System includes the Devonian-sourced oils of the Bonaparte and Canning Basins (Edwards et al. 1997: APPEA Journal 37, 351–379). The Gilmore 2 oil shares some strikingly similar GC and carbon-isotope characteristics with these Western Australian Devonian-sourced oils (Boreham et al.: op. cit.).

The biomarker patterns of the Gilmore 2

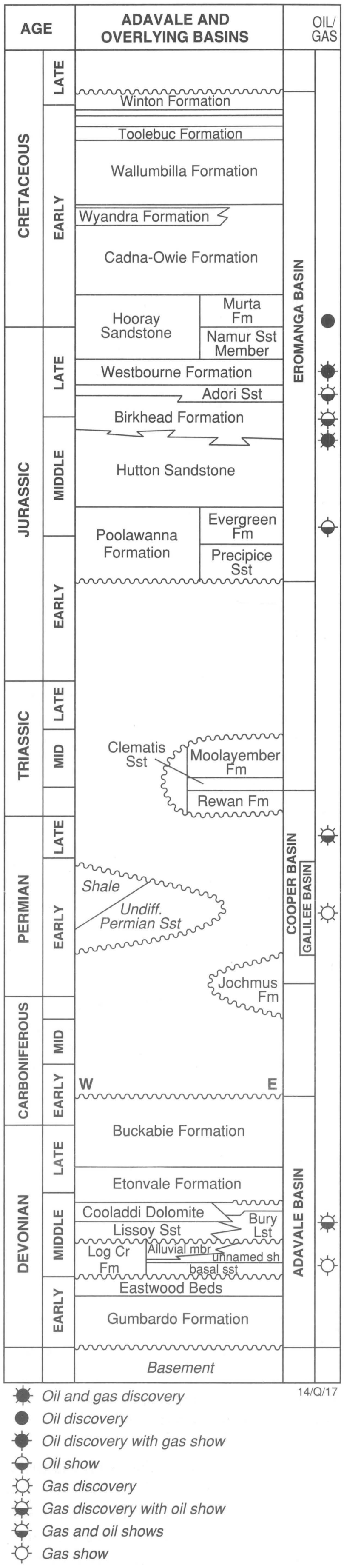

Fig. 9. Lithostratigraphy of the Adavale Basin and overlying sedimentary basins (modified after de Boer 1996).

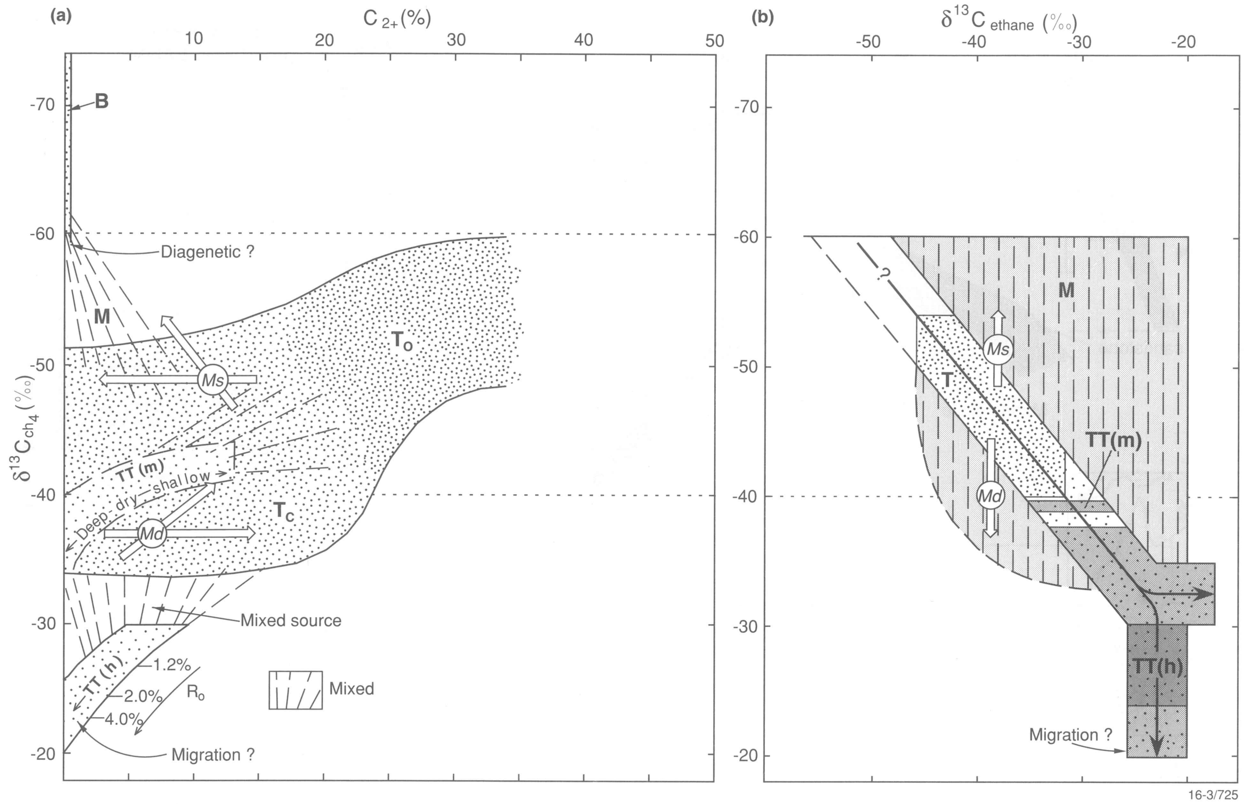

Fig. 10. Carbon-isotope ratio of methane (‰) versus (a) % wet gas, and (b) δ13C ethane (after Schoell 1983). Note: B = gas of biogenic origin from terrestrial and marine environments; M = gas of mixed origins, where Ms indicates direction of shallow methane mix and Md indicates direction of deep methane mix; T = gas of thermogenic origin, where To and Tc are associated with oil and condensate formation respectively; TT = gas of thermogenic origin non-associated with oil formation from sapropelic organic matter, TT(m), and humic organic matter, TT(h).

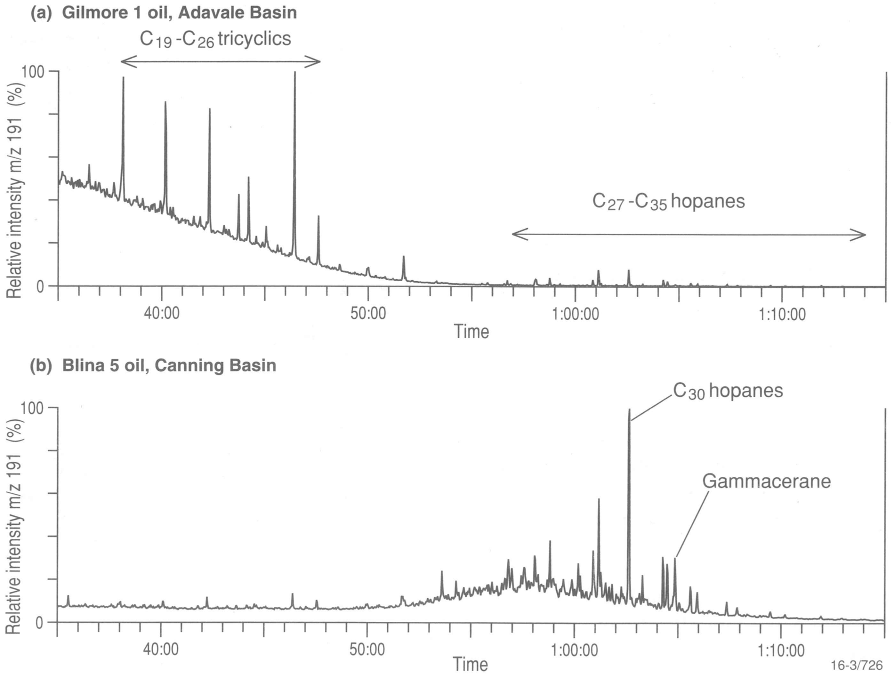

Fig. 11. Gas-chromatograph–mass-spectrometer (selected-ion-mode) trace of m/z 191 dalton for Gilmore 2 oil and Blina 5 oil.

oil are most revealing. The high maturity of the Gilmore 2 oil is graphically illustrated in the GCMS (SIM) traces (Fig. 11), in which the thermally more stable biomarkers are enhanced relative to those which undergo rearrangement/decomposition. For example, the tricyclic hydrocarbons are dominant over the pentacyclic hopanes (Fig. 11). In comparison, the Blina oil, from the Canning Basin, shows a more 'normal' maturity relationship characteristic of an oil generated within the main oil window. Owing to the high maturity of the Gilmore 2 oil, various source parameters have been attenuated, depending on the relative isomer or homologue stability. However, when maturity effects are taken into account, the source-specific biomarkers of marine/evaporitic origin in the Gilmore 2 oil are quite similar to those in Devonian-sourced oils of the Canning and Bonaparte Basins (Boreham et al.: op. cit.).

Palaeogeographic reconstructions suggest that the source rocks of the Devonian petroleum systems in the Canning and Bonaparte Basins were deposited within the arms of shallow restricted seas extending into the continent (Palaeogeographic Group 1990: 'Australia: evolution of a continent'; BMR [AGSO]). Thus, similar potential source rocks may have been deposited within a more extensive seaway connecting the Officer, western Georgina, and Canning Basins during the Early and Middle Devonian. This interval coincided with marine sedimentation not only in the Adavale Basin but in the Darling Basin (NSW) too. Further exploration in these areas thus may prove fruitful.

Acknowledgment

Peter Green (Geological Survey of Queensland) generously donated the Gilmore 2 oil. Tony Yeates, Barry Willcox, and Dianne Edwards (all AGSO) provided informative peer reviews of the manuscript.

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Archaean geology of the Lake Violet 1:100 000 Sheet area, Yandal greenstone belt, Eastern Goldfields Province, Western Australia

Alastair Stewart[1]

A solid-geology map is essential for mineral exploration and prospectivity studies, as it shows the composition, relationships, and structure of the outcropping rocks. In the Eastern Goldfields, thick regolith conceals much of the bedrock, and typically requires intensive drilling to determine the underlying geology. In the Lake Violet Sheet area, which lies between major gold mines at Jundee and Nimary to the north and Bronzewing and Mount McClure to the south, a new solid-geology map of the Archaean rocks will help prospectivity assessment and improve exploration models.

The Lake Violet Sheet area (Fig. 12) lies within Western Australia's Yilgarn Craton of late Archaean greenstone, intrusive granite, and granitic gneiss. The solid-geology map (Fig. 13) was compiled from new surface mapping (1995), aeromagnetic interpretation, and identification of 1094 rotary air-blast- (RAB) hole bottom samples spaced 600 to 1000 m apart. Stewart & Kamprad (1997: AGSO Research Newsletter 26, 9–11) used X-ray diffraction and portable infra-red mineral analysis (PIMA), to assign parent rock types to RAB samples of the weathered assemblages.

Archaean geology

The greenstone succession comprises two main sequences. The lower consists mainly of basalt, with smaller amounts of high-magnesium basalt, komatiite, and serpentinite; its upper part includes lenses of shale and felsic volcanics in the east, and banded iron formation (BIF) and chert in the west. The upper sequence is a thick pile of felsic volcanics, mainly dacite flows, tuffs, and volcaniclastic rocks, with lesser amounts of andesite, rhyolite, basalt, and shale. No stratigraphic facings have been found. Cross-sections (Fig. 14) indicate a thickness of 10 000 m for the total preserved succession, if none of it is repeated. Felsic porphyry and dolerite bodies presumably intrude the greenstone succession; dolerites are particularly abundant in the east.

Granite*, mainly monzogranite of the low-Ca group of Champion & Sheraton (1997: Precambrian Research 83, 109–132), underlies much of the area in the west. It ranges from massive to foliated, the latter being confined to a zone up to 15 km wide bordering the greenstone belt. Outcrops of banded gneiss within the foliated zone appear to be parts of elongate bodies up to 30 km long, which may be rafts of pre- or syntectonic granite. Two granite bodies enriched in high-field-strength elements are located in the south between the low-Ca granite and the greenstone belt. Stoped rafts of chert, BIF, and arkose along the eastern margin of the granite, the scalloped granite–greenstone boundary in the south, and centimetre-size magnetite porphyroblasts with grunerite beards in the adjoining BIF, indicate an intrusive contact.

Porphyritic granite in the northeast is foliated because of its proximity to the Ninnis Fault. Granite in the north and southeast is generally massive and coarse-grained, and belongs to the high-Ca group (Champion & Sheraton 1997: op. cit.). Numerous small leucocratic 'internal' granites, many known only from RAB holes, are present within the greenstone belt.

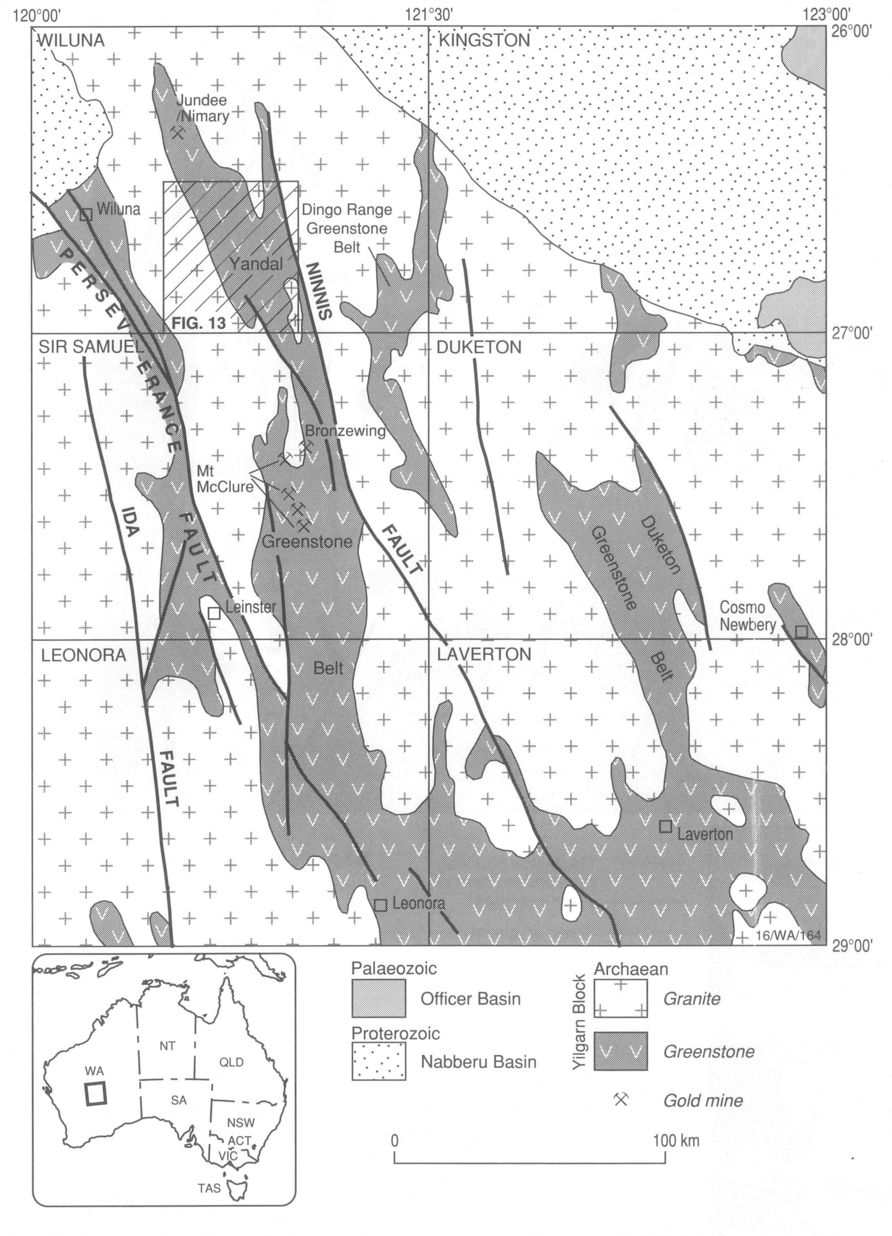

Fig. 12. Regional geology of the northern part of the Eastern Goldfields province, Western Australia (after Myers & Hocking, compilers, 1988: Geological map of Western Australia, 1:2 500 000; Geological Survey of Western Australia). The Lake Violet 1:100 000 Sheet area is hachured.

Metamorphism

All Archaean rocks are metamorphosed. The presence of chlorite, epidote–clinozoisite, actinolite–tremolite, biotite, serpentine, talc, and muscovite indicates the greenschist facies; lower-grade minerals such as prehnite, pumpellyite, and stilpnomelane were not found. The new minerals are well aligned in the pervasive foliation of the region, but are strain-free, indicating that metamorphism accompanied and outlasted deformation.

Grunerite in BIF at the western margin of the greenstone belt, and xenoblastic to poikiloblastic clinopyroxene in altered metabasalt in the southwest, are within a few metres of granite, and are attributed to contact metamorphism.

Structure

D1 structures noted elsewhere in the eastern Yilgarn Craton — recumbent folds, thrusts and duplexes, or extensional detachments — have not been recognised in the Lake Violet area. The most prominent structure is the Lake Violet synform (assigned to D2), which has a gentle to horizontal plunge and north-northwest trend (Fig. 13). A complementary D2 antiform–synform pair to the east is inferred from the symmetrical distribution of ultramafic units. In outcrop areas in the south, and in the granite adjoining the western margin of the greenstone belt, a regional steep D2 foliation strikes north-northwest, parallel to the axial plane of the Lake Violet synform. Regional D2 lineation is represented principally by the alignment of elongate recrystallised amphibole and mica, and mostly plunges north-northwest at about 25°. A 'zigzag' distribution of rock types revealed in RAB holes on the west limb of the synform indicates west-verging flexural-slip parasitic folds, consistent with the synformal structure.

* According to Myers (1997: Precambrian Research, 83, 1–10), 'granite' includes syenogranite, monzogranite (the most common), granodiorite, and tonalite.

The D3 transcurrent Ninnis Fault in the northeast is very poorly exposed, although clear on aeromagnetic images. It is marked by steeply dipping, intensely foliated mafic gneiss with felsic augen, and by flattened quartz in the adjoining granite. The northeast-dipping Kooyong Fault in the south is marked by iron-oxide-cemented siliceous breccia, or by quartz–muscovite schist zones up to 30 m wide, and has a gently northwest-

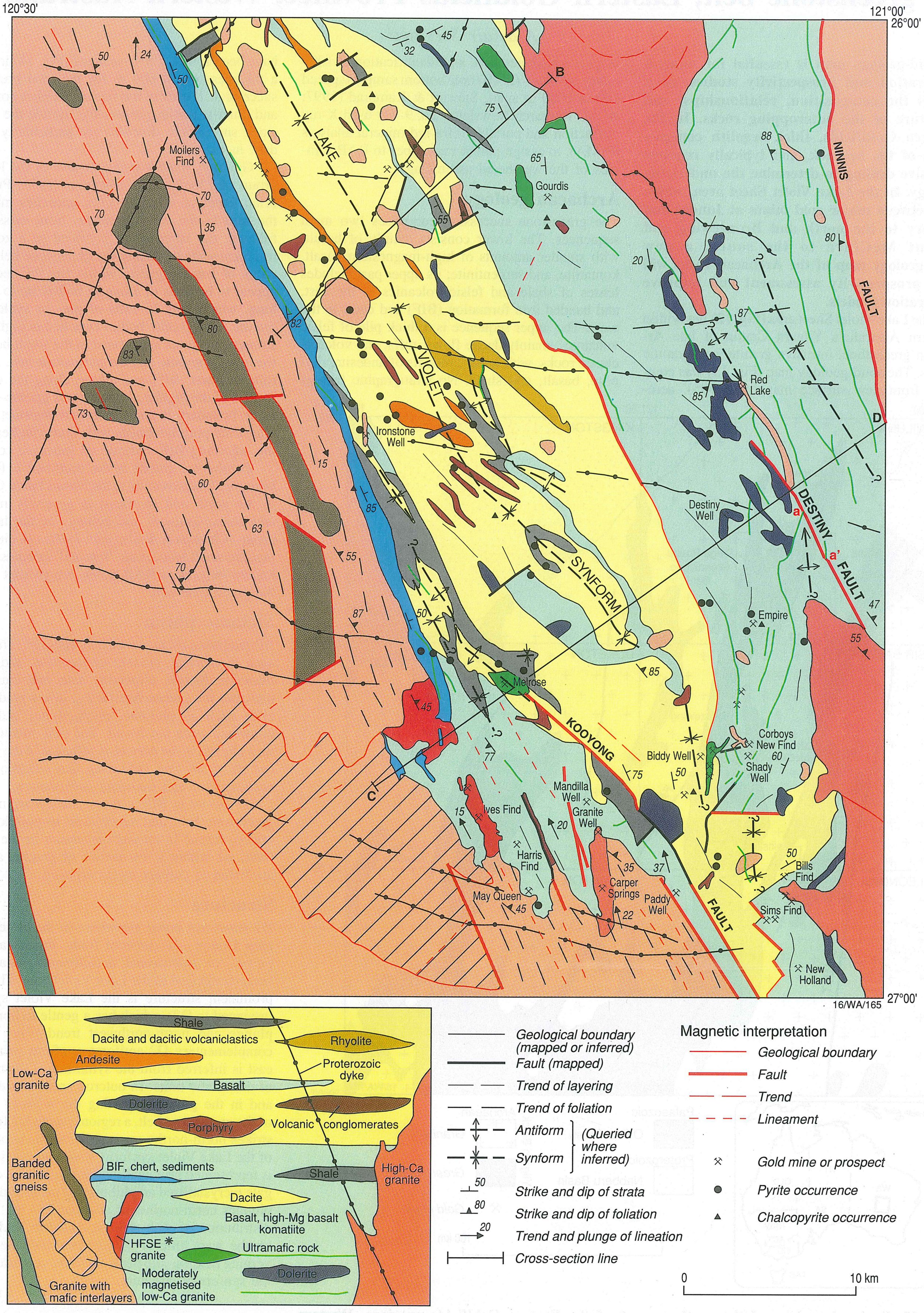

Fig. 13. Solid-geology map of the Lake Violet 1:100 000 Sheet area, compiled from geological mapping and interpretation of aeromagnetic data by the author, exploration company mapping, and analysis and interpretation of RAB-hole bottom samples by J. Kamprad (AGSO) and the author. *High-field-strength element.

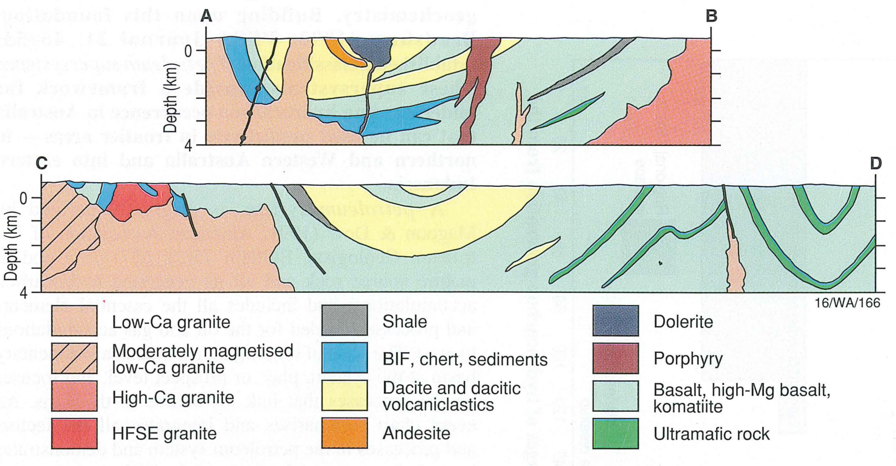

Fig. 14. Generalised cross-sections through the Yandal greenstone belt in the Lake Violet 1:100 000 Sheet area. For clarity, thin units are not shown. Legend as for Fig. 13.

plunging lineation. It appears to reflect westward thrusting of about 1.5 km (cf. cross-section CD; Fig. 14), and the lineation indicates substantial dextral strike-slip as well. The Destiny Fault in the east evinces about 2.5 km of dextral strike-slip, measured by offset ultramafic units a–a′ (Fig. 13). These two faults formed late in D2, after the major D2 folds, or during D3. Short cross-faults segmenting the Lake Violet synform are inferred from abrupt changes in lithology of RAB samples, and are not exposed. Some are visible on aeromagnetic images.

Structural history

D2 deformation formed a train of open to close upright folds with axial-plane foliation and gentle plunge, and subsequent transpressional faults in the south. The foliation and faulting affected the western granite and porphyry bodies, so the intrusions are pre- or syn-D2. The bodies of banded gneiss must be pre- or early syn-D2. D3 deformation produced the Ninnis Fault in the northeast.

Northeast-striking cross-faults and lineaments cutting the Lake Violet synform and western granite also affect undeformed post-tectonic and post-D3 granite (Ag_m) in the south. Hence, the cross-faults and lineaments are probably syn- or post-D4.

Proterozoic mafic and intermediate dykes intrude the Archaean rocks, and have undergone low-grade alteration. They form a conjugate set that indicates a principal compressive stress oriented east-northeast, the same as that indicated by the orientation of the D2 folds.

Relationships with surrounding areas

The Lake Violet greenstone succession extends north as two separate parts into the Millrose 1:100 000 Sheet area. The western part links with the Lake Violet synform, but 'appears to have an overall west facing' across its entire width (Wyche 1996: Geological Survey of Western Australia, Annual Review 1995–96, 188). This is based on two facing determinations near its east margin. Notwithstanding, a cross-section through the western part of the greenstone succession (Farrell & Wyche 1997: Millrose 1:100 000 Geological Series map; Geological Survey of Western Australia) shows fold vergences indicative of a synform. Another major difference is the depiction in the Millrose cross-sections of major but unexposed listric faults coincident with the margins of both parts of the succession.

Relevant maps and data

AGSO has previously released geophysical data* for the Lake Violet Sheet area, and will release new 1:100 000-scale geological and basement-geology maps in digital form and as coloured on-demand paper prints.

Acknowledgments

Dave Blake, Kevin Cassidy, Dave Champion (who also determined the geochemical classification of the granites), Dave Huston, and Terry Mernagh reviewed and greatly improved the paper. Alan Whitaker helped with magnetic interpretation.

* AGSO has released for sale Lake Violet 1:100 000 dyeline and transparency maps of total magnetic intensity (TMI) contours and profiles, total-count contours, and flight lines; and magnetic and gamma-ray spectrometric digital data (point-located and gridded); and, for the Wiluna 1:250 000 Sheet area, pixel-image maps (TMI in colour and grey-scale; see *AUS.GEO News 35,* for August 1996, p. 9). Also available is a 1:500 000 image of the first vertical derivative (reduced to the pole) of the TMI (image intensity) combined with Bouguer gravity in colour; it covers the Wiluna, Sir Samuel, Duketon, Leonora, Laverton, and Edjudina 1:250 000 Sheet areas (see *AUS.GEO News 36,* for October 1996, p. 13).

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Oil families, petroleum systems and supersystems

North West Shelf and eastern Indonesian synergies — today Australia, tomorrow the world!

Marita Bradshaw[1]

Work over a dozen years at AGSO has produced a continent-wide coverage of data for palaeogeography, petroleum systems, and oil

Table 2. Characteristics of key Australian petroleum supersystems

Supersystem	Subunit	Age	Source facies	Examples	Distribution — basin	Key discoveries
LARAPINTINE	1	Cambrian	marine calc. shale	Goulburn Gp, Tempe	Arafura, Amadeus	Arafura 1 oil shows
Early Palaeozoic: tropical-climate carbonates, evaporites, and marine clastics	2	Ordovician	marine	Horn Valley, Goldwyer	Amadeus, Canning	Mereenie oilfield
	3	Middle–Late Devonian	marine carbonate	Gogo, Ningbing	Canning, Bonaparte	Blina oilfield
	4	Early Carboniferous	marine anoxic shale	Anderson, Milligans	Canning, Bonaparte	Sundown oilfield
GONDWANAN	1	Early Permian	non-marine	Irwin River, Patchawarra	Perth, Cooper, Bowen	Tirrawarra gas & oil field
Late Carb.–Early Triassic: glaciation; clastics; higher-plant contribution to source rocks			marine	Treachery, Keyling	Bonaparte	
	2	Late Permian	non-marine	Blackwater Gp	Bowen	Rolleston gas field
			marine	Wagina	Perth	
			deltaic	Hyland Bay	Bonaparte	Petrel gas field
	3	earliest Triassic	marine	Kockatea	Perth	Dongara oil & gas field
WESTRALIAN	1	Late Triassic–E/M Jurassic	deltaic	Mungaroo	Carnarvon	Rankin Trend giant gas fields
Traissic–Cainozoic: break-up of northern and western margins; marine-rift environments	2	Late Jurassic	marine, anoxic?	Dingo, Flamingo	Carnarvon, Bonaparte	Barrow Island oilfield
	3	Early Cretaceous	marine	Echuca Shoals	Bonaparte, Browse	Undan/Bayu; Cornea?
	4 **Sahul**	Mesozoic	marine carbonate		Bonaparte, Timor, Seram	
AUSTRAL	1	Late Jurassic–Early Cret.	fluviolacustrine shale	Casterton, Pretty Hill, Parmelia	Otway, Perth, Carnarvon?	Katnook gas field, Gage Roads oil show
Late Jurassic–Cainozoic: break-up of southern and southwestern margins; terrestrial-rift environments	2	Early Cretaceous	fluvial — coaly	Eumeralla	Otway	Windermere, Minerva
	3	Late Cretaceous	fluviodeltaic	Latrobe Gp	Gippsland, Bass	Kingfish

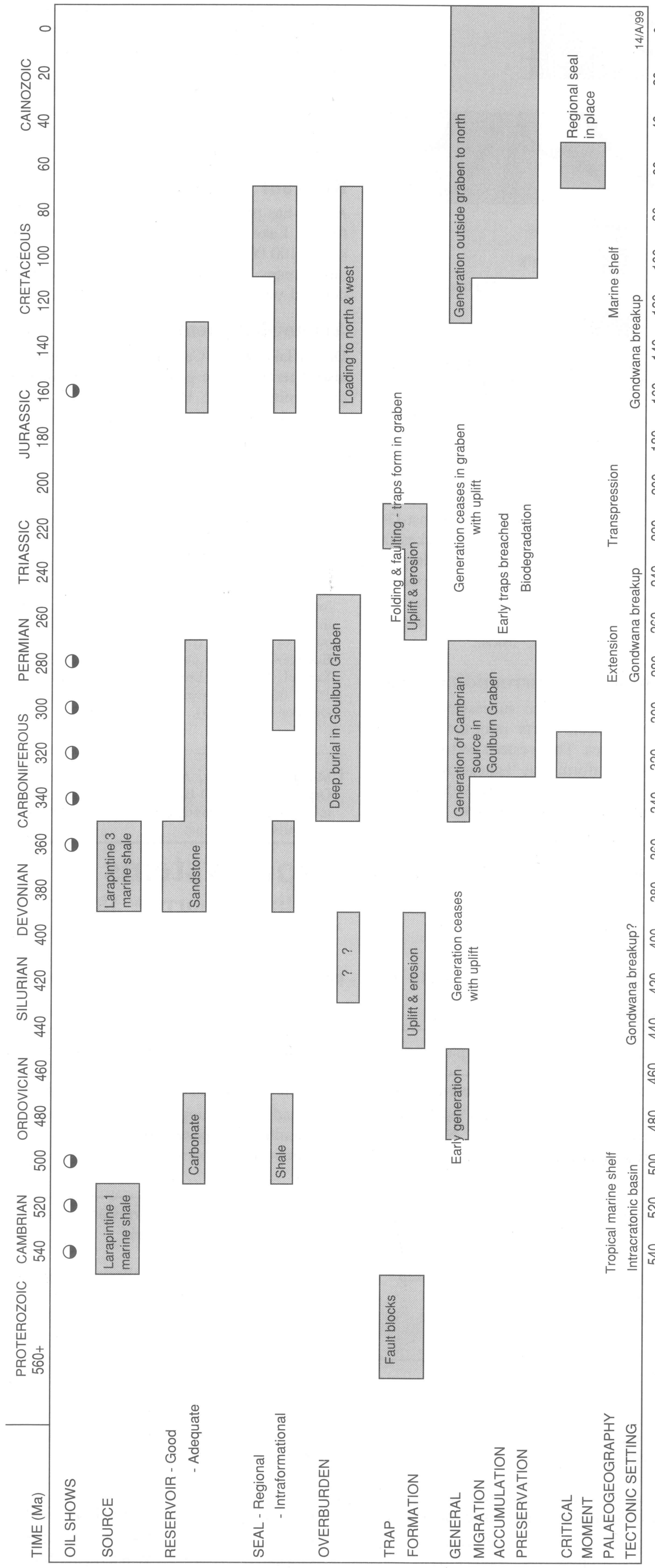

Fig. 15. An event chart for the Arafura Basin in which the key factors and processes in the petroleum system are plotted against time. Note the different ages of hydrocarbon generation from the Cambrian source rocks outside and inside the Goulburn Graben

geochemistry. Building upon this foundation, Bradshaw (1993: PESA Journal 21, 43–53) established a classification of *petroleum supersystems*. These supersystems provide a framework for understanding hydrocarbon occurrence in Australia that can be used predictively in frontier areas — in northern and Western Australia and into eastern Indonesia.

A *petroleum system*, as originally defined by Magoon & Dow (1991: American Association of Petroleum Geologists, Bulletin 75(3), 627), is a pod of mature source rock and all its generated hydrocarbon accumulations; and includes all the essential elements and processes needed for the oil and gas accumulations to exist. The scale of investigation is within a sedimentary basin at the system, play, or prospect level, and focuses on the processes that link the source to the traps. An event chart summarises and integrates all the factors and processes in the petroleum system and demonstrates how the system works to produce hydrocarbon accumulations. An event chart for the Arafura Basin. (Fig. 15) shows that the main phase of generation occurred before trap formation in the Goulburn Graben, and explains the absence of large discoveries in the wells drilled to date. The timing of generation, regional seal deposition, and trap formation are better aligned outside the graben, where hydrocarbon accumulations are more likely.

The petroleum system concept has been extended in Australia to establish a broad classification of supersystems (Table 2). A petroleum supersystem links individual petroleum systems that share the same age and facies of source rock across basin boundaries. Source-rock environment is a strong control on hydrocarbon chemistry and maturation behaviour. Hence the supersystem framework is mirrored and verified in the structure of Australian ***oil families*** (Fig. 16) in work jointly carried out by AGSO & GeoMark Research (1996: unpublished proprietary report).

Unlike the petroleum supersystem classification, which emphasises the geological age of a source, oil families are classified purely on geochemical criteria. In the oil family classification, the chemical characteristics inherited from the depositional environment generally prevail over the more subtle age-specific biomarkers that reflect the original biochemistry of plants, algae, and bacteria contributing the organic matter to the source rock. Hence, oils of different ages but of the same depositional facies tend to group together into a single oil family. In the Australian context, this occurs especially in non-marine settings; even so, some source-rock environments changed so dramatically through the Phanerozoic as the continent undertook its journey from the equator to the pole and back again that the distinction between the oil geochemistry of each of the supersystems is clear.

In contrast to petroleum systems, supersystems and oil families occur regionally across several basins, and from Australia into other parts of the plate in Indonesia and Papua New Guinea. For example, Late Devonian Larapintine 3 oils from the Canning Basin are more like Late Devonian oils from the Petrel Sub-basin of the Bonaparte Basin, 600 km away across the Proterozoic Kimberley Block, than Early Carboniferous Larapintine 4 oils from nearby fields. Oils from the Adavale Basin in eastern Australia (Boreham et al.: this newsletter, p. 8) are also part of the Larapintine Petroleum Supersystem, and current research is investigating whether Argentine and Bolivian oils, also derived from Devonian marine source rocks, belong to the same (Larapintine 3) oil family.

The shift in exploration focus in Indonesia to pre-Tertiary objectives provides an opportunity for the understanding gained in Australian petroleum systems to be usefully applied across international borders. The template provided by Australian oil families will enable hydrocarbons found in the pre-Tertiary of Indonesia to be typed by petroleum supersystem. Examples of this synergy in action include the Arafura and Bintuni Basins, the Timor Sea, Timor, and Seram (Fig. 17).

Excellent oil-prone source rocks occur in the Cambrian (Larapintine 1) and Late Devonian (Larapintine 3) sections of the Arafura Basin. The Cambrian source rock has been typed to the oil recovered from Devonian sandstones in Arafura 1 by Edwards et al. (1997: APPEA Journal 37(1), 351–379). The extension of the Arafura Basin to the north into Indonesia is indicated by well, seismic, aeromagnetic, and outcrop evidence. Exploration in the Arafura Basin has been restricted to the Goulburn Graben, where the large structures drilled postdate the main phase of hydrocarbon generation in the Carboniferous as modelled by Moore et al. (1996: PESA Journal 24, 25–51). Uplift and erosion arrested generation in the Late Triassic, before the major structural traps formed (Fig. 15). Earlier-formed accumulations were disrupted, as indicated by the biodegraded oil in the Arafura 1 well.

The Goulburn Graben is not a normal extensional feature but the site of an early Palaeozoic hingeline, later subjected to transpression during the break-up of Gondwana. Seismic interpretation indicates that the depocentre of the Palaeozoic Arafura Basin is to the north of the Goulburn Graben where the basin forms an intracratonic sag resembling the Williston Basin. Petroleum potential of the Larapintine Supersystem improves to the north outside the graben, towards Indonesian waters, where drape over Proterozoic features provides early formed traps and generation was delayed until the Cretaceous and Cainozoic (Fig. 15).

Permian-sourced oil and gas from the Gondwanan Supersystem is produced in eastern Australia from the Cooper–Eromanga and Bowen–Surat Basins. Undeveloped gas and condensate accumulations in the Petrel Sub-basin have also been typed to Permian source rocks by their heavy isotopic signature. Isotopic and stratigraphic evidence indicates that gas and condensate in the pre-Tertiary section of the Bintuni Basin in Irian Jaya (Fig. 16) may also be part of the Gondwanan Supersystem and sourced from similar Permian deltaic sequences.

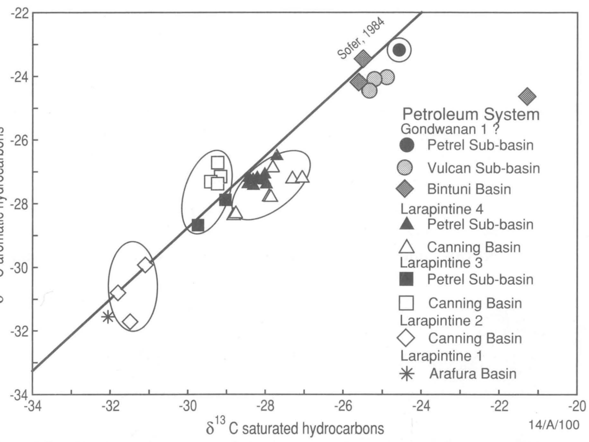

Fig. 16. Carbon-isotope signatures of Palaeozoic petroleum samples from Australian basins (Edwards et al. 1997: op. cit.) and isotopic data from the Bintuni Basin in Indonesia (Perkins & Livsey 1993: Proceedings of the Indonesian Petroleum Association 22nd Annual Convention, 794–829). (Sofer 1984: American Association of Petroleum Geologists, Bulletin 68(1), 31–49.)

The characteristic Westralian oils (Westralian 2, Table 2) are derived from Jurassic marine siliciclastic source rocks with some terrestrial input, and are found along the Australian margin from the Carnarvon Basin to Papuan Fold Belt (Fig. 17). These source rocks were deposited along the rifted margin of Gondwana in deep-marine troughs bordered by emergent highlands. Other source intervals identified in the Westralian Supersystem include deltaic Triassic facies in the Carnarvon Basin, considered to be the source of the giant gas and condensate fields of Australia's North West Shelf (Westralian 1; Table 2); and recently recognised marine Early Cretaceous sources (Westralian 3, Table 2) in the Browse and Bonaparte Basins.

Yet a fourth group of oils in the Westralian region is derived from calcareous marine Mesozoic source rocks, and has the geochemical characteristics befitting a separate (Sahul) oil family or petroleum supersystem (Table 2). These oils occur in wells in the Vulcan Sub-basin and Sahul Block in Australian waters and on the Indonesian islands of Timor and Seram (Fig. 17), and represent another example of petroleum supersystems and oil families shared by the two countries.

Acknowledgment

Aidan Moore and Dianne Edwards kindly reviewed the manuscript.

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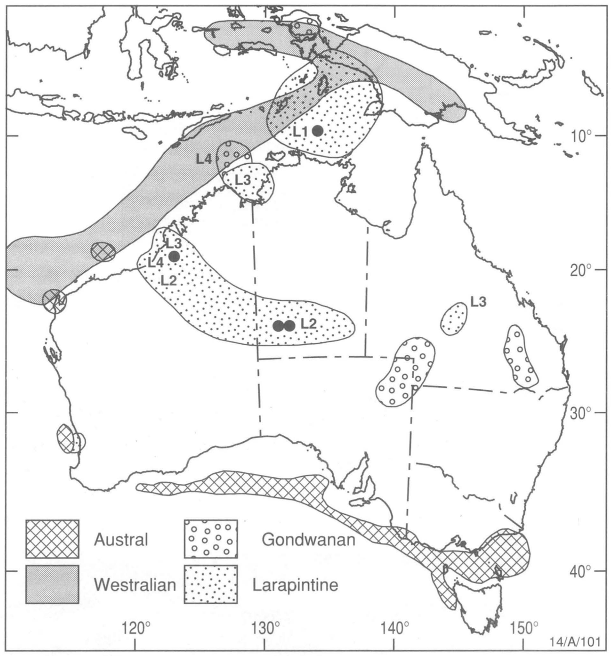

Fig. 17. Petroleum supersystems in Australia.

Lineament interpretation for groundwater assessment in arid central Australia

Pauline English[1]

Most communities inhabiting the Lake Mackay, Mount Doreen, Mount Liebig, and Mount Rennie 1:250 000 Sheet areas rely on groundwater as their main or only water supply. This 60 000 km^2 tract of Aboriginal land occupies the arid heart of central Australia. It spans three distinct geological provinces: the Proterozoic Arunta Block and the Proterozoic–Palaeozoic intracratonic Amadeus and Ngalia Basins (Fig. 18). At least half of it is underlain by igneous and metamorphic rocks, whose permeability and groundwater storage capacity depend on interconnected networks of fractures and fissures. In the sedimentary rocks, tectonically induced secondary fractures are as important to groundwater yields as primary porosity and permeability characteristics. Consequently, the identification of fracture zones, where increased permeability is likely to enhance hydraulic conductivity, is important here and elsewhere in inland Australia where groundwater resources need to be assessed and developed.

Objectives, methodology, source of data

Water supply in these four 1:250 000 Sheet areas has been the focus of the collaborative 'Western water' study (*Wiluraratja Kapi*) by AGSO, the Northern Territory Department of Lands, Planning & Environment, and the Central Land Council. Geologically based lineaments in this area have been interpreted from processed Landsat Thematic Mapper (TM) scenes in fulfilment of two objectives of the study:

- to develop methodologies for assessing water resources and providing adequate water supplies to people living on Aboriginal land; and
- to improve the long-term success of water-resource developments on Aboriginal land.

The specific objectives of the lineament interpretation were:

- to interpret all geologically based lineaments from processed Landsat TM data, and generate 1:250 000-scale 'lineament maps' to serve as a dataset for a GIS; and
- to define drill sites favourable to the recovery of groundwater from lineament networks that are interpreted as representing fracture zones of enhanced permeability.

Mineral-unmixing (Bierwirth 1990: International Journal of Remote Sensing, 11, 1999–2017) and band-ratioing techniques were applied to the processing of the Landsat TM data. Interactive enhancement of the processed images helped to mitigate the spectral dominance of fire scars and sand dunes, and to elucidate intrinsic linear geological features.

Lineament analysis

Many of the interpreted lineaments are in Cainozoic cover; their visibility is due to minor Tertiary to Recent reactivation of basement structures transmitted through it, and to the processing applied to the imagery. The interpreted lineament array includes a west-northwesterly to northwesterly striking zone >150 km long by >30 km wide diagonally traversing the entire Mount Doreen Sheet area (Fig. 19). This lineament zone is most prominent in the Ngalia Basin where it propagates through thick Cainozoic cover. It continues across the northern Arunta Block, in the northwest corner of the Sheet area, and the central Arunta Block, in the southeast. It is assumed to be the surface expression of a regional-scale fault or shear system that gravity data indicate is continent-wide in extent. Some of the composite northwest-striking lineaments truncate a series of linear east–west-oriented sand dunes, indicating that faults have been reactivated in recent times.

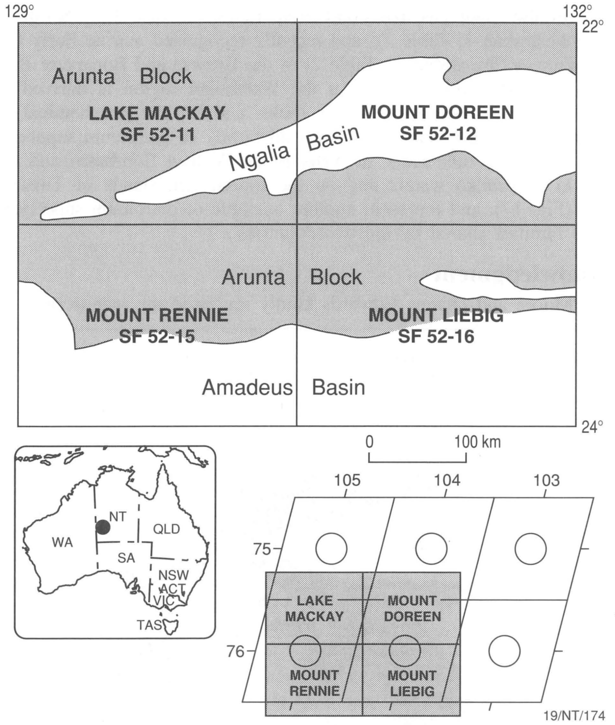

Fig. 18. The 'Western water' study area relative to the main geological provinces, and covering Landsat–5-TM scenes, including flight paths (103–105) and rows (75–76).

A high density of lineaments is readily apparent in outcrop (Fig. 19), and particularly conspicuous in erosionally resistant quartzite- and sandstone-capped ranges. Most of these lineaments are a product of pervasive fracturing in the brittle rocks during periods of tectonic relaxation after compressive episodes; the fracturing also might reflect insolation weathering in response to diurnal temperature extremes over a prolonged period. Such fractures have evolved into rills and gullies on the slopes of the ranges. Many of them extend from the quartzite and sandstone through adjacent lithologies. These factors indicate that the fractured quartzite and sandstone ridges are important recharge areas for groundwater. Additionally, numerous lineaments traverse alluvial fans adjacent to outcrops. Although these lineaments may correspond to structures that played a role in fan formation and propagation, they are also likely to function latterly as conduits for recharge waters from the adjoining ranges to potential aquifers in the fans.

Salt lakes and playa margins in the area coincide with high densities of intersecting fractures that are conduits for groundwater discharge rather than for recharge or storage. Conspicuous lineaments in the salt lakes may represent seepages and series of springs fed under hydraulic pressure from local Cainozoic stratal and fissure groundwater and/or saturated fractured bedrock. Fault or fracture traces are rendered visible by linear concentrations of evaporites that have precipitated from discharging water as it evaporates at the playa surface preferentially along the structures.

Within calcrete expanses around playa margins and in calcreted palaeochannel zones, the character of faults and fractures is commonly distinguishable from that of the lineaments in the salt lakes. Alignments of dolines are visible in some of the calcrete settings. The dolines represent karstic dissolution hollows which probably formed from percolating surface waters descending preferentially along fractures during periodic floods. Beneath the surface of the calcrete zones, the dissolution hollows are likely to be vesicular or cavernous, and to interconnect with one another via a network

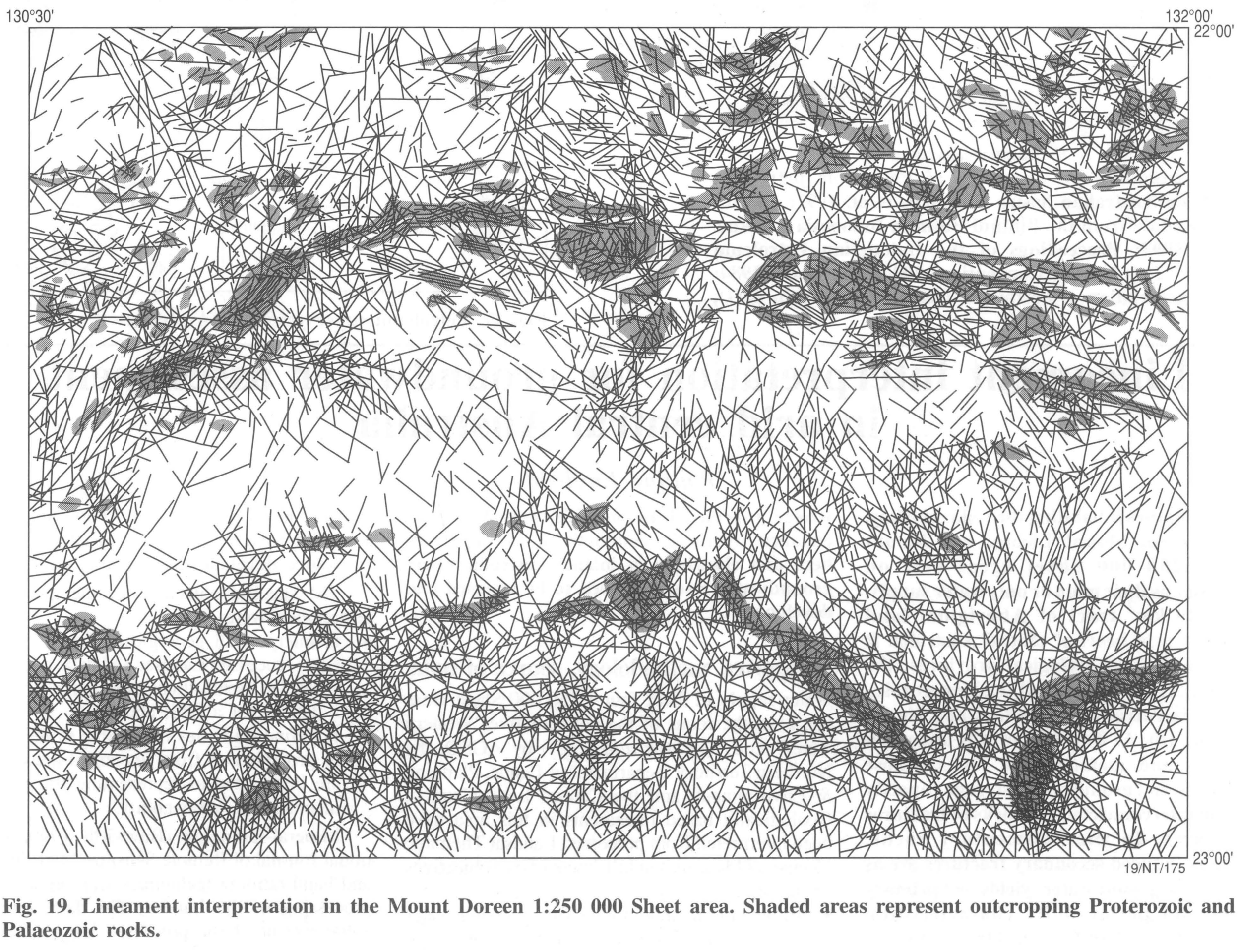

Fig. 19. Lineament interpretation in the Mount Doreen 1:250 000 Sheet area. Shaded areas represent outcropping Proterozoic and Palaeozoic rocks.

of 'chemical fissures'. They are capable of facilitating diffuse recharge to underlying shallow aquifers, or, depending on the present-day water-table levels, may serve as aquifers themselves or as discharge zones.

Criteria for applying the lineament interpretation to the definition of drilling targets — namely, long fractures and dense intersecting networks of fractures — have been identified. The geometry of lineament zones provides information about likely causative stress directions and deformation styles of sets of zones, and, accordingly, facilitates predictions about areas of increased fluid flow.

In the 'Western water' study area, northerly striking lineament zones and conjugate northwesterly and northeasterly striking lineament intersections are favoured as being hydrogeologically important, although relationships between lineaments, lithologies, topography, and local water-table depths need to be accommodated in the selection of drill sites. The interpreted lineament array has been synthesised, at 1:1 000 000 scale, into regional-scale lineament zones, some of which represent previously unmapped major crustal structures.

The rationale, methodology, theoretical considerations, and lineament interpretation of the four 1:250 000 Sheet areas have been documented in *AGSO Record 1997/8*. The methodology is transferable to inland areas elsewhere in Australia, and to other arid and semiarid countries where groundwater resources need to be assessed, and where a first-pass overview may aid definition of areas or zones that warrant more detailed investigation.

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Are there Voisey's Bay-type Ni–Cu–Co sulphide deposits in the East Kimberley of Western Australia?

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The world-class Voisey's Bay Ni–Cu–Co sulphide deposit in Labrador, Canada, is one of the most important mineral discoveries in the last decade. Since the announcement of its discovery in late 1994, Voisey's Bay has stimulated exploration for magmatic Ni–Cu–Co deposits associated with layered mafic–ultramafic intrusions in Proterozoic terranes in Australia and elsewhere. Companies have intensively explored the Palaeoproterozoic layered intrusions in the East Kimberley over the last 30 years for stratabound chromitite layers enriched in platinum-group elements and for concentrations of base-metal sulphides along basal contacts, but no economic deposits have been found. The recent recognition of a possible mineralised feeder conduit in the Sally Malay layered mafic–ultramafic intrusion in the East Kimberley, similar to that at Voisey's Bay, significantly increases the economic potential of other layered intrusions in this province.

In collaboration with the Geological Survey of Western Australia, AGSO has re-evaluated the geological setting and economic potential of the Palaeoproterozoic layered mafic–ultramafic intrusions in the Halls Creek Orogen (HCO) of the East Kimberley, a contribution to the Kimberley–Arunta project for the National Geoscience Mapping Accord. Recent outcomes are summarised in previous AGSO Research Newsletter articles — namely, on the geology (Hoatson & Tyler 1993: 18, 8–9; Blake 1997: this newsletter, p. 19), mineralisation (Hoatson 1993: 19, 9–10; Hoatson et al. 1995: 22, 1–2; Hoatson 1995: 22, 9–11), geochronology (Page et al. 1995: 22, 7–8), and depths of emplacement (Trudu & Hoatson 1996: 25, 10–12) of the intrusions.

Geological settings of the Voisey's Bay and Sally Malay deposits

The Voisey's Bay Ni–Cu–Co deposit (Naldrett 1997: Australian Journal of Earth Sciences, 44, 283–315) occurs in the 1.8-Ga collisional zone (Torngat Orogen) that separates the Palaeoproterozoic Churchill Province to the west from the Archaean Nain Province to the east (Fig. 20). It occurs in a troctolite sheet, 30 to 100 m thick, that intrudes Archaean biotite–feldspar–quartz gneiss of the Nain Province. This sheet is interpreted to be a feeder for the nearby Reid Brook intrusion, which belongs to the 1.34–1.29-Ga Nain Plutonic Suite. Massive and disseminated sulphides are hosted by troctolite and a basal breccia sequence (BBS) in three different but closely related settings that are considered to reflect contrasting erosion levels — namely, the Western Extension, the Ovoid, and the Eastern Deeps. The BBS consists of brecciated fragments of basement gneiss, and unmineralised troctolite and peridotite cut by sulphide-bearing troctolite veins. Ore reserves for the Ovoid are currently 32 Mt @ 2.83% Ni, 1.68% Cu, and 0.12% Co (Canadian Mining Journal, February 1997, 24). The entire deposit is estimated to be 150 Mt with a similar grade.

The 1845-Ma Sally Malay layered mafic–ultramafic intrusion (Fig. 21) in the central zone of the HCO contains the largest Ni–Cu–Co sulphide

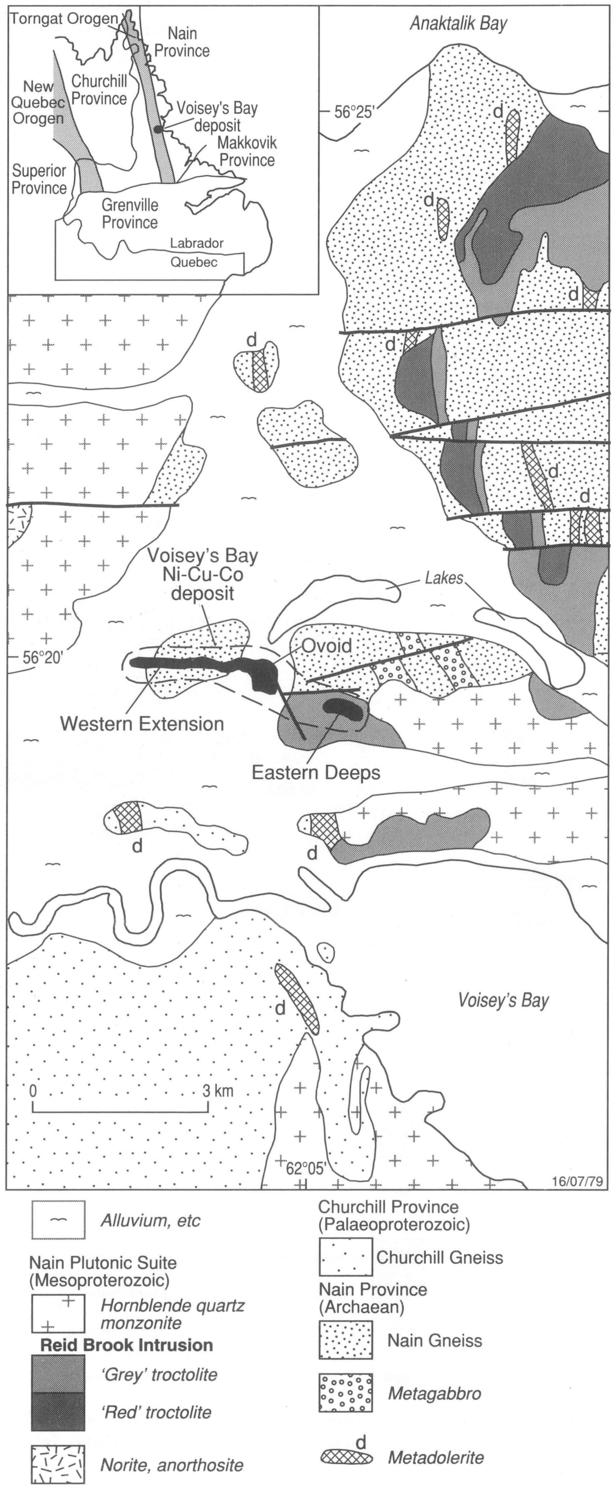

Fig. 20. Tectonic setting (inset) and geology of the Voisey's Bay Ni–Cu–Co deposit, Labrador, Canada (modified after Naldrett 1997: op. cit.).

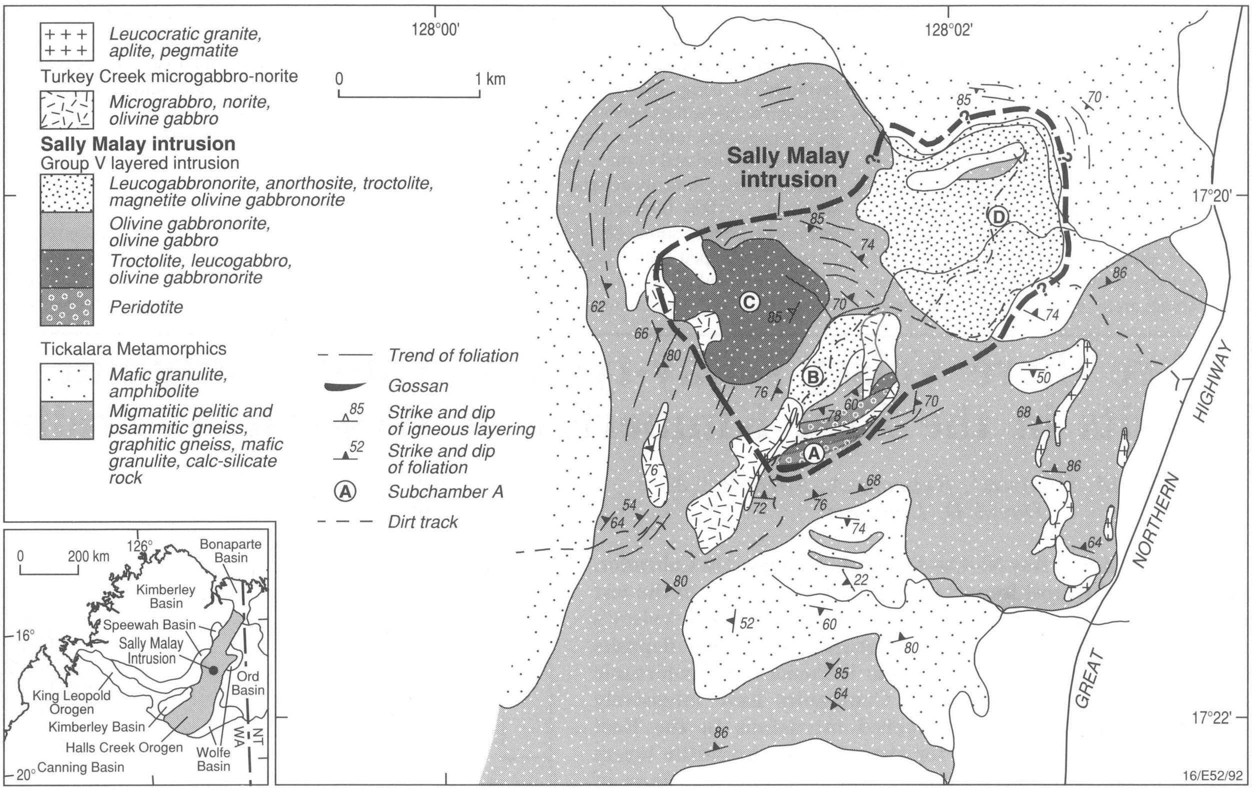

Fig. 21. Tectonic setting (inset) and geology of the Sally Malay Ni–Cu–Co deposit, East Kimberley, Western Australia.

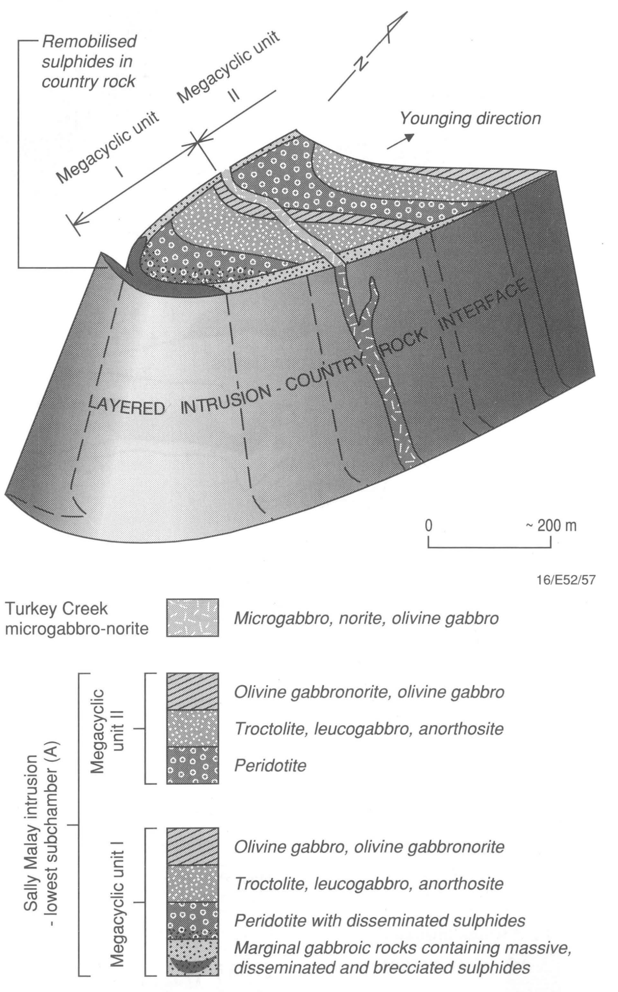

Fig. 22. Schematic diagram of megacyclic units and different mineralisation styles in subchamber A of the Sally Malay intrusion (modified after Thornett 1981: op. cit.).

resource (indicated and inferred) in the East Kimberley: 5.5 Mt @ 1.75% Ni, 0.66% Cu, and 0.1% Co (Shedden & Barnes 1996: 'Nickel 96 — mineral to market', Australasian Institute of Mining & Metallurgy, Melbourne, Publication Series 6/96, 145–155). The ~1.7-km-thick differentiated intrusion, which covers an area of ~1.5 by 3 km, comprises four subchambers (A to D) separated from one another by narrow 'corridors' of gneissic biotite–feldspar–quartz paramigmatite ± garnet ± cordierite ± graphite and mafic granulite country rock belonging to the Tickalara Metamorphics.

Subchamber A is a northeast-trending gently arcuate body 1200 m long by 200 m wide containing the most primitive and economically important rocks in the intrusion. It comprises two differentiated megacyclic units (Fig. 22), each consisting of serpentinised peridotite and minor gabbroic rocks at the base, followed by overlying mottled troctolite and anorthosite, and various olivine-bearing gabbroic rocks in the upper parts. The cyclic units indicate open fractionation systems that involved regular magma replenishments into the subchamber. A thin basal veneer of fractionated gabbroic rocks, separating the lowest megacyclic unit from the paramigmatite country rocks, is the major host to massive, disseminated, and brecciated Ni–Cu–Co sulphides. The massive sulphides are concentrated in embayments along the basal contact below the thickest section of peridotites. Cu-rich sulphide veins remobilised from the basal-contact sulphides occur for several metres into the country rocks.

Subchamber B is an elongated leucogabbro–anorthosite body 250 m wide between subchambers A and C. Subchamber C, 1 km wide, is a lobate body of interlayered troctolite and olivine gabbronorite, similar to those in the upper part of subchamber A. Subchamber D is a poorly exposed lobate body of leucogabbro, anorthosite, and magnetite gabbronorite 1200 m wide. A younger, unrelated fine-grained gabbro (Turkey Creek microgabbro–norite) cuts the lower parts of the intrusion (Figs. 21 and 22).

Most mafic–ultramafic lithologies in the four subchambers show well-preserved primary cumulus textures and little evidence of recrystallisation. Two-pyroxene geothermometry of the intrusion and mafic granulites (Thornett 1981: Economic Geology, 76, 1568–1580) indicates that the Sally Malay intrusion was emplaced after granulite-facies metamorphism.

The Sally Malay subchambers are considered to represent four related bodies which were emplaced into the crust at a depth of about 22 km (0.63 GPa; Trudu & Hoatson 1996: op. cit.), and connected to a 'parent magma chamber' by a network of feeder conduits. The mineralised elongated subchamber A was first interpreted by Hoatson (in press: AGSO Journal of Australian Geology & Geophysics, 17/4) to represent the main feeder conduit to the more evolved B, C, and D subchambers higher in the crust. The contrasting shapes of these subchambers may be a primary feature, or reflect slightly different erosion levels, as at Voisey's Bay.

Comparison between the Voisey's Bay and Sally Malay deposits

Although the Reid Brook intrusion is 500 Ma younger than the Sally Malay intrusion and was emplaced well after orogenesis, both intrusions display many striking similarities in regional setting, stratigraphy, and mineralisation.

- The Torngat and Halls Creek orogenic zones are of the same age (1.8 Ga), and may have formed from similar tectonic processes. The Torngat orogenic zone (Naldrett 1997: op. cit.) shows some parallels with the plate-tectonic model of Tyler et al. (1995: Geological Survey of Western Australia, Annual Review 1993–94, 37–46) for the HCO, which involves modern-style collisional–subduction processes in a magmatic-arc environment.
- The Reid Brook and Sally Malay intrusions are Proterozoic multichambered bodies whose spatially close, genetically related subchambers have different geometries.
- Sulphides, generally hosted by mafic rocks near the basal contacts of both intrusions, occur in massive and disseminated forms and as a matrix to brecciated rock.
- Both intrusions have similar mineralisation assemblages (hexagonal pyrrhotite–pentlandite–chalcopyrite ± magnetite ± ?cubanite) and sulphide–silicate textures.
- Troctolites are a substantial component of the mineralised stratigraphy, although the significance of these plagioclase–olivine cumulates is not fully understood (Wiebe 1990: American Mineralogist, 75, 1–12).
- There is considerable evidence (breccia-tion, xenoliths, xenocrysts, hybridised magma) for interaction and contamination of mafic magmas with country-rock gneisses in both deposits.
- Xenolithic gneiss fragments in the brecciated basal parts of both intrusions contain green hercynitic spinel in reaction coronas.
- Sulphur saturation in both intrusions was probably triggered by silicification of the magmas and/or by addition of external sulphur from the crust. Re–Os isotopic-data modelling of the Sally Malay intrusion (Sproule et al. 1997: '7th Annual Goldschmidt Conference, June 2–6, 1997, Tucson, Arizona', Lunar & Planetary Institute Contribution 921, Houston, 195–196) suggests that the sulphide mineralisation was the result of crustal contamination of the magma.

Implications for exploration

The identification of a possible mineralised feeder conduit in the Sally Malay intrusion similar to that of Voisey's Bay has important implications for the exploration of Palaeoproterozoic layered intrusions in the HCO. Ni–Cu–Co sulphide in these intrusions is likely to accumulate passively as sulphide layers in depressions or embayments along the basal contacts, or to be deposited in feeder conduits to these intrusions. Sulphide accumulation in these environments is controlled by contrasts in fluid-dynamic regimes of magma flow (slow versus fast and turbulent). For example, a widening or 'bending' of the magma conduit would slow the magma flow rate, and allow sulphide deposition (e.g., Voisey's Bay). Exploration for Ni–Cu–Co sulphides at Sally Malay has focused on the basal contact of subchamber A, but the different mineralised settings at Voisey's Bay suggest that subchambers B, C, and D may also be prospective, if they represent parts of the feeder conduit system which had favourable flow rates of magma.

The major challenge in exploring for Voisey's Bay-type deposits in the HCO is to locate feeder conduits that may be poorly exposed or hidden beneath thick sequences of mafic–ultramafic cumulates. The Discovery Hill gossan at Voisey's Bay was found fortuitously during a regional stream-sampling program for diamond indicator minerals. This was followed up by a horizontal-loop electromagnetic survey, which indicated a 1200-m-long continuous conductor.

Intrusions in the HCO similar to Sally Malay (Keller Creek, McKenzie Spring, Corkwood; fig. 10 in Trudu & Hoatson 1996: op. cit.) and the mafic granulites in the Tickalara Metamorphics (Norton intrusion: Hoatson 1995: op. cit.) have prominent gossans near their basal contacts, and potentially contain mineralised feeder conduits. Other large mafic intrusions, such as McIntosh (7.8 km thick and covering an area of ~84 km^2), Springvale, and Toby are characterised by gravity anomalies of ~200 to 350 μm s^{-2} (Dixon Range, Western Australia — 1:250 000 gravity survey series, 1967; BMR [AGSO]). Detailed gravity traverses across these intrusions might identify superimposed anomalies that could define feeder conduits similar to that of the Cadgerina feeder dyke of the Munni Munni Complex, in the west Pilbara Craton (Barnes & Hoatson 1994: Journal of Petrology, 35, 715–751). Some mafic intrusions in the HCO (McKenzie Spring, Fletcher Creek, and Corridor gabbro; Trudu & Hoatson 1996: op. cit.) have narrow dyke-like forms that have strike extents of tens of kilometres. Parts of these elongated bodies may represent the deep roots of feeder systems with related subchambers either eroded off or unexposed.

The recognition of a possible Voisey's Bay-type deposit in the East Kimberley also highlights the potential of other Proterozoic provinces in Australia, such as the Musgrave Block of central Australia, which contains several large 1.08-Ga troctolitic intrusions (Jameson Range, Blackstone Range, Bell Rock Range; Glikson et al. 1996: AGSO Bulletin 239).

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Speculations relating to the layered mafic–ultramafic intrusions of the East Kimberley, Western Australia

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Recent research on the Palaeoproterozoic layered mafic–ultramafic intrusions of the East Kimberley, carried out as part of the Kimberley–Arunta project for the National Geoscience Mapping Accord, has some intriguing ramifications for interpreting the local and regional geology. The layered intrusions crop out in the central and western zones of the Halls Creek Orogen (as defined by Tyler et al. 1995: Geological Survey of Western Australia, Annual Review 1993–94, 37–46), to the west of the Halls Creek Fault, and are spatially associated with voluminous coeval (1860–1820 Ma) granites.

In AGSO Research Newsletter 25, Trudu & Hoatson (1996: p. 10–12) reported the results of geothermobarometric studies which showed that the layered intrusions were emplaced at depths ranging from about 8 km (0.24 GPa) to 24 km (0.67 GPa) — deeper in the north than in the south (Fig. 23). Previous articles reported that the intrusions range in age from about 1860–1825 Ma (Page et al. 1995: AGSO Research Newsletter 22, 7–8), and are prospective for several styles of plati-

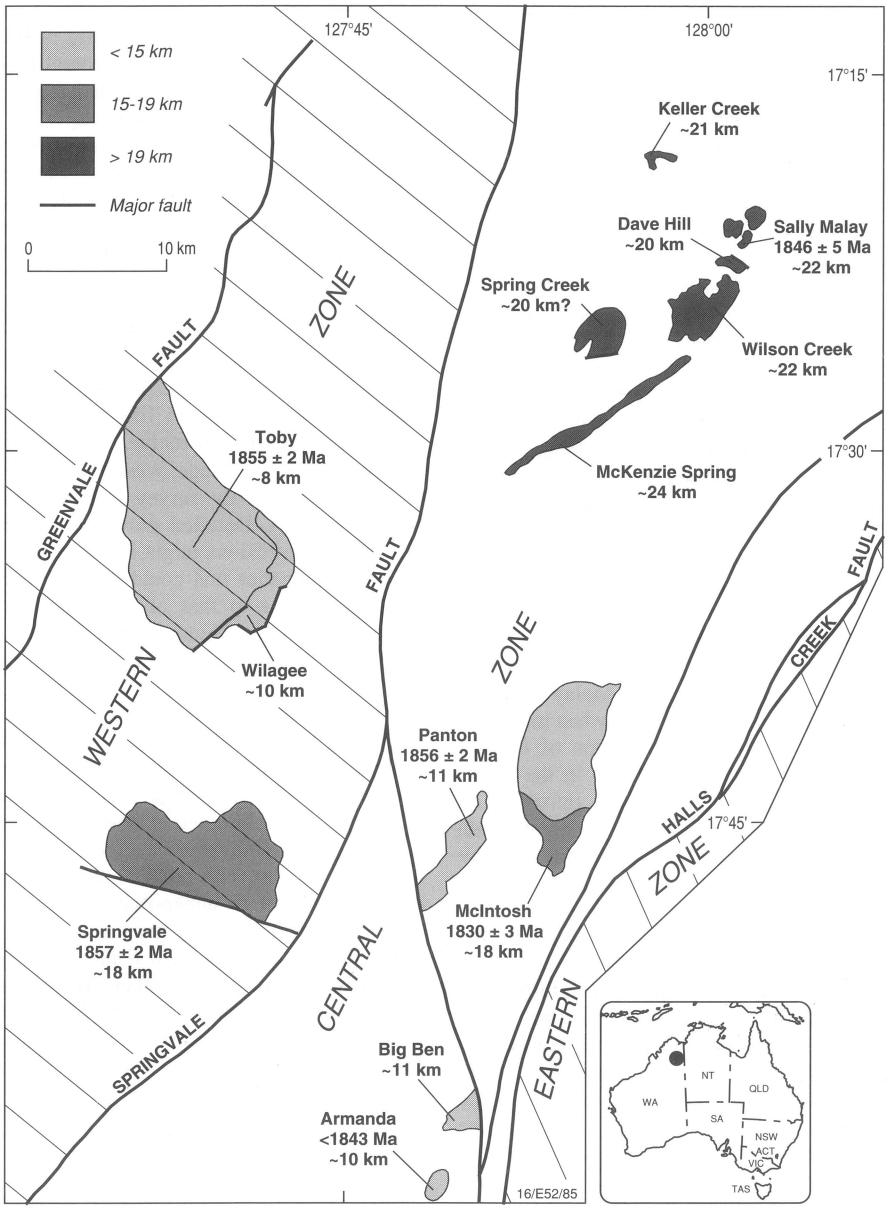

Fig. 23. Layered mafic–ultramafic intrusions for which ages and depths of emplacement are available, western and central zones of the Halls Creek Orogen, East Kimberley.

num-group-element (PGE), Cr, Ni, Cu, Co, and Au deposits (Hoatson et al. 1995: AGSO Research Newsletter 22, 1–2). Field evidence indicates that the intrusions crystallised in situ, rather than being tectonically uplifted fault-bounded segments of larger bodies that had crystallised at greater depths, as suggested by Hancock & Rutland (1984: Journal of Geodynamics, 1, 387–432). The evidence for crystallisation in situ includes:

- chilled and contaminated margins, contact aureoles, and nearby satellite intrusions (Hoatson & Tyler 1993: AGSO Research Newsletter 18, 8–9);
- adjacent net-veined complexes formed by commingling of mafic magma with melted granite and other country rocks (Blake & Hoatson 1993: AGSO Journal of Australian Geology & Geophysics, 14, 319–330); and
- compositional layering indicating that many intrusions were emplaced as saucer, funnel, or pipe-like bodies.

In situ crystallisation implies that the adjacent country rocks and coeval granitic plutons were at the same depths as the layered intrusions during emplacement, and were already very hot — perhaps 350°C at 8 km and 1100°C at 24 km (for a geothermal gradient of around 45°C/km; Grambling 1981: Earth and Planetary Science Letters, 53, 63–68). Hence, only a little extra heat from intruding mafic–ultramafic magma could cause widespread melting of the country rocks.

Central zone of the Halls Creek Orogen

The mafic–ultramafic body with the largest known PGE resource in the region, the **Panton intrusion**, was emplaced at 1856 ± 2 Ma at a depth of about 11 km (0.32 GPa, for a sample from the upper part of the intrusion) into the central zone of the Halls Creek Orogen. The Panton intrusion is preserved in the form of a steep-sided syncline with a well-developed axial planar foliation. Adjacent country rocks exposed in the Panton River on its south side include retrogressed pelitic migmatite and gneissic granite (dated at 1863 ± 4 Ma[2]), which are mapped as Tickalara Metamorphics. The migmatitic rocks are restricted to within about 100 m of the Panton intrusion. To speculate: rather than predating the Panton intrusion, was the country-rock migmatite formed by local partial melting adjacent to the feeder for the intrusion during the emplacement of the mafic–ultramafic magma? And, if so, was the intrusion originally a saucer or funnel-shaped body which, when largely crystallised, sagged inwards (into underlying much less dense and partly melted country rocks) to form a steep-sided 'syncline'?

A lithologically and structurally similar body to the south, the **Big Ben intrusion,** was emplaced at close to the same depth (0.31 GPa) as the Panton intrusion. This, together with similarities in local geology, supports the view of Hoatson (1993: AGSO Research Newsletter 19, 9–10) that the Big Ben intrusion represents the displaced southwestern extension of the Panton intrusion, transported 15 km laterally southwards along the western side of a major sinistral strike-slip fault. Two implications are that the entire central zone west of the fault is displaced 15 km southwards relative to this zone east of the fault, and that there has been little vertical movement on the fault.

The larger **McIntosh intrusion**, exposed to within 3 km northeast of the Panton intrusion, is a funnel-shaped body nearly 8 km thick, the basal part of which was emplaced at a depth of about 18 km (0.5 GPa). Hence the upper parts of both intrusions crystallised at about the same depth (10–11 km) in the crust. The McIntosh body intrudes Wild Dog Creek gabbro, and turbiditic metasediments, metavolcanics, and tonalite mapped as Tickalara Metamorphics. Its age is given by zircon from a large xenolithic block of metasediments, contact-metamorphosed to migmatite, on the northwestern margin of the intrusion. This migmatite contains detrital zircon grains dated at 1865 ± 2 Ma and high-uranium metamorphic zircon, mainly as overgrowths, dated at 1830 ± 3 Ma. The metamorphic age is interpreted to be both the age of migmatite formation and the emplacement age of the McIntosh intrusion (Page et al. 1995: op. cit.), indicating that the McIntosh intrusion is about 25 m.y. younger than the Panton intrusion.

The **Armanda intrusion**, 24 km to the south (Fig. 23), belongs to the same group of intrusions as the McIntosh intrusion, and hence is regarded as probably similar in age. It was emplaced at a depth of about 10 km (0.28 GPa), not very different from the nearby Big Ben intrusion, into metavolcanics and metasediments of the Koongie Park Formation. Rhyolitic volcanics from this formation to the southwest have been dated at 1843 ± 3 Ma (Page et al. 1994: AGSO Research Newsletter 20, 5–7). The Koongie Park Formation is contact-metamorphosed by the Armanda intrusion, and leucogranite forming a net-veined complex with Armanda gabbro on the southeast side is considered to represent country-rock rhyolite partly melted by the gabbro. The Koongie Park Formation here was at a depth of 10 km when the Armanda intrusion was emplaced, presumably at around 1830 Ma, implying a minimum burial rate for this formation of close to 1 km per 1.5 m.y.

Layered mafic intrusions in the northern part of the central zone (Fig. 23) were emplaced at deeper crustal levels (19–24 km; 0.56–0.67 GPa) than those to the south. Most of these deep intrusions have moderately small outcrop areas, but may represent feeders for much larger bodies removed by erosion. The main country rocks are migmatitic metasediments of the Tickalara Metamorphics, some of which contain detrital zircon dated at around 1865 Ma[2]. The only mafic–ultramafic body here that has been dated, the highly prospective **Sally Malay intrusion** (Hoatson et al. 1997: this newsletter, p. 17), was emplaced at a depth of about 22 km (0.63 GPa), into rocks that may have been as hot as 1000°C, at around 1845 Ma[2]. The protoliths of these Tickalara Metamorphics appear to have been buried to a depth of about 22 km between 1865 Ma and 1845 Ma, indicating a minimum burial rate of 1.1 km per m.y. for this period.

Country-rock **migmatite** near Turkey Creek (Warmun) in the northeast contains numerous small sheet-like mafic intrusions, probably emplaced at about the same time as migmatite formation (Blake & Hoatson 1993: op. cit.). High-U metamorphic zircon from this migmatite is dated at 1852 ± 2 Ma[2], appreciably younger than Tickalara migmatite adjacent to the Panton intrusion and older than Tickalara migmatite at the margin of the McIntosh intrusion, implying at least three ages of migmatite formation in the central zone. The extensive migmatites in the north may predate the layered intrusions here, or, as suggested by Blake (in Blake & Hoatson 1993: op. cit.), may have formed by partial melting related to the emplacement of these intrusions, and, like the intrusions, may be of several different ages.

The Sally Malay intrusion was emplaced at about the same time as the sediments and volcanics that make up the **Koongie Park Formation** were being laid down in the same zone 70 km to the south. Hence the northern part of this zone has been uplifted more than 22 km relative to the southern part since 1845 Ma.

Also in the central zone, on Mount Barrett, 15 km west of Halls Creek (south of the area shown in Fig. 23), gabbroic and granitic intrusive rocks and contact-metamorphosed Koongie Park Formation are overlain unconformably by the **King Leopold Sandstone** of the Kimberley Group. An inference is that before being blanketed by the Kimberley Group, probably about 1800 Ma ago, this part of the central zone had been stripped by erosion to the extent that the same rocks were exposed then as are exposed today. Whether or not this was also the case near the Sally Malay intrusion is uncertain, as no Kimberley Group rocks are preserved in the northern part of the central zone — either they were never deposited or they have been removed by erosion.

Western zone of the Halls Creek Orogen

The **Toby intrusion** in the western zone of the Halls Creek Orogen (Fig. 23) was emplaced into country-rock granites at a depth of about 8 km (0.24 GPa) at 1855 ± 2 Ma. The granites form large plutons which were intruded into, and contact-metamorphosed, metasediments of the Marboo Formation. A well-developed net-veined complex on the south side of the Toby intrusion was probably formed at the time of mafic magma emplacement. Numerous small bodies of leucogranite in the central part of the intrusion may represent melted granitic country rock that back-intruded the mafic body.

A major fault, the **Greenvale Fault**, separates the Toby intrusion from extensive felsic extrusives of similar age to the west — the Whitewater Volcanics, dated at 1855 ± 5 Ma[2]. A vertical displacement of 8 km can be presumed for this fault, upthrown to the east, accounting for why no Whitewater Volcanics are preserved to the east.

The **Wilagee intrusion**, on the east side of Toby, has been correlated with the Springvale intrusion to the south on the basis of rock types and chromite occurrence. However, its depth of emplacement, about 10 km (0.28 GPa), is not inconsistent with it representing a fault-uplifted lower part of the Toby intrusion.

The **Springvale intrusion** was emplaced in the western zone at a depth of about 18 km (0.51 GPa) 1857 ± 2 Ma ago, at about the same time as, but 10 km deeper than, the Toby intrusion 14 km to the north. The exposed country rocks are mainly granite, but rafts of cordierite-rich rock, which may represent metasomatised aluminous metasediments of the Marboo Formation, occur in the northwestern part of the intrusion. That the Toby and Springvale intrusions are coeval and exposed on the present land surface, although they crystallised at very different depths, might indicate that major tilting or unidentified faulting took place after their emplacement.

Regional implications

The layered intrusions and the coeval granite plutons, felsic and mafic volcanics, and migmatites indicate that the crust in the central and western zones of the Halls Creek Orogen was subjected to repeated major influxes of heat between about 1860 and 1825 Ma — it was abnormally hot for more than 30 m.y., and parts may have been close to their melting temperatures at depths as shallow as 10 km. The presence of large bodies of mafic magma (the McIntosh intrusion is about 8 km thick and covers an area of about 80 km^2), laterally continuous rhythmic layering (for many kilometres in several intrusions), and internal cumulate textures implies that the crust was also tectonically stable, at least during emplacement and crystallisation of individual layered intrusions.

The emplacement of voluminous granitic and mafic–ultramafic intrusions and the presumed stable conditions during their crystallisation would appear to favour an extensional tectonic regime involving rifting in an intracontinental setting. Yet the 1860–1825-Ma period also included one or more major compressional deformations which Tyler & others (1995: op. cit.) suggest are related to the coming together of three discrete terranes (the western, central, and eastern zones of the Halls Creek Orogen) with different geological histories. This model of collisional tectonics involves subduction of oceanic crust at a continental margin. Because of these apparent contradictions, the East Kimberley layered intrusions do not fit readily into the scheme of Naldrett (1997: Australian Journal of Earth Sciences, 44, 283–315), who has divided layered mafic–ultramafic intrusions into four main categories related to tectonic settings: I, Archaean greenstone belts; II, rifted continental margins; III, intracratonic regions; and IV, active orogenic belts. According to this scheme, only category I is precluded for the East Kimberley intrusions.

The ideas expressed in this article have evolved during many discussions with AGSO colleagues, especially Dean Hoatson, Russell Shaw, Alastair Stewart, Shen-su Sun, and Lesley Wyborn.

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[2] Dated by R.W. Page; AGSO's OZCHRON database.

Nutrients, catchment run-off, and estuarine response in the Swan–Canning estuary, Western Australia

David Heggie[1], David Fredericks[1], & Andrew Longmore[2]

During 1996, AGSO conducted surveys for the Waters & Rivers Commission of Western Australia to assess the effects of catchment run-off on water quality in the Swan–Canning estuary. This estuary receives run-off from the Avon and Ellenbrook Rivers and from urban areas of the City of Perth. Run-off is seasonally dependent: it is near-zero during the summer months, and increases dramatically during the winter rains (July through October), when the estuary is flushed.

In association with the Marine & Freshwater Resources Institute of Victoria, AGSO has been pioneering the use of continuous geochemical tracers (CGT) to monitor nutrients, petroleum hydrocarbons, agrichemicals, and other potential toxicants in estuaries and the coastal marine environment. The CGT system comprises a submersible pump housed in a tow-fish towed by a marine vessel, and pumps estuarine water into a mobile laboratory aboard the survey vessel. A probe attached to the submerged tow-fish records temperature, salinity, and turbidity, and displays these results in the laboratory as the vessel moves along. A portion of the pumped water is filtered and continuously analysed for dissolved nitrite (NO_2-N), nitrate (NO_3-N), ammonia (NH_3-N), orthophosphate (PO_4-P), and silicate (SiO_4-Si) by flow-through colorimetric methods, and for chlorophyll-*a* by fluorescence. These data are continuously recorded, and the technique provides nutrient-concentration data every 75 m at vessel speed of 5 knots.

The behaviour of nutrients in the estuary was investigated by constructing mixing-diagrams in which the concentration of a nutrient is plotted against salinity, a conservative tracer. Where a nutrient is conservative the relationship with salinity is linear, where a nutrient is added to or removed from estuarine waters then the relationship with salinity becomes non-linear. Convex-up relationships indicate a net addition to the estuary, and concave-down relationships indicate a net removal.

Mixing-diagrams for ammonia and nitrate (Fig. 24), the two important species of nitrogen in estuarine waters, illustrate the behaviour of different nitrogen species under high and low flow conditions. During low flow, nitrate concentrations in the freshwater end-member (0‰ salinity) are high (~30 μM), and input to the estuary is primarily from the catchment. However, nitrate concentrations in the middle and lower estuary (18–35‰) are lower than expected from simple mixing, and indicate that nitrate has been removed by biological processes in the shallow waters of the middle estuary (Perth and Melville Waters).

Ammonia concentrations in the estuary also show a complex pattern of addition and removal during low flow. The low concentration of ammonia in the freshwater end-member (< 5 μM) indicates little or no ammonia input from the catchment. The dome-like curve in the mixing-diagram at low salinities suggests an 'internal' input of ammonia to the estuary, probably from the underlying sediments. Within these sediments, ammonia is produced during the oxidation of organic matter under anoxic conditions, and recycled to the overlying water. Ammonia, like nitrate, is effectively removed from the water column in the middle estuary. These results suggest that the relatively low biological productivity in the shallow Melville Water is sufficient to prevent nitrogen leaving the estuary during the low flow conditions of the first survey (June 1996).

During high flow, high nitrate concentrations (~80 μM) occur in the freshwater end-member; the lowest nitrate concentrations (< 1 μM) again occur in the marine water. By contrast with the low flow condition, however, there is no evidence of biological removal of nitrate from anywhere in the estuary: all data points lie on the mixing-line between high-nitrate freshwater sources and low-nitrate marine water. By contrast, ammonia concentrations are low in the freshwater end-member (< 5 μM) and in the marine water (< 5 μM). The distinct dome-like curve of the mixing-diagram indicates that the internal input of ammonia persists during high flow, but, like nitrate, there is no evidence of biological removal of N in the middle estuary. Under high flow conditions therefore, all the nitrate added from the catchment and the ammonia added from the underlying sediments apparently are flushed to the adjacent coastal water. The apparent lack of biological activity in the Swan–Canning estuary during high flow probably results from the combined effects of low temperature, limited light, and short residence time of water in the estuary.

The examples shown here illustrate the contrasting behaviour of different forms of N during low and high flow conditions in winter. We have also examined the behaviour of P, Si, and other important nutrients controlling water quality. We identified significant catchment and internal sources of P to the estuary; unlike N, these inputs were always greater than the biological uptake in the middle estuary. Dissolved inorganic P was flushed to coastal water, even during low flow, but suspended sediments (and the forms of P associated with particulate matter) were effectively retained within the estuary, even during high flow. Silicate was found to be derived almost entirely from the catchment and was effectively flushed from the estuary under all flow conditions examined.

The knowledge of nutrient cycling in the Swan–Canning estuary that we have gained fom this study will be used by the Waters & Rivers Commission to initiate remedial measures for reducing the flux of nutrients to and algal productivity within the estuary.

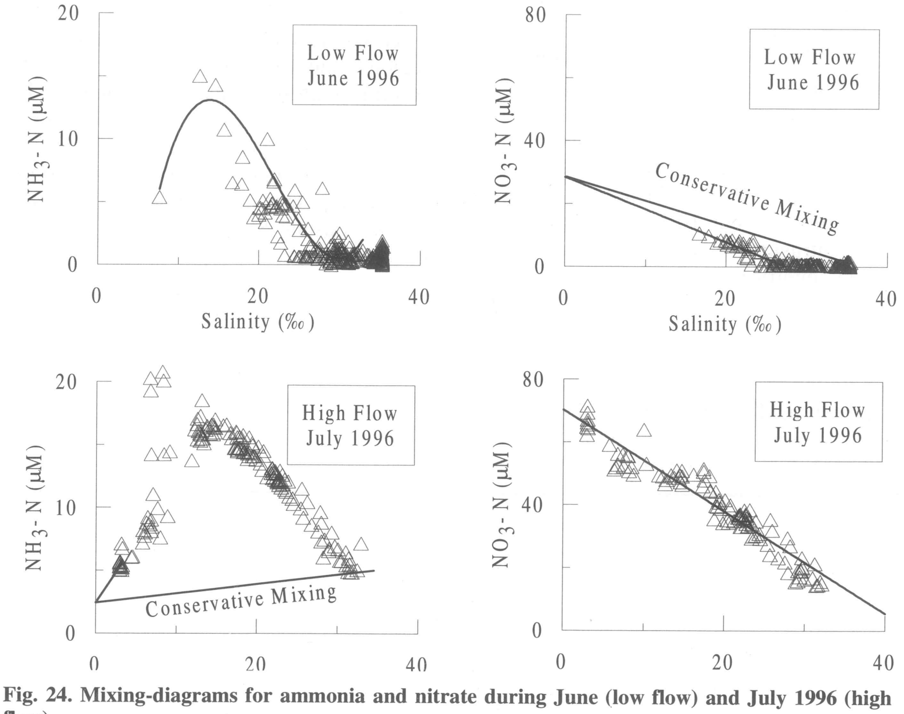

Fig. 24. Mixing-diagrams for ammonia and nitrate during June (low flow) and July 1996 (high flow).

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of a region. In regional geological studies, such a map should be prepared early in a project, and incorporate geological, geophysical, satellite, and topographic data built into a digital data/GIS package. The map can be revised and the GIS can be progressively updated as more data become available. Such a map provides an overview of the regional picture, thus enabling the geologist to focus on geological problems that need to be addressed. It also assists communication between all geologists working in the region, and is an excellent base on which to plot and place in context existing data and to assimilate new data, thus assisting the planning of complementary work.

The solid-geology map of the Nabberu 1:250 000 Sheet area is based on interpretations of aeromagnetic and gamma-ray spectrometric data (400-m line spacing), gravity data (11-km station spacing), and Landsat Thematic Mapper data, and on the published geological map by Leech et al. (1981: Geological Survey of Western Australia, 1:250 000 Geological Series), all combined into a digital data/GIS package. These datasets provide geological information from the surface to deep in the crust.

The solid-geology interpretations were undertaken with the aid of GIS software to digitise images on the screen. Digitising on screen ensures precise location of line-work, in contrast to digitising from or scanning line-work on paper or film, which commonly results in minor shifts in the positions of lines. The GIS software was also used for the checking and integration of different datasets.

Geological setting

The Nabberu area (Fig. 25), at the northeast margin of the Yilgarn Block, consists of an Archaean granite–greenstone terrane in the west and south, and unconformably overlying Proterozoic sedimentary rocks in the centre, east, and north. The Proterozoic rocks comprise:

- in the centre, the Palaeoproterozoic Earaheedy Group of the Nabberu Basin, which is now structurally reconstituted as the Nabberu Syncline;
- in the northeast, the Palaeoproterozoic Troy Creek beds and Mesoproterozoic Scorpion Group, and the Mesoproterozoic Bangemall Group of the Bangemall Basin; and
- in the far west, the Palaeoproterozoic Glengarry Group.

The Sheet area is dominated structurally by the northwest end of the Nabberu Syncline, which is clearly defined in outcrop geology and magnetic data by the hilly and highly magnetic Earaheedy Group banded iron formation. A prominent late Palaeoproterozoic impact structure, the Teague Ring, is located in the south (Shoemaker & Shoemaker 1996: AGSO Journal of Australian Geology & Geophysics, 379–398).

Archaean greenstone belts and major faults

Greenstone exposures in the area are limited. In this study a major greenstone belt in the west, the Merrie greenstone belt, is interpreted as being of considerably greater extent than previously known. Its eastern boundary, the Merrie Fault, correlates with a sharp change in gravity, and appears to be of crustal scale. The southern part of the Merrie greenstone belt appears to be an antiform. The Nabberu greenstone belt in the central south appears to be bounded by faults on both sides.

Archaean granite–greenstone appears to underlie much or all of the Nabberu Basin, and may extend farther north beneath the southernmost part of the Bangemall Basin. A north-northeast-trending gravity high under the Nabberu Syncline in the centre of the Sheet area is attributed to underlying Archaean greenstone, whose western boundary appears to be a crustal-scale north-northeast-trending fault (1) extending from Archaean granitoid to the south. This fault apparently formed during the Archaean, and predates the formation of the Nabberu Syncline. The interpreted greenstone unit may be the northern extension of the Nabberu greenstone belt, which contains gold deposits.

A late (Proterozoic?) north-northwest-trending fault (2) with little displacement is evident from the aeromagnetic data in the west. Northeast-trending en echelon faults (3) in the northwest may be conjugate to the north-northwest-trending fault system.

Proterozoic units

Leech et al. (1981: op. cit.) mapped some rocks of the Frere Formation (Earaheedy Group) north of the closure of the Nabberu Syncline. These rocks show a magnetic pattern of many east–west-trending, short-wavelength, highly magnetic anomalies, similar to those of the same formation in the syncline closure area. Outcrops in the interpreted unit at (4) were shown to belong to the Frere Formation as well. Some rocks of the Yelma Formation (mainly non-magnetic quartz arenite, shale, and phyllite of the Earaheedy Group) crop out at (5), but are indistinguishable from those in area (4) in the aeromagnetic data. The magnetic pattern in these areas shows features that can be attributed to both the highly magnetic Frere Formation and the underlying Archaean granitoid. The linear east–west-trending anomalies in these areas are similar to those of the Frere Formation west and south of the interpreted unit at (4), but the lower magnitude is similar to those of the underlying granitoid. A plausible interpretation is that the magnetic unit(s) in the Earaheedy Group overlying Archaean granitoid in the areas of (4) and (5) are thin.

Several small Proterozoic outcrops overlie the Archaean in the north-northwest. They have little expression in the magnetic data (which show patterns typical of the underlying granitoids), and are probably poorly magnetised and thin.

The Troy Creek beds are composed mostly of shale, phyllite, and sandstone. The aeromagnetic data reveal an apparent fold (6) in the unit, not previously mapped. The fold is attenuated by a fault in the west, and is surrounded by little-magnetised rocks, also of the Troy Creek beds, with fewer short-wavelength anomalies. The Troy Creek beds are lithologically and structurally similar to the Palaeoproterozoic Glengarry Group, which is exposed west of the Merrie greenstone belt.

The rocks immediately north of the interpreted fold (6) were mapped as Troy Creek beds by Leech et al. (1981: op. cit.), as shown in the solid-geology map. However, this area is similar magnetically to, and may be composed of, the younger Bangemall Group.

The Scorpion Group (7) — of quartz, lithic, and silty sandstone — corresponds to an area of low and very smooth magnetic responses, and is cut by a prominent, unmapped dyke.

The Bangemall Group, which consists mostly of quartz sandstone, siltstone, shale, and minor conglomerate, unconformably overlies the other Proterozoic units. Four units are identified from the magnetic data in the area of the Group, although the causes of the anomalies are not fully understood:

- The most prominent unit (8) occurs as an elongate northwest-trending strip 7 km wide in the central north. This area is highly magnetic and has few short-wavelength anomalies. Outcrops in this area include the Calyie Sandstone and Wonyulgunna Sandstone, which are probably non-magnetic. The strong magnetic anomaly here may be due to basement, to an underlying intrusive body, or to magnetic units within the sequence rather than the outcropping lithologies.
- A few areas within the Group have low magnetisation and have few or no short-wavelength anomalies. Some of these areas are more than 10 km across (9).
- A few unexplained small high magnetic anomalies in the Group might reflect intrusive bodies at depth.
- The rest of the Group outcrop, undivided on the map, shows mainly an incoherent high-frequency anomaly pattern, probably due to flat-lying magnetic units (mafic sills or volcanics) within the Group.

Acknowledgment

This work has benefited from numerous discussions with Peter Gunn and Alan Whitaker. Alastair Stewart, David Blake, Alan Whitaker, and Peter Gunn reviewed and improved the manuscript.

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Solid geology of the Nabberu 1:250 000 Sheet area, Western Australia

Songfa Liu[1]

A solid-geology map based on all available spatial datasets is important for an understanding of the geological evolution

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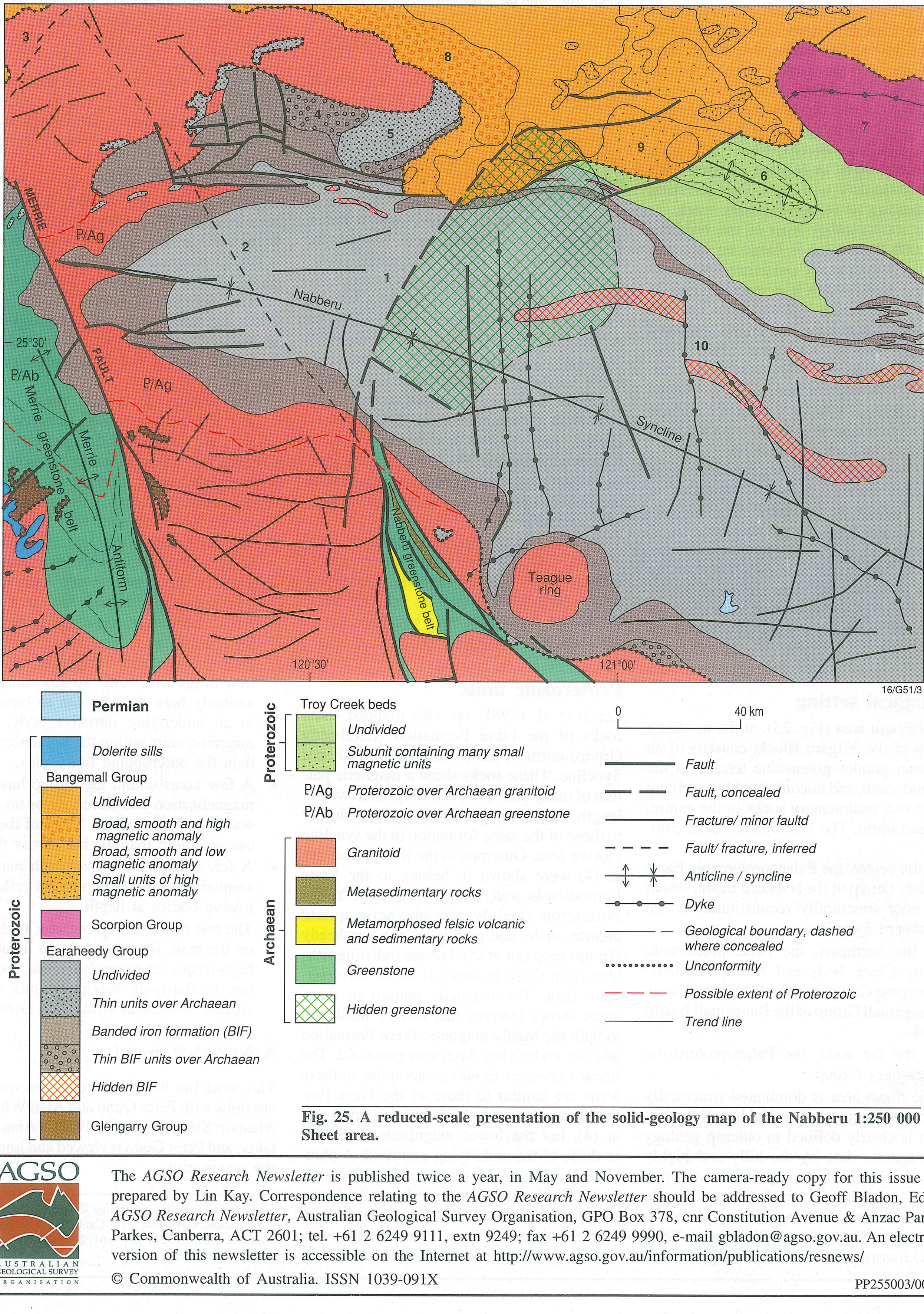

Fig. 25. A reduced-scale presentation of the solid-geology map of the Nabberu 1:250 000 Sheet area.

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 ISSN 1039-091X

PP255003/00266