agso
RESEARCH NEWSLETTER
'Geoscience for Australia's Future'

Number 23 | November 1995

'Australian crustal elements' map

A geophysical model for the tectonic framework of the continent

Russell D. Shaw[1], Peter Wellman[1], Peter Gunn[2], Alan J. Whitaker[1], Chris Tarlowski[2], & Michael Morse[2]

AGSO has released for sale this month an innovative full-colour map of 'Australian crustal elements' at 1:5 million scale. This map delineates upper-crustal elements, primarily based on composite geophysical domains, each of which shows a distinctive pattern of magnetic and gravity anomalies. These elements generally relate to the basement, rather than the sedimentary

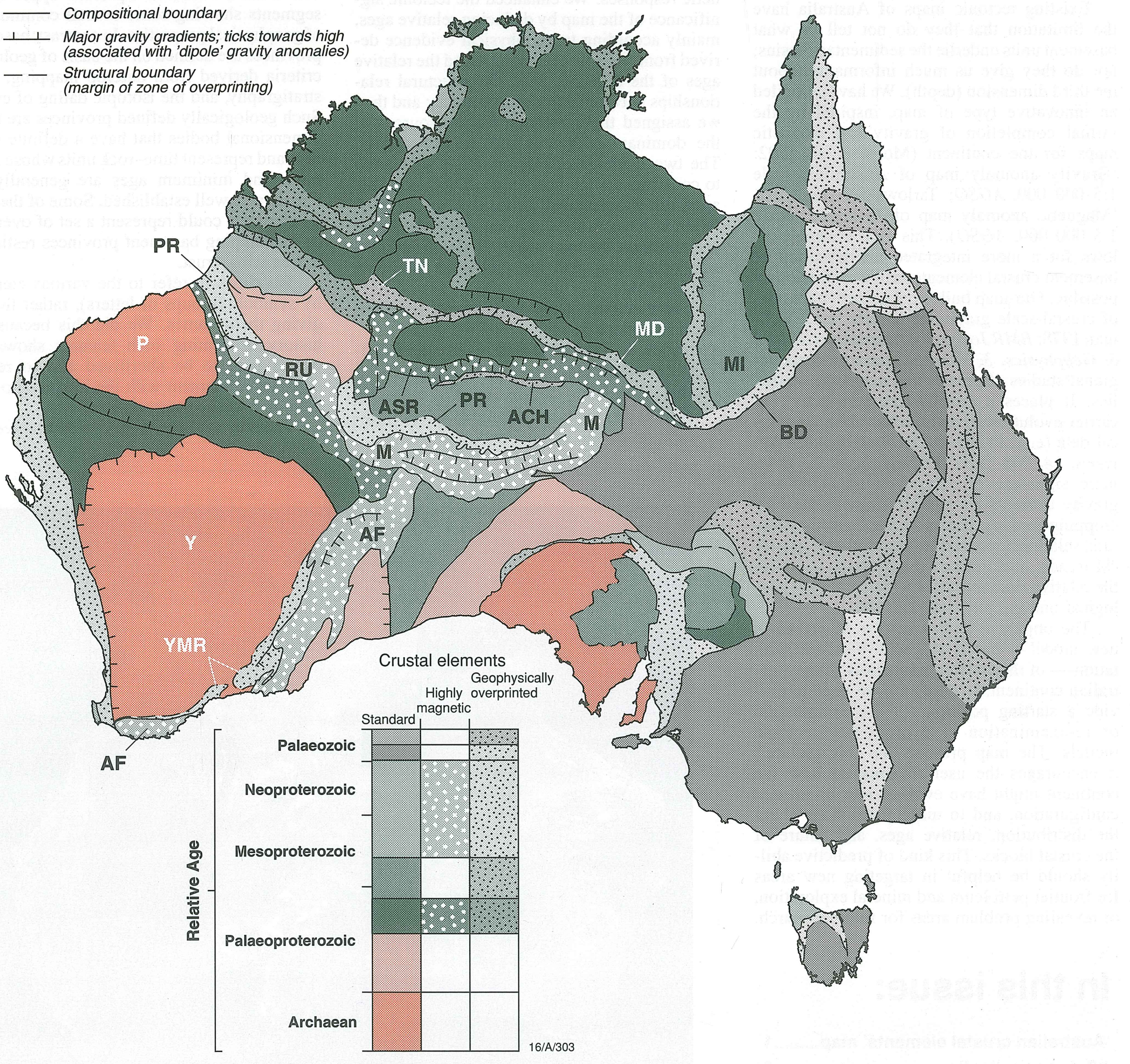

Fig. 1. Simplified crustal elements map of Australia, 1995. (See text for an explanation of letter symbols.)

Table of Contents on page 2

AGSO
Australian Geological Survey Organisation
a research organisation of the Department of Primary Industries & Energy

basins, which tend to mask or distort — rather than define — the magnetic and gravity characteristics. Boundaries between these elements are interpreted to mark crustal-scale changes in composition or structural pattern, or both composition and structural pattern. Where feasible, these boundaries are chosen to emphasise their correlation with the outcropping boundaries of geological provinces. The elements are categorised secondarily according to their magnetic character, in a way which places them in a tectonic context. Finally, a tentative relative timescale emphasises the range of time over which the geophysical features, normally the magnetic patterns, were imposed.

Existing tectonic maps of Australia have the limitation that they do not tell us what basement units underlie the sedimentary basins; nor do they give us much information about the third dimension (depth). We have compiled an innovative type of map, inspired by the virtual completion of gravity and magnetic maps for the continent (Morse et al. 1992: 'Gravity anomaly map of Australia', scale 1:5 000 000, *AGSO*; Tarlowski et al. 1995: 'Magnetic anomaly map of Australia', scale 1:5 000 000, *AGSO*). This dual coverage allows for a more integrated interpretation of basement crustal elements than was previously possible. Our map builds on an earlier analysis of crustal-scale gravity anomalies (e.g., Wellman 1978*: BMR Journal of Australian Geology & Geophysics*, 3, 153–162), and on other regional studies of gravity and magnetic anomalies. It places a geophysical perspective on earlier evolutionary models based on geological data (e.g., Plumb 1978: *Earth Science Reviews*, 14, 205–249). The map uses the magnetic signature of composite magnetic and gravity domains to provide links to the outcropping geology. It goes farther by using structural relationships, deduced from the geophysical trends, and links to the geology to reveal the relative time implied by the combined geological and geophysical data sets.

The objective of this map is to present a new model — based on geophysical interpretation — of the tectonic framework of the Australian continent. In doing so, we hope to provide a starting position for the examination or re-examination of evolutionary tectonic models. The map presents the 'big picture'; it encourages the user to consider how the continent might have evolved into its present configuration, and to make predictions about the distribution, relative ages, and nature of the crustal blocks. This kind of predictive ability should be helpful in targeting new areas for frontier petroleum and mineral exploration, or revealing problem areas for future research.

In this issue:

Principles of the map

In attempting to build our model for the tectonic framework of the continent, we began by looking for coherence between gravity and magnetic domains so that we could delineate composite geophysical domains. After analysing several portrayals of amalgamated magnetic and gravity data sets (e.g., Fig. 2), we erected compositional and structural province-scale boundaries that correlate where possible with geological features. Such boundaries can then be extrapolated under the sedimentary basins. To give the map an added tectonic flavour, we characterised the domains according to their magnetic and gravity character, in a way that reflects the tectonic significance of their magnetic responses. We enhanced the tectonic significance of the map by deducing relative ages, mainly according to geophysical evidence derived from two sources: we deduced the relative ages of the domains from the structural relationships between adjoining domains; and then we assigned the age-range for the sources of the dominant magnetic and gravity signals. The two methods of interpretation were used to construct an age-box for each domain. This approach has enabled us to express the evolution of the continent as a sequence of relative age slices on the map sheet. A simplified version of the map and the age-boxes is shown in Figure 1.

Three classes of crustal elements are identified in Figure 1:

- standard — not modified by any geophysical overprinting;
- highly magnetic — dominated by magnetic and gravity highs, which imply gross modification of the upper crust; and
- geophysically overprinted.

We emphasise that the magnetic and gravity boundaries shown on the 1:5 million map are not always coincident for the crustal elements, unlike typical geophysical domains. Where there is some mismatch, the crustal boundary favoured is that which most closely corresponds to an established geological boundary. Also unlike typical geophysical domains, the crustal elements have relative age range as an attribute.

We emphasise too that the crustal elements are not geologically defined features, because they have been defined primarily from magnetic and gravity data sets, which largely monitor the overall properties of the upper crust. The crustal elements represent upper-crustal segments showing some overall commonality of geophysical properties. In contrast, basement provinces are defined on the basis of geological criteria derived from outcrop mapping, event stratigraphy, and the isotopic dating of events. Such geologically defined provinces are three-dimensional bodies that have a definite thickness and represent time–rock units whose maximum and minimum ages are generally, but not always, well established. Some of the crustal elements could represent a set of overlying or overlapping basement provinces resting on pre-existing crust.

We chose to refer to the various elements by symbols (groups of letters), rather than by giving them names. We did this because the history of naming such features shows that names tend to be shortlived and to require constant refinement with the incoming of new data and fresh interpretations.

The crustal elements have a distinctive geo-

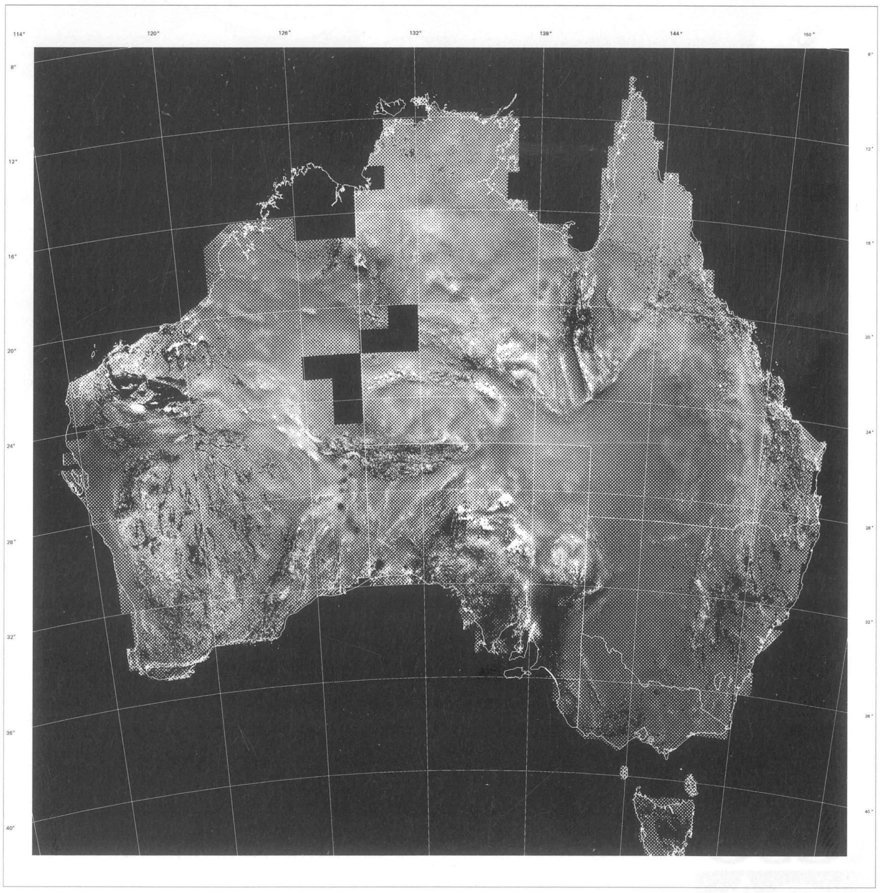

Fig. 2. Gravity-enhanced magnetic image of Australia.

physical character and show unique structural relationships with their neighbours, suggesting that each has experienced a distinct tectonic history. Thus, overprinting and discordant relationships in geophysical anomalies show that the MI (Mount Isa) element is younger than the elements to its east and west, as it truncates structures to the east and west (cf. Wellman 1992: *BMR (AGSO) Bulletin*, 232, 15–27); it is interpreted from geology to be a region of complex extensional structures with three periods of rifting along a north–south axis.

The mega-elements

The general picture that has emerged from the new map is of a continent made up of eight coherent mega-elements. These represent groups of crustal elements having similar geological and geophysical characteristics, and lying within a common set of boundaries (Fig. 3).

Boundaries between mega-elements

The boundaries between mega-elements and between many of the crustal elements are commonly associated with two broad classes of geophysical anomaly type. One is a major change in mean density or mean apparent susceptibility of the crust, which gives rise to paired high and low gravity or magnetic anomalies along the boundary — dipole anomalies. The other is that generated as a result of interactive processes at the boundary; anomalies within this class include three main types:

- zones of geophysical overprinting, commonly associated with shearing, where trends of one element replace those of another;
- zones of overprinting characterised by extensive magnetic lows generated as a result of processes such as demagnetisation associated with heating of the older element when the younger element was emplaced against it; and
- zones characterised by major gravity and magnetic highs — the so-called highly magnetic zones — formed alongside the younger element; these are the result of either major intrusions along the boundary, or uplift of the lower crust by overthrusting along the boundary.

Significance of the boundaries between mega-elements

Mega-element boundaries are well illustrated by the overprinting zone at the boundary between mega-elements **WA** (Western Australia) and **SA** (South Australia; Fig. 3), which separates the element labelled Y (Yilgarn) from element AF (Albany–Fraser; Fig. 1: see discussion by Wellman 1988: *Precambrian Research*, 40/41, 89–100). This zone (YMR in Fig. 1) is characterised by a drop in magnetic intensity (demagnetisation) and the progressive disruption of the magnetic pattern of element Y. The demagnetisation is the result of Mesoproterozoic deformation and high-grade metamorphism of the Archaean gneisses and greenstones (Yilgarn) during convergence of the elements (Beeston et al. 1988: *Precambrian Research*, 40/41, 117–136). This overprinted zone, YMR, is adjoined immediately to the west by a highly magnetic zone, the 40–200-km wide element AF (Albany–Fraser). It correlates with a complex orogenic belt of orthogneiss, paragneiss, dolerite and gabbro that was extensively intruded by granite at about 1150 Ma (Myers 1990: *Geology*, 18, 537–540). Zone YMR and the western margin of the magnetic zone corresponding to element AF are overlain by major gravity highs and lows — a gravity dipole. At this complex boundary (corresponding to the WA–SA mega-element boundary), the gravity anomaly reflects the change in crustal density across the boundary, and the magnetic anomaly reflects the crustal effect of processes acting at the crustal-element boundaries.

The mega-element **CA** (central Australia; Fig. 3) is a complex zone separating simpler and more coherent mega-elements. It comprises an assembly of long narrow crustal elements, more-equidimensional elements, and relatively small elements. These include several highly magnetic zones and overprinted zones, similar to those described above. The geophysical evidence indicates that mega-element **CA** corresponds to a wide region of interaction between, on the one hand, the more cratonic mega-element **NA** (north Australia) and, on the other, **WA** and **SA**, which are even more cratonic in character. Geological evidence suggests that mega-element **CA** evolved between 1900 Ma and 1100 Ma (Collins & Shaw 1995: *Precambrian Research*, 71, 315–346).

Major discordant boundaries within mega-element **CA** (Fig. 3) imply large strike-slip displacements. These include the discordant boundary where element ASR (Fig. 1; a highly magnetic zone that borders the Redbank Thrust Zone, in the central Arunta Block) truncates element M (Musgrave). Another markedly discordant boundary is that marked by the zone of overprinting BD (Bright Downs). This zone truncates element MI (Mount Isa), and swings from southwest to northwest to merge with the boundary between mega-elements **CA** and **NA** (TN and MD overprinted zones; Fig. 1).

The tectonic significance of such discordant boundaries between elements can be assessed by their degree of discordance and whether they mark abrupt changes in crustal composition. Studies in Canada (Gibb et al. 1983: *Precambrian Research*, 19, 349–384), west Africa, and Brazil (Lesguer et al. 1984: *Tectonics*, 110, 9–26) suggest that many discordant boundaries showing abrupt changes in mean crustal composition can represent geosutures between previously separated lithospheric plates.

Fig. 3. Australian mega-elements, representing continent-scale groups of crustal elements. The mega-elements are: NA, north Australia; NQ, north Queensland; CA, central Australia; P, Pinjarra (orogen); WA, Western Australia; SA, South Australia, T, Tasman (orogenic system/fold belt); and NE, New England.

Conclusion

Our new map of Australian crustal elements delineates and classifies the geophysical domains in a way that sheds new light on the tectonic development of the continent. The map recognises many abrupt or discordant boundaries in the upper crust, some of which may be plate or subplate boundaries that have been active at various stages in the continent's history.

The release date for the 1:5 000 000-scale 'Australian crustal elements' map is 17 November 1995, coinciding with the project-presentation seminar of AGSO's Division of Regional Geology & Minerals.

[1] AGSO Division of Regional Geology & Minerals, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9665 (RDS), (06) 249 9653 (PW), (06) 249 9702 (AJW), fax (06) 249 9983.

[2] AGSO Division of Geophysical Mapping & Observatories, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9226 (PG), (06) 249 9265 (CT), (06) 249 9251 (MM), fax (06) 249 9986.

A reality and a winner — automated AF demagnetisation comes of age in palaeomagnetic methodology at AGSO

John Giddings[1]

In the current funding environment, in which scientific projects — like tubes of toothpaste — are being squeezed to get the most out for the funds in, it has to be good news when a labour-intensive routine data-acquisition task is fully automated, and yields data quality superior to that of the procedure it replaces. Such is the case at the Black Mountain palaeomagnetic laboratory, where state-of-the-art automated alternating-field (AF) demagnetisation of rock specimens has recently become a reality with the commissioning of AF control software, and the resolution of problems inherent in the AF method. As a measure of the time savings involved, a demagnetisation task on eight specimens, which previously consumed a day, now requires only twenty minutes of operator intervention, and saves a cumulative walk, to tend equipment, of one kilometre.

Why demagnetise rocks?

We may regard the natural magnetic remanence of a rock as a palaeomagnetic signature of

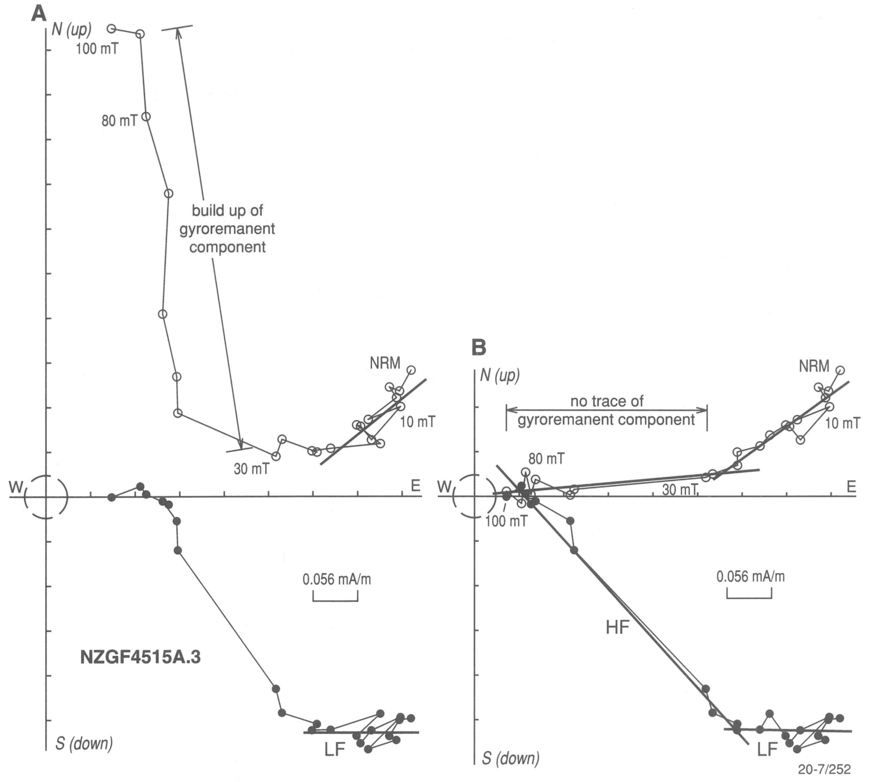

Fig. 4. Orthogonal plots (Zijderveld 1967: ***in*** **'Methods in palaeomagnetism',** ***Elsevier, Amsterdam,*** **254–286) of static AF demagnetisation results from our automated AF system: (a) without procedure for counteracting gyroremanent magnetisation build-up; and (b) with counteracting procedure in place. Note the effectiveness of this procedure for eliminating gyroremanence. The circle represents the level of holder magnetisation. Each diagram displays, in 2-dimensions, the 3-dimensional vector endpoints of the residual remanence measured after each demagnetisation step, from the initial remanence (NRM) to the highest peak AF (100 mT) that we selected (the maximum selectable field is 180/300 mT for automatic/semi-automatic mode). Each diagram comprises two views: a view of the horizontal plane (solid symbols), which shows the azimuth of remanence (plan view); and a view of the vertical plane (open symbols), up/down tagged (elevation view), rotated into the horizontal plane by 90° about the east–west axis. Two components of remanence can be interpreted: a low-field one (LF); and a high-field one (HF), which is obliterated by introduced gyroremanence in (a).**

geological events that have affected it. The natural remanence is generally built up of several components of magnetisation, each acquired at a different period in the rock's history. For instance, the remanence may comprise the following components: one acquired at the time of formation of the rock; one acquired in response to chemical change during a period of fluid flow; one acquired through burial at mildly elevated temperatures; and one acquired by viscous build up of magnetisation in the recent Earth's field. Apart from the last component, each of the others has a story to tell, which is respectively: the relative position, with respect to the Earth's rotational axis, of the crustal unit on which the rock crops out; the timing of fluid flow; and the timing of tectonic events and raised heat flux.

In order to be able to interpret, from a palaeomagnetic perspective, the geological events recorded by a rock — events which experience has shown may sometimes be of a type that is irresolvable by other mainstream techniques — we must have access to the component composition of its remanence. Since remanence is a vector quantity, however, all we can measure with a magnetometer is the resultant or 'average' magnetisation. This, in itself, is of no geological significance. To gain access to the component structure, we have to demagnetise the remanence. As all rocks in a palaeomagnetic study must be demagnetised, the process figures prominently in all studies; in fact, it consumes most of the time devoted to a project. We therefore have a responsibility to ensure that the demagnetisation process is executed as efficiently as possible by paring to a minimum the time devoted to it.

AF demagnetisation

Until now, the AF method of demagnetisation has been a labour-intensive operation. In the AF method (e.g., Collinson 1983: 'Methods in rock magnetism and palaeomagnetism', *Chapman and Hall, London*), a specimen is demagnetised by subjecting it to a series of alternating magnetic fields, of increasing strength (peak fields), which are smoothly reduced to zero while the specimen is shielded from external steady magnetic fields. After each peak-field treatment, the residual remanence of the specimen is measured. In the absence of a biasing steady field, all remanence between a peak field and zero is randomised and lost. Clearly, by incrementally increasing the peak field we incrementally demagnetise the natural remanence. The remanence destroyed between peak-field increments is retrieved from the measurements of residual remanence made after each treatment. Analysis of special plots used to display these measurements yields the sought-after component structure of natural remanence.

Up to ~25 different peak AFs and measurements of remanence may be required to completely demagnetise a specimen, and 100+ specimens could comprise a study. With current AF systems in use around the world, constant operator involvement is required throughout the complete demagnetisation cycle. It is this continuity of operator involvement that we targeted in our bid for substantial time-savings, by successfully automating the AF process using a combination of integrated measurement and AF-coil control software and sophisticated demagnetisation equipment and procedure.

Our automated AF system is based on the static method of AF demagnetisation, whereby a peak AF is applied to a specimen along each of its three orthogonal axes in turn. The static method, however, has received only marginal acceptance from the palaeomagnetic community as a routine method of demagnetisation: the use of standard equipment and procedure carries a high risk of contaminating results with coherently directed components of remanence arising from harmonic distortion of the applied alternating fields or from the gyromagnetic effect (Stephenson 1993: *Journal of Geophysical Research*, 98, 373–381, and fig. 1a). The alternative, widely used tumbling-specimen method of AF demagnetisation is apparently free of this problem by virtue of the act of tumbling, but is unsuited to automation. We have overcome the major drawback of the static AF method, though, by using more sophisticated equipment for AF generation and a more complex demagnetisation procedure (Stephenson 1993: *op. cit.*, and fig. 1b). This procedure requires that, for a *particular* peak field, five AF treatments of a specimen and three determinations of its residual remanence be made, rather than the standard three AF treatments and a single remanence determination.

The automated AF environment

The automated AF demagnetising environment is built around our 2G-Enterprises through-bore cryogenic magnetometer system, using AF components supplied by 2G-Enterprises. The AF equipment comprises the following units: two pairs of AF coils mounted in-line and along the axis of the magnetometer; a sophisticated computer-controllable power supply for driving the AF coils and ensuring that they deliver demagnetising fields that are free of distortion; and an extended-reach specimen-handler to accommodate the extra distance between the specimen load-point and magnetometer measurement region, resulting from attachment of the AF coils to the magnetometer. Stepper-motors control translation and orientation of specimens, so that the three axes of a specimen can be presented, in turn, along the axis of a coil for field treatment. This arrangement of the components of the AF system means that, after a specimen has been loaded, it can be passed through the coil system for static demagnetisation, and then positioned into the measurement region for determining its residual remanence.

In-house-developed PC-based software binds these elements of the AF environment together, and activates the system. The processes which control the peak-magnetic-field profiles and specimen-exposure times, the position and orientation of specimens for measurement/magnetic-field treatment, the measurements of residual remanence, and the instantaneous screen-graphics display of the progress of demagnetisation, have been rolled into a single but flexible menu-driven data-acqusition procedure that runs automatically. This means that complete demagnetisations of specimens, comprising up to 25+ AF treatments and associated measurements of remanence, can be carried out *unsupervised*, releasing the operator to perform other tasks simultaneously. Operator intervention is required only to change specimens. The ability to adapt the progress of demagnetisation to suit the behaviour of a specimen is available whenever the need arises: the real-time graphics display of demagnetisation facilitates this requirement. Indeed, for those unusual or 'special' specimens which occasionally turn up and require nursing through demagnetisation, there is a toggle option to switch the equipment into semi-automatic mode: operator involvement will then be continuous.

Test results

Results obtained to date bear witness to the efficacy of the system to demagnetise cleanly and neutralise spurious magnetisation. The specimen chosen to illustrate this point is rather an extreme test: its initial remanence is weak (0.56 mA/m), and it is very prone to acquiring disturbing gyroremanent magnetisation. Figure 4a displays the result of statically demagnetising the specimen in the absence of a procedure to counteract the gyromagnetic effect. It dramatically shows the magnitude of the disturbing gyroremanence introduced at higher AFs. Above a peak AF of 30 mT, an increasingly large remanence develops along the *up*-axis of the specimen, orthogonal to the axis being demagnetised. The final magnetisation, at the highest peak AF we selected, is *larger* than the undemagnetised initial remanence (NRM). We would normally expect the magnitude of this final magnetisation to be close to that of the specimen holder (shown as an origin-centred circle in the figure). Obviously, all information on components of remanence of geological significance, between 30 mT and the highest peak AF, has been obliterated.

The result shown in Figure 4b (same scale) was obtained with the more complex demagnetisation procedure in place to counteract the gyromagnetic effect. The result speaks for itself: there is no trace of the large component of magnetisation introduced at higher AFs, and demagnetisation of the specimen proceeds down to the level of magnetisation of the holder. The result allows us to view the real component composition of natural remanence. The high-field component (HF) is now revealed as a southeast-directed, shallow, upward-pointing magnetisation. The low-field component (LF), of course, is evident from either procedure: approximately east-directed with moderate upward inclination. The quality of this result is remarkable in view of the extremely low magnetic intensities. Indeed, other testing has demonstrated that its quality is superior to what we can get from our labour-intensive tumbling-specimen equipment. Remanence of gyromagnetic origin (rotational remanence) is introduced with this equipment by the act of tumbling, but, rather than being coherently directed, it is dispersed and manifests itself as increasingly large scatter in the demagnetisation trend at higher fields. The chances of retrieving the HF magnetisation with this equipment is slim.

Benefits

We have won very significant productivity and efficiency gains with our automated AF system, without compromising the quality of results. For instance, for dedicated AF treatment and measurement activities, using both our manual and automated units, an operator can increase daily specimen throughput by 100–130 per cent. In terms of efficiency, the automated unit can produce the same output for twenty minutes of operator attention, as the manual system can for eight-hours' operator attention. Scientifically, the data quality that the AF system delivers is superior to that of the manual tumbling-specimen method. Commercial opportunities present themselves with the prospect of marketing the software package to other palaeomagnetic laboratories.

In terms of future potential, the AF system as it now stands, provides us with the necessary foundation to extend automated AF treatment to long core material in long-core format. This will unlock further productivity and efficiency gains by removing the need for manual subsampling to get the same results.

[1] AGSO Division of Geophysical Observatories & Mapping, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9319, fax (06) 249 9986.

Is oil being generated beneath the northern Arafura Sea?

Aidan Moore[1]

Geohistory analysis of data from oil exploration wells in the Arafura Sea indicates that the Palaeozoic source rocks in the Goulburn Graben expelled their hydrocarbons before traps formed in the Triassic Period. Larger areas outside the graben were not deformed to the same extent. These areas have a low geothermal gradient, and may have remained immature until they were buried by the Tertiary sediments of the Money Shoal Basin. Areas to the north, therefore, could be more prospective for hydrocarbons than the Goulburn Graben, in which exploration has been concentrated. Analysis of synthetic well sites in the northern area suggests that hydrocarbons could have been generated there since the Jurassic.

Exploration for hydrocarbons in the Arafura Sea to the east of Darwin has been confined to the area of youngest pre-Mesozoic rocks, namely the Goulburn Graben (Fig. 5). Early seismic reconnaissance outside the graben failed to show a seismic succession that would encourage further exploration there. Shallow basement with a thin cover of latest Mesozoic and Tertiary sediments was thought to underlie the huge area outside the graben. Eight wells now have been drilled in the graben, and some major plays have been tested, without finding a commercial accumulation. Therefore, exploration has ceased in the area conventionally given the highest rating for prospectivity. But, with hindsight, is the Goulburn Graben the best place to explore for hydrocarbons?

Reflection seismic reconnaissance surveys by AGSO in 1990 and 1991, over the area north of the graben, failed to find the signature of igneous basement. Aeromagnetic data acquired by Shell Development in 1965 and interpreted by Robertson et al. (1976: *BMR Record* 1976/66) indicate a basement depth of up to 10 000 m. The AGSO seismic data revealed a stratified succession that is interpreted to be of Mesoproterozoic to Palaeozoic age (Labutis et al. 1992: *AGSO Record* 1992/84). Drilling onshore in the Arafura Basin found oil-source rocks (TOC up to 10%) and free oil in the Mesoproterozoic McArthur Basin succession (Crick et al. 1988: *AAPG Bulletin* 72(12), 1495–1514; Powell et al. 1985: *BMR Research Newsletter* 3, 1–2). That succession is now thought to underlie the Arafura Basin north of the Goulburn Graben. In addition, a re-evaluation of the palynological data from wells and islands in the Arafura Sea has led to the redefinition of some sequences — for example, at the base of the Arafura 1 well and onshore — as being younger than previously thought; these studies were described by Bradshaw et al. (1990: *APEA Journal*, 30, 107–127).

Geohistory studies in the Goulburn Graben

AGSO has recently completed geohistory studies of seven wells drilled in the Goulburn Graben before 1992, and one nearby (*AGSO Record* 1995/65). Torres 1 well, drilled on top of the largest anticline, has spawned a large and diverse record of thermal maturity measurements — including vitrinite reflectance (VR), thermal alteration index (TAI), pyrolysis (TMAX), and (essential for early Palaeozoic samples in which vitrinite from coal is absent) conodont alteration index (CAI). These, and data from other wells, constrain the thermal-history model that was developed during the study. The hydrocarbon maturation profile derived directly from the measurements (Fig. 6) shows rightward steps in the VR profile. This indicates that prospective Palaeozoic successions were buried early, and were then subjected to episodes of major erosion. The seismic data confirm that erosion amounted to over 2 km in places.

The temperature history of Torres 1 (Fig. 7) shows that potential source rocks within the Goulburn Graben are not now at their maximum temperature, and therefore are not now generating hydrocarbons. The Ordovician and older source rocks were heated to advanced maturity or even beyond maturity for hydrocarbons in the Late Ordovician, then uplifted during the first, Siluro–Devonian, erosion event in the following 50 million years. Oil generation was halted after a period of early migration. The succeeding Late Devonian to Early Carboniferous sediments were buried and matured in the Early Triassic, then uplifted and partly eroded in the Late Triassic and Early Jurassic. These episodes predated or accompanied the

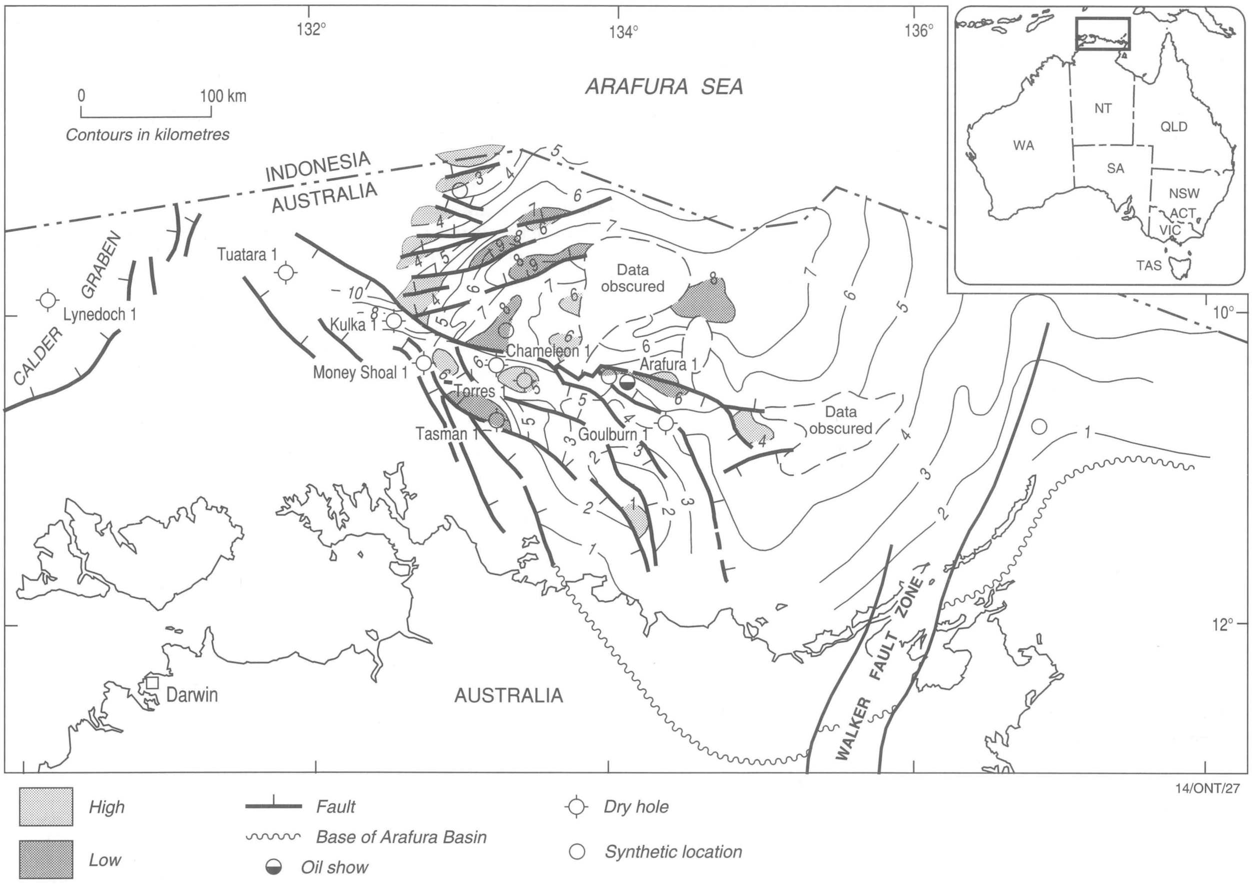

Fig. 5. Depth–structure map of the base of the Arafura Basin (base Cambrian). It shows the synclinal form of the basin north of the Goulburn Graben, and the complex of fault terraces on its rim in the west. The regional dip of the faulted western flank is eastward, opposing that of the overlying Money Shoal succession, whose westward thickening might have contributed to the development of stratigraphic traps with composite seals in this large undrilled and unknown basinal area.

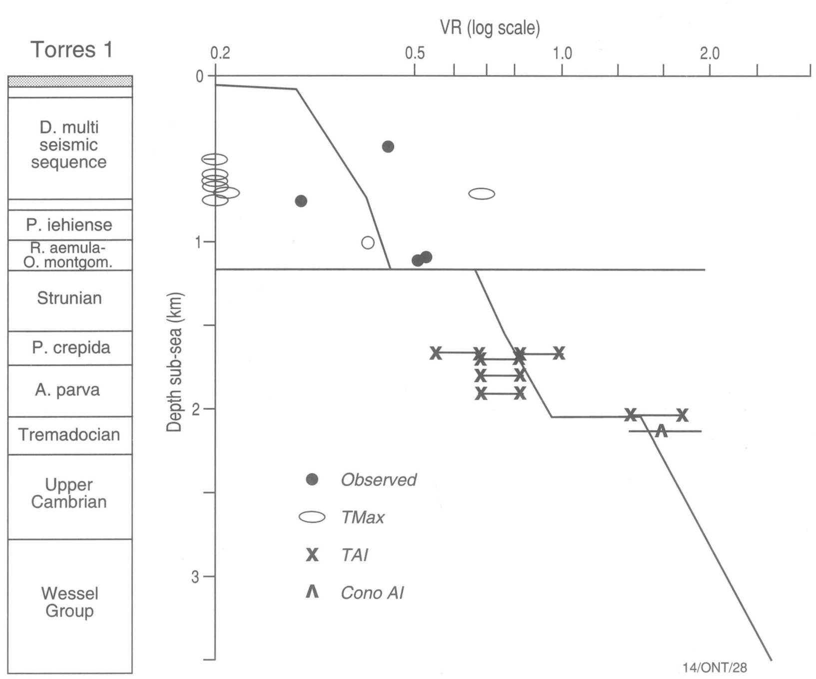

Fig. 6. Thermal maturity measurements (symbols with error bars) in Torres 1 well, in the Goulburn Graben. Various measures are used, but on this plot, they have all been converted to vitrinite reflectance equivalents. The plotted line is the maturity calculated from the model of deposition, heat flow, and uplift. Rightward steps indicating large increases in maturity are seen at the two main unconformities — the base of the Devonian and the base of the Mesozoic. The younger of these two unconformities is a product of the Late Triassic diastrophism, which created the Goulburn Graben.

initial rifting and subsidence, and then the transpression, uplift and erosion, that created the Goulburn Graben and the Torres anticline. Significant features associated with the graben — anticlines, fault traps and even stratigraphic traps — were not in existence when the oil migrated, so could not intercept and accumulate it. The Jurassic and younger rocks that overlie the Goulburn Graben have not yet reached maturity for hydrocarbons.

Geohistory and seismic studies north of the Goulburn Graben

Three synthetic well sites in the Arafura Sea outside and north of the Goulburn Graben were analysed according to the basin-history model derived from the wells drilled in the Goulburn Graben. The stratigraphy is based on seismic interpretation only, since no wells have been drilled in the northern province. The seismic configuration is of parallel, low- to high-amplitude continuous low-frequency reflections with concordant boundaries, but reveals no basement erosion surface and no internal onlap or offlap. This configuration is typical of a low-energy marine environment. It is thought to represent a Palaeozoic tropical shallow-water continental-margin platform covered by clastic and carbonate rocks, typical of the Larapintine system of northern Australia and somewhat similar to today's environment in the Arafura Sea. The seismic reflections are poor, and even absent in places. The poor seismic record might be attributable either to the weathering of carbonates at the base of

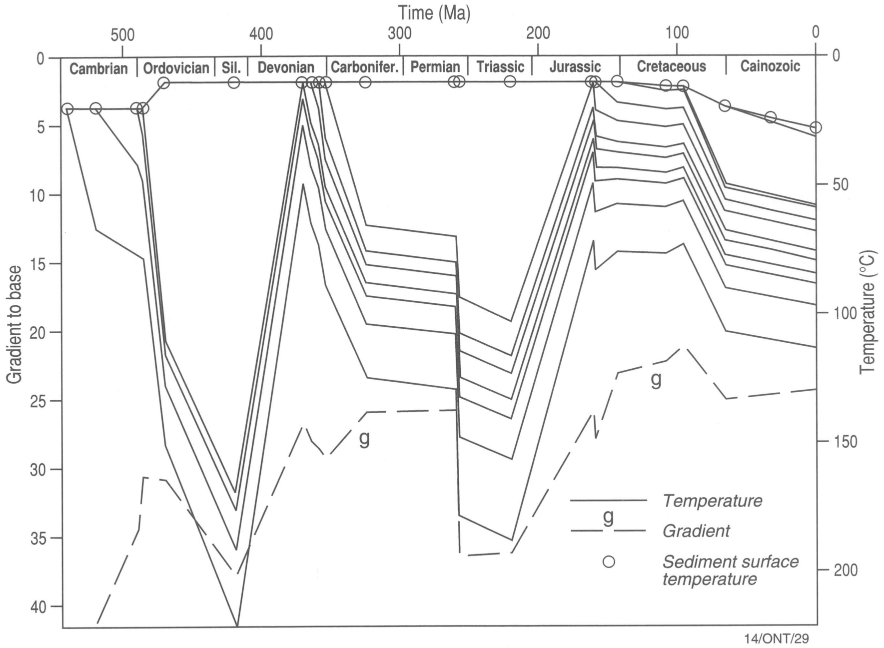

Fig. 7. Bed-temperature plot for Torres 1 well in the Goulburn Graben. It shows that the prospective Palaeozoic rocks are far below their maximum temperature, and hence are not now generating hydrocarbons. They are not at their maximum past depth of burial, and the geothermal gradient is lower than in the distant past. The Goulburn Graben and its associated structures are too young to host hydrocarbons generated by these rocks.

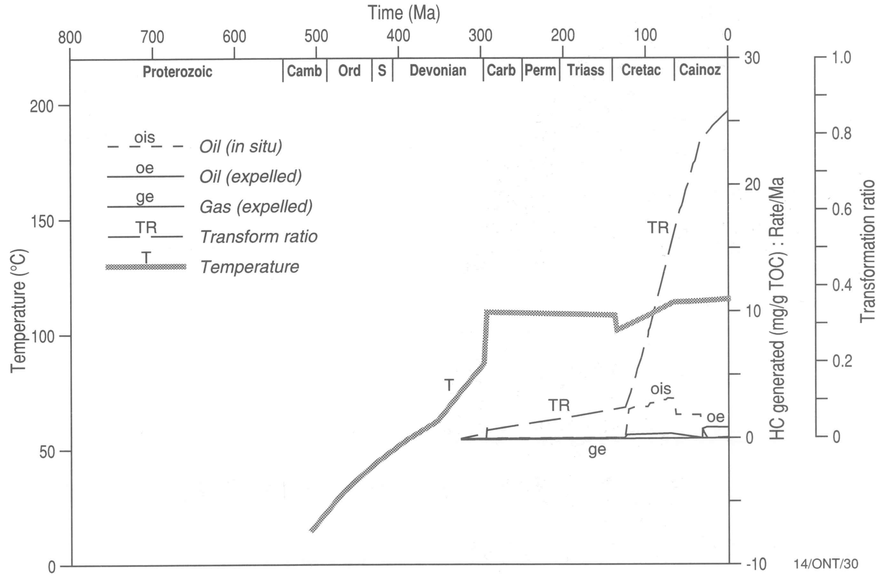

Fig. 8. Plot of the timing of events at the top of the Cambrian in a synthetic site in the undrilled northern province of the Arafura Basin. The plot suggests that generation of oil (oil in situ, ois) effectively began during the Jurassic, and migration (oil expulsion, oe) continues to the present day. The process is approaching completion, as the transformation ratio (TR) is 0.85. Temperature (T) has never risen above about 120°C, thus prolonging the generation period.

the Mesozoic succession, or to a lack of large seismic impedance changes. The Palaeozoic rocks are thought to be underlain by a low-energy marine succession of Proterozoic age whose seismic stratigraphy is more fully described by Labutis et al. (1992: *op. cit.*).

Outside the Goulburn Graben (and also, surprisingly, within it), evidence of growth is generally sparse. An angular unconformity at the base of the post-Goulburn Graben sequence is apparent only at the basin edges, which are upturned and bevelled by erosion. At the depocentre north of Chameleon 1 well, and outside the graben where a synthetic well site is located, the age of the succession is considered to be Cambrian to Permian in the plot of the timing of oil generation (Fig. 8). Seismic data suggest that the tectonic history here was much quieter than in the graben. No major episodes of burial or erosion are apparent, apart from rapid subsidence and burial in the earliest Cambrian. Owing to the low geothermal gradient, the oil window, beginning at about 2200 m, is about 4 km thick. This enhances the prospect of it containing hydrocarbon source rocks.

The oil-generation history at the level of the top of the presumed Cambrian strata (Fig. 8) shows that generation was initiated in the Permo-Carboniferous, then stalled, having barely begun. Whereas the western, southern, and eastern parts of the basin were exhumed, exhumation had negligible effects at this depocentre in the north. Generation recommenced in the Jurassic, and expulsion, driven by the accumulation of Money Shoal Basin sediments, continues to the present time. This means that even young structures, such as those on the northern rim of the Goulburn Graben, may be in a position to accumulate hydrocarbons from the northern basinal areas. Within the graben, in contrast, hydrocarbons were generated during the early Palaeozoic. Consequently, structures within the feature formed too late to intercept them, and the graben today is less prospective on this account than the northern part of the Arafura Basin.

Two questions remain in relation to the northern basin: 'Are source rocks present?', and 'Are reservoirs preserved?' Only drilling can provide the answers.

[1] AGSO Division of Marine, Petroleum & Sedimentary Resources, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9583, fax (06) 249 9983.

Ocean-bottom-seismograph cruise on the North West Shelf

Chao-Shing Lee & Clive Collins[1]

The lithosphere of many continental margins demonstrates evidence that it has been modified, over a period of 300 Ma or more before break-up and seafloor spreading, by rifting and sag due to a variety of extensional styles and episodes. Understanding the mechanical evolution of continental margins and their basins is essential for offshore environmental and resource management.

During the last 5 years, AGSO has acquired about 40 000 km of deep-seismic reflection data (~50–100-km grid) over all the main basins of the North West Shelf (Fig. 9) as part of its Continental Margins Program. These data provide a unique data set for imaging the gross geometry of crustal structures, and features that have controlled the development of the margin and its basins. However, not only are the images in two-way time but the reflection method provides only poor constraints on seismic velocity, particularly at depth, so conversion of seismic images to a meaningful true-depth section poses a problem. Moreover, the lack of good velocity information also means that the lithology and composition of imaged features are poorly constrained.

To overcome these problems and set the scene for major advances in our understanding of the North West Shelf, AGSO will use ocean-bottom-seismograph (OBS) and land-seismometer stations to record large-offset seismic arrivals sourced from the RV *Rig Seismic* airgun array.

AGSO will conduct its first OBS cruise on the North West Shelf in November–December this year. The plan is to collect OBS data from five seismic refraction and wide-angle reflection traverses along existing deep-crustal seismic reflection profiles, and to record simultaneously data on land-seismometer stations too (Fig. 9). These data will provide us with another dimension to our understanding of the deep-crustal structure beneath the northwest Australian continental margin and its relationship to major tectonic events.

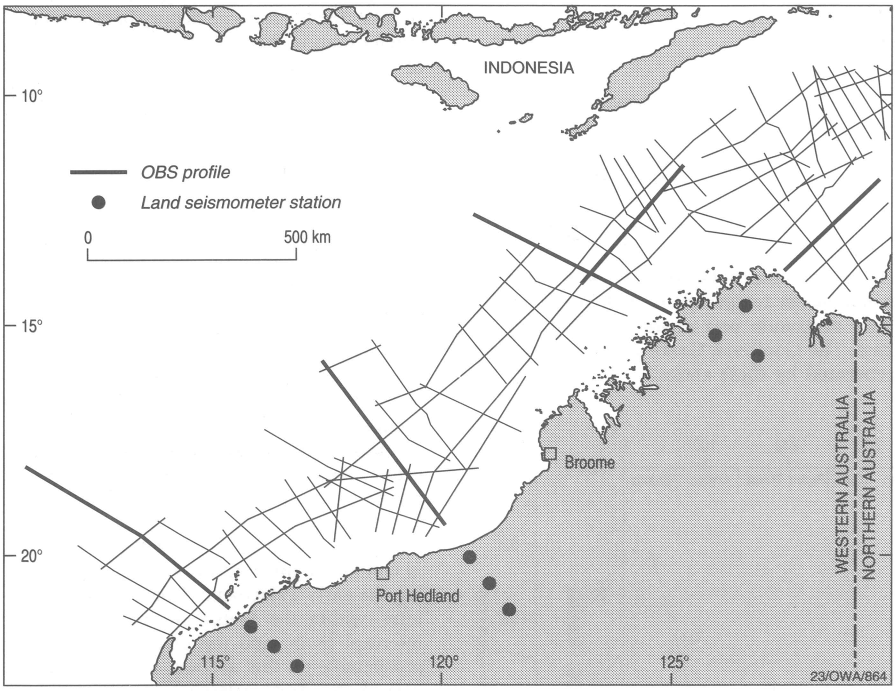

Fig. 9. Proposed locations of OBS profiles and land-seismometer stations.

The major objectives of the sea–land refraction survey are:

- to image the nature of deeply buried crust in order to map the Moho, basement, and structure in the ocean–continent transition zone;
- to deduce the velocity structure of any basin-forming ramp and high-displacement features, and of the deeper part of the sedimentary-sag section, in order to assist basin modelling and depth conversion; and
- to understand the extent and nature of crustal thinning by mapping the Moho topography.

The use of OBSs is a new technique for AGSO, and it will also be the first time that such technology and such an approach have been used in Australia. In the last 2 years, AGSO staff have spent a great deal of time studying the design and development of OBS systems. OBSs are not commercially available, and only a few research institutes in the world have developed and built such instruments. The OBS designed by the University of Texas, Institute for Geophysics (UTIG), appears to be the most cost-effective instrument: it has great potential for future development, and can be used for other applications (e.g., for ocean-bottom earthquake monitoring, for seismic tomography, and as a magnetic observatory). France and Taiwan have both joined with UTIG to construct the OBSs, and there is now a growing worldwide pool of these instruments.

AGSO is negotiating to borrow 15 OBSs from UTIG and five from the National Taiwan Ocean University. Both universities cooperated on an OBS cruise off Taiwan in August–September. This provided a model for the North West Shelf cruise, and Chao-Shing Lee and Jack Pittar participated on it to gain the necessary experience for AGSO in the use of the OBSs.

[1] AGSO Division of Marine, Petroleum & Sedimentary Resources, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9439 (C-SL), (06) 249 9544 (CC), fax (06) 249 9983.

NABRE's first field season facilitates the discrimination of sequence boundaries and maximum-flooding and transgressive surfaces in the Mount Isa–Lawn Hill region

NABRE research team[1]

The 'North Australian basins resource evaluation' (NABRE) project, constituted as part of the National Geoscience Mapping Accord (NGMA), is designed to resolve the major geological processes that control the distribution of resources in northern Australia. The project team — comprising scientists from AGSO, the Northern Territory Geological Survey (NTGS), and the Geological Survey of Queensland (GSQ) — defined the concepts relating to the distribution of mineral and petroleum resources in Proterozoic sedimentary basins before embarking on an initial field season. The fieldwork began on 19 June with a 17-day reconnaissance field trip for the entire project team, and continued with an eight-week period of data collection. The fieldwork served to familiarise project staff with the geology of northern Australia, and to provide a first-pass structural and sequence stratigraphic framework that would be tested during the remainder of the field season. One of the main objectives of the fieldwork is to demonstrate the significance of the application of sequence stratigraphy to Proterozoic outcrop and subsurface sections in northern Australia.

The field studies focused on rocks of the McArthur Group around the Kilgour River; the upper and lower McNamara Groups in the Kennedy Gap, Mammoth Mines, Mount Oxide, and Lawn Hill 1:100 000 Sheet areas; and the Fickling Group south of the Murphy Inlier. As well as measuring detailed stratigraphic sections by traditional descriptive methods, the project team made extensive use of hand-held spectrometers to generate gamma-ray curves similar to those used in the petroleum industry. These outcrop data are being complemented by gamma-ray curves generated from drillcore and, where available, by wireline logs held by mineral exploration companies. Poor exposure over some parts of the study area has necessitated the use of drillcore-derived data sets to divide the sedimentary succession into its basin phases and associated stratigraphic sequences. To facilitate the acquisition of gamma-ray curves from drillcore, AGSO has invested $40 000 in crystal detectors, computer hardware and software, and the appropriate lead-shielding. Several mineral exploration companies are currently cooperating with the project during the collection of this data set, and over the next few months NABRE will be logging core at Lady Loretta (Pancontinental), Century (Century Zinc Ltd and CRA), HYC (MIMEX), and Mount Isa (North Ltd). Publicly available drillcore stored at the GSQ and NTGS core libraries in Brisbane and Darwin will also be examined. Several other companies have made offers of drillcore access (both open-file and confidential) for the project to examine and log during 1996.

Detailed sections measured through the Gunpowder Creek, Paradise Creek, and Esperanza Formations at several localities in the Mount Oxide and Mammoth Mines Sheet areas have already demonstrated the value of outcrop-derived gamma-ray curves for stratigraphic correlation, and for the identification of progradational cycles, their stacking patterns, and the bounding surfaces that define depositional sequences.

The combination of descriptive, graphically based sedimentological logs and the gamma-ray curves enable us to divide the lithostratigraphic Gunpowder Creek, Paradise Creek, and Esperanza Formations into a series of genetically linked depositional sequences that lie within one tectonostratigraphic basin phase or megasequence (Fig. 10). Although the Torpedo Creek Quartzite and the Surprise Creek and Lady Loretta Formations have not been examined in similar detail, preliminary investigations suggest that the lower basin phase boundary lies at or near the base of the Surprise Creek Formation and the upper basin phase boundary occurs within the Lady Loretta Formation.

According to the sequence stratigraphic method of packaging the facies, the Gunpowder Creek Formation comprises five or six depositional sequences, each tens of metres thick. In the Mammoth Mines Sheet area, an abrupt flooding or transgression reflected near the base of each sequence is followed by progradation from very fine-grained mid-shelf facies with hummocky cross-stratification to coarser-grained lower and upper shoreface environments in the upper part. Carbonate rocks containing stromatolites and mixed intraclast, peloid, and siliciclastic grainstones and packstones form the upper parts of some of these progradational cycles. These carbonate intervals commonly are extensively ferruginised, providing evidence of fluid flow at these levels. The upper Gunpowder Creek sequences are generally finer-grained, and contain deeper-water facies than those below, interpretations consistent with overall transgression and backstepping through the siliciclastic-rich formation.

The uppermost Gunpowder Creek interval (Ꝑmw3) of Hutton & Wilson (1985: Mammoth Mines Region, 1:100 000 Geological Map Commentary, *Bureau of Mineral Resources, Australia*) contains black fine-grained laminated dolomudstone, carbonaceous shale, and siltstone. Phosphatic stromatolites and hardgrounds have been identified at the base of the carbonate package in Ꝑmw3, consistent with an interpretation that the entire interval represents the deepest-water environments found in this area during this phase of basin evolution. Thus Ꝑmw3 represents a condensed section and contains the basin-phase maximum-flooding surface (Fig. 10). Shales in this interval are likely to form regional seals across the basin.

The condensed section is overlain by the Mount Oxide Chert Member (of the Paradise Creek Formation), and a thick, initially ag-

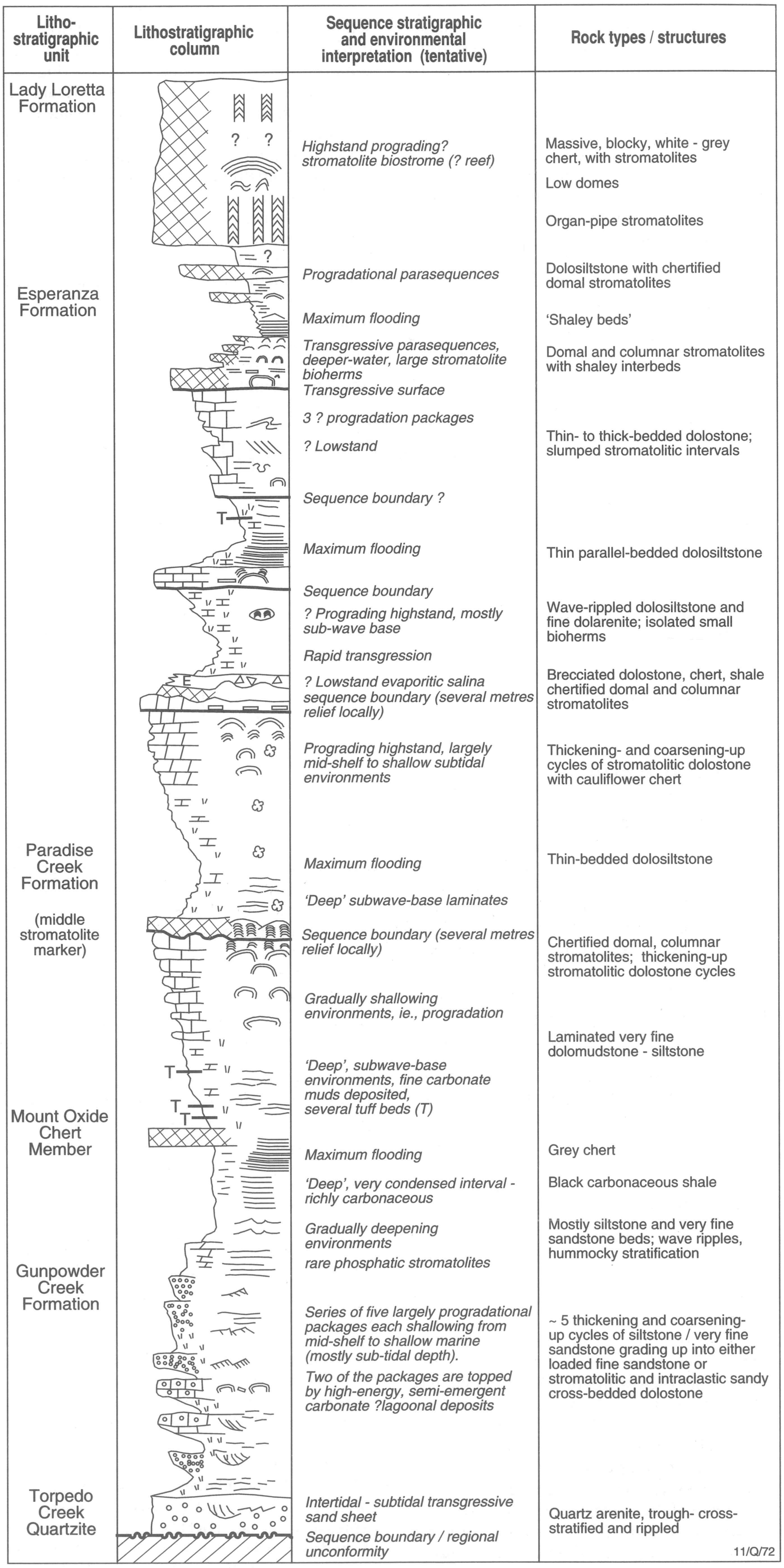

Fig. 10. Schematic and generalised log through the lower McNamara Group based on several sections from the northern Mammoth Mines 1:100 000 Sheet area. Lithostratigraphic divisions to the left of the column are contrasted with our tentative sequence divisions to the right of the column.

gradational and then progradational package of fine-grained to mud-dominated carbonate rocks of the lower Paradise Creek Formation.

This progradational package is capped by a sequence boundary, locally with 1–2 m of relief and, in some places, up to 15 m of incision. Silicified stromatolites forming the middle stromatolite marker bed (Fig. 10) overlie the sequence boundary and herald the commencement of sedimentation in the upper Paradise Creek stratigraphic sequence. At Esperanza Waters, 6 km south of Gunpowder, this sequence is dominated by subtidal stromatolite cycles. Cauliflower chert nodules — pseudomorphs of nodular anhydrite — provide evidence of nearby evaporitic environments and brine flow through these rocks. The succession of depositional environments indicates that accommodation space decreased during the deposition of the Paradise Creek Formation.

Accommodation rates increased during sedimentation of the overlying Esperanza Formation, a second-order supersequence that comprises several third-order sequences (Fig. 10). At Esperanza Waters, large aggradational domal stromatolite biostromes occur in the early transgressive and highstand parts of the uppermost sequence. Backstepping and progradational stromatolite bioherms and biostromes also characterise this sequence (Fig. 10).

The identification of a series of genetically linked depositional sequences in these formations clearly demonstrates that the scientific philosophy behind the NABRE project is appropriate for providing new insights into the stratigraphic architecture of Palaeo- and Mesoproterozoic successions in northern Australia. Furthermore, the recognition of key surfaces (sequence boundaries, and maximum-flooding and transgressive surfaces) at a number of sequence scales throughout these formations will provide the project, mineral industry, and other geoscientists with a series of chronostratigraphic surfaces to construct a regional stratigraphic framework in northern Australia.

The preliminary results discussed herein represent the results of three weeks of fieldwork by the project team. These results and subsequently acquired data will be the subject of a two-day workshop in Canberra (15–16 November 1995). Field-based workshops in Gunpowder are under consideration for 1996; the most appropriate timing for them will be discussed at the November workshop.

[1] For further information, contact Peter Southgate at AGSO Division of Marine, Petroleum & Sedimentary Resources, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9206, fax (06) 249 9983.

AGSO's 'fill–spill' project: reducing exploration risk on the North West Shelf

Geoffrey W. O'Brien[1]

Two of the key exploration risks which confront explorers on Australia's North West Shelf are the drilling of:

- **subcommercial gas versus commercial oil accumulations; and**
- **breached traps.**

Carnarvon Basin

In the Carnarvon Basin, or, more particularly, in the Barrow Sub-basin, the former risk dominates. There, gas, oil, and mixed accumulations commonly occur in close spatial proximity; examples include the South Pepper and North Herald (oil) versus Pepper and Elder (gas) accumulations, and the Harriet oil accumulation versus the Rosette, Campbell, and Sinbad gas accumulations. The reasons for this variation in hydrocarbon phase over such short distances have been variously attributed to source quality, source maturity, trap integrity, migration pathways, or even overpressuring. Whatever the reason, the lack of understanding about this issue effectively precludes explorers from predicting, with even reasonable confidence, the likely hydrocarbon composition of the prospects that they are evaluating.

Timor Sea

In contrast to the Barrow Sub-basin, trap integrity is clearly the most *obvious* problem confronting explorers in the Timor Sea, including the Zone of Cooperation. The far-field effects of the collision between the Australian and Eurasian plates in the Late Miocene resulted in the structural reactivation and, ultimately, the breaching of many previously charged traps in the Timor Sea; examples include those tested by the East Swan, Avocet, and Keppler wells.

A recent preliminary study by O'Brien & Woods (1994: *AGSO Research Newsletter* 21, 8–11; 1995: *APEA Journal*, 35, 220–252) and O'Brien & Lisk (1995: *Australian Organic Geochemistry Conference*, Adelaide, SA, June 1995) has, however, suggested that some minor structural/fault reactivation might have contributed significantly to the preservation of oil accumulations. Thus, geochemical and fluid-inclusion studies have shown that the large gas accumulations in the Vulcan Sub-basin — such as Oliver, which was virtually unaffected by Late Miocene tectonism — previously contained thick oil columns. The original oil column in the Oliver Field was about 100 m thick, as opposed to the present-day, thin 14-m rim at the base of the closure. Oil columns such as this one were displaced by gas, which migrated into the traps after the oil had accumulated in them. In contrast to the gas accumulations, all the commercial oil fields in the Vulcan Sub-basin — namely Skua, Challis, and Jabiru — were somewhat but not greatly reactivated during this event, which resulted in decreased trap integrity and the loss of the gas cap and/or part of the oil leg. As a result, these oil fields invariably have a residual oil column at their base.

These observations have led to the development of a preliminary model in which the most prospective traps in the Timor Sea region appear to be characterised by slight to moderate fault reactivation, which has partly breached the seal and resulted in an inadequate sealing capacity for gas but adequate for oil. Thus, the gas migrating into the trap (post-oil charge) continually bleeds off out of the reservoir section, up the faults, and thereby enhances the preservation of the oil charge.

This recent study has provided two important contributions. Firstly, it has highlighted the critical importance of the interplay between trap integrity and charge history in controlling the distribution of oil and gas in the Timor Sea. Secondly, it has led to the identification of hydrocarbon-related diagenetic zones (HRDZs) in the post-rift section overlying present-day and palaeo-hydrocarbon accumulations. These HRDZs formed as a result of hydrocarbon oxidation (and subsequent carbonate cementation) above leaky traps. Importantly, this cementation is seismically resolvable, and relationships between the seismic expression of the HRDZs, the total amount of hydrocarbons that have leaked from the traps, and the obliquity between the Jurassic and Late Miocene fault trends over the respective structures are predictable. There is a continuum between high-integrity accumulations, in which the fault trends are parallel and the HRDZs are small or absent, and highly reactivated breached accumulations, in which the respective fault trends are distinguishable by their obliquity and the HRDZs are large and seismically intense. *These observations provide a potential predictive tool for evaluating undrilled structures.*

'Fill–spill' project

AGSO is building on the results of this preliminary study in the Timor Sea, and broadening its regional coverage to include the Carnarvon Basin. The resulting 'fill–spill' project will provide a semiquantitative suite of criteria for evaluating, from the prospect to sub-basin scale, the probability of encountering oil or gas, or of drilling palaeo-accumulations in breached traps.

To achieve this ambitious end, AGSO has entered into cooperative research arrangements with a number of outside agencies, which are listed below along with summaries of the research being carried out in each of three subprojects.

To support this research, AGSO has already acquired and will acquire further new data sets in both the Timor Sea and Carnarvon Basin. In addition to the framework provided by regional deep-crustal seismic and aeromagnetic data sets, AGSO has recently acquired high-resolution semiregional seismic data — 5000 km in the Vulcan Sub-basin (VTT survey), and 2000 km in the northeastern Browse Basin (Yampi Tertiary-tie, YTT, survey). In association with World Geoscience Corporation, it has also acquired 19 000 km of high-resolution aeromagnetic (150–300-m line spacing) and 3000 km of airborne laser fluorescence (ALF) data in the southern Vulcan Sub-basin for an investigation of the relationships between micromagnetic anomalies, hydrocarbon seepage, and trap integrity. Several thousand kilometres of additional (water-column) geochemical-sniffer data will also be acquired in both the Timor Sea and Carnarvon Basin in 1996. The sniffer data will complement the ALF data, and, importantly, provide a detailed understanding of the orientation and nature of the faults which leak (as opposed to those which seal) in both areas.

Project objective and structure

Objective: ***To establish a detailed understanding of the hydrocarbon generation, migration, entrapment, and preservation (i.e., the fill–spill) history for representative regions in the Timor Sea and Carnarvon Basin.***

Subproject I

Theme: Basement architecture, structural development, event history, and controls on reactivation environment

Participants: AGSO; World Geoscience Corporation; Victorian Institute of Earth & Planetary Sciences; University of Western Australia; Louisiana State University

Objectives:
- Define the composition of the pre-rift basement, its fabric, and thickness, and determine its influence on the development of the assorted tectonic elements through time.
- Determine the nature and timing of the events that have controlled the initiation, distribution, tectonic evolution, and reactivation of the basin.
- Define the reactivation 'environment', specifically the spatial and temporal distribution of reactivation 'fairways' within the Timor Sea, and characterise the effect that underlying rift and basement features have on structural reactivation in the overlying section.
- Determine in detail the nature of the fault linkages between the rift and Late Miocene fault systems, and the manner in which they affect seal integrity.
- Quantify foreland development, and the development of the Cartier Trough.
- Develop analogue models to test the structural concepts derived above.

Subproject II

Theme: Remote sensing of trap integrity

Participants: AGSO; World Geoscience Corporation; CSIRO Division of Exploration & Mining

Objectives:
- Establish a regional, sequence-based, chronostratigraphic framework for the Triassic–Jurassic and the Cretaceous–Tertiary sequences, so that the distribution, thickness, and quality of respective reservoir and sealing facies can be predicted (via high-resolution seismic data).
- Distinguish the micromagnetic effects of hydrocarbon accumulations, HRDZs, and brine-migration fairways.
- Constrain intrasedimentary magnetic sources, particularly diagenetic zones.
- Identify (from the ALF and geochemical sniffer measurements) zones of present-day hydrocarbon seepage.

Subproject III

Theme: Fluid flow and migration history, trap integrity, seal quality

Participants: AGSO; CSIRO Division of Petroleum; Geotrack Pty Ltd; Curtin University; Centre for Ore Deposit & Exploration Studies, University of Tasmania; World Geoscience Corporation

Objectives:
- Establish present-day and palaeo-charge history from trap to sub-basin scale (fluid-inclusion determinations on palaeo-oil saturations, salinities, temperatures; gas-chromatograph–mass-spectrometry and stable-isotope studies on oils, gases, and fluid inclusions; ALF and geochemical sniffer).
- Discriminate palaeo- and present-day hydrodynamics and fault-seal integrity.
- Identify and characterise mixed oils.
- Characterise in detail the nature and significance of HRDZs and HRSAs (hydrocarbon-related seismic anomalies).
- Determine thermal and maturation history (including fission-track analysis).
- Characterise the brine and hydrocarbon migration/degradation history via sulphur-isotope determinations on diagenetic sulphides.
- Determine the possibility of tertiary migration, entrapment, and preservation of hydrocarbons in the Cretaceous and Tertiary sequences.

These subprojects will be continually integrated with one another, in order to establish a substantially improved understanding of the relationships between the hydrocarbon charge–preservation history and trap integrity in the Timor Sea and Carnarvon Basin. Ultimately, the objective is to develop a genuinely predictive capability for the evaluation of undrilled prospects and sub-basin elements.

[1] AGSO Division of Marine, Petroleum & Sedimentary Resources, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9342, fax (06) 249 9980.

The Fundamental Gravity Network in Victoria

Alice S. Murray[1]

The Fundamental Gravity Network of Australia is an interconnected set of precisely measured gravity stations covering the continent. The network is the link between AGSO's national gravity coverage, global networks, and local gravity surveys conducted by AGSO, State Governments, and private exploration companies. A complete refurbishment and augmentation of the network throughout Victoria has recently been completed. This survey has not only provided definitive values for gravity base stations in Victoria but also a wealth of information on the performance of the LaCoste & Romberg gravimeters used for the measurements.

The Fundamental Gravity Network, formerly known as the Isogal network, must be continually maintained and upgraded to meet the needs of clients and to conform to accurate and timely standards. As time passes many gravity base stations are lost owing to redevelopment, renovations, and roadworks; this is particularly true of stations located at airports. To protect the network from unexpected destruction of stations there are usually two or three widely separated stations established at each locality.

The Fundamental Gravity Network in Victoria before 1994

AGSO was aware of a high attrition of gravity base stations in Victoria. An officer from the Geological Survey of Victoria made a reconnaissance of all gravity base stations in Victoria during 1992, and provided AGSO with a report on the status of each one early in 1993.

Most of the pre-existing base network in Victoria had not been surveyed since the 1960s, and had then been measured using instruments of lower accuracy than the LaCoste gravimeters currently in use. To achieve a state-of-the-art level of accuracy it is necessary to use at least four and preferably six LaCoste (or similarly precise) gravimeters; this number will provide sufficient data for a sound statistical analysis of the results. There were strong indications of errors up to 2.0 $\mu\ ms^{-2}$ in the original gravity values based on the 1965 Isogal (Potsdam) datum. Reworking of the gravity measurements in the early 1980s to bring the network to the 1984 Isogal (IGSN71) datum had improved the accuracy of the network, but the uncertainty of the values at most stations was still undefined. A high-quality precision survey of selected points on the national network was carried out in 1980 (Wellman et al. 1985: *BMR Journal of Australian Geology & Geophysics*, 9, 225–231), but only one locality in Victoria (Melbourne) was included; however, three near-border localities were measured: Albury, Canberra, and Mount Gambier. Unfortunately, both the stations at Albury had been destroyed since 1980 so that Canberra and Mount Gambier had to be used as primary control points for the new network, as well as stations at Essendon Airport and Mount Macedon. The station at Canberra had also been tied to the site of the absolute gravity measurements made in Sydney (Soviet 1979; Japanese 1993).

The 1995 survey for the Fundamental Gravity Network in Victoria

Planning for a complete resurvey and augmentation of the Fundamental Gravity Network covering Victoria was undertaken in 1994. This survey would extend the network to many new localities about 100 km apart throughout the State, of which most parts would be within 50 km of a gravity base station. The survey was also designed to tie into existing and new stations in South Australia and New South Wales as part of the national network. The survey was divided into three parts for operational convenience, each part being tied into both the other parts. The first part was a short series of measurements between Canberra and Bairnsdale; the second covered northern Victoria; and the third covered southern and western Victoria. The new gravity base network

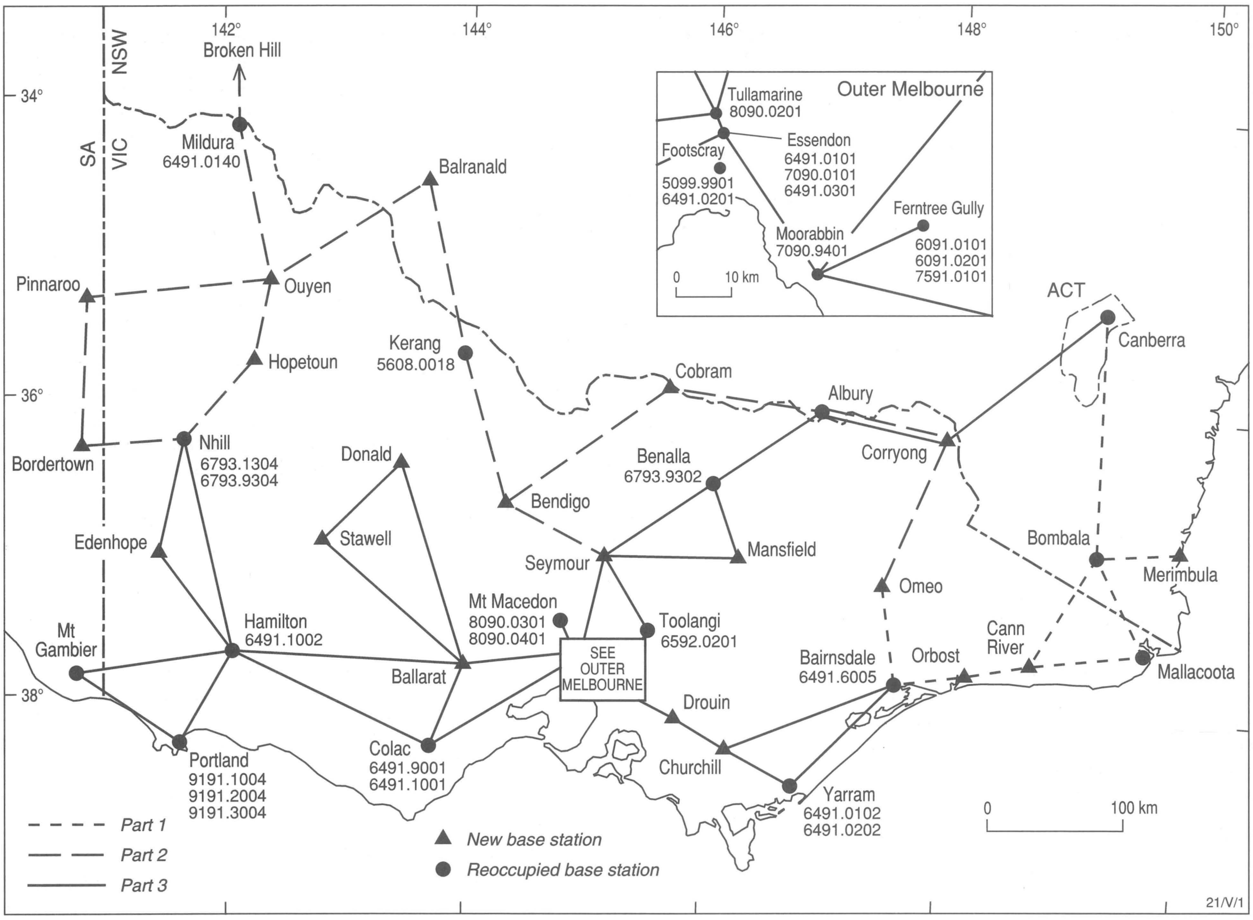

Fig. 11. The Fundamental Gravity Network in Victoria 1995.

in Victoria is shown in Figure 11.

Measurements were made at 84 gravity base stations — including 28 pre-existing stations, at which the gravity values calculated for the new network differed by up to 0.58 μ ms^{-2}; the average absolute difference was 0.22 μ ms^{-2}. Three of the old stations (at Kerang, Hamilton, and Portland) had been slightly modified. Four of the old stations were used as points of known gravity to control this survey as described above. The new network includes 29 localities of which 16 are new localities. Ties were made to South Australia at Mount Gambier, Bordertown, and Pinnaroo; the last two are new sites. Ties to New South Wales were made at Broken Hill, Balranald, Albury, and Bombala, and through these to Canberra.

Six LaCoste gravimeters were used to make the gravity observations. One meter demonstrated an unacceptable scatter in its results of about 1.0 μ ms^{-2}, so its measurements were disregarded; this meter will have to be returned to the manufacturer for repair. The results from the remaining five meters were individually processed to give a standard deviation (SD) of adjustments between 0.07 and 0.09 μ ms^{-2}, and maximum adjustments (MA) between 0.22 and 0.25 μ ms^{-2}. These accuracies were achieved within the projected SD of 0.10 μ ms^{-2} and MA of 0.25 μ ms^{-2} after a minimal rejection of data.

Though consistent for each meter, the results between meters showed significant differences; this indicated that the scale factors being used were in error or had changed over time. According to the aforementioned 1980 network survey, the scale factors provided by the LaCoste & Romberg Company for each meter did not match with the intervals being measured between stations of otherwise known gravity. A correction factor — assumed, for convenience, to be linear, and based on the intervals measured in 1980 — was determined for each meter. Since 1980, however, inconsistencies between the meters again became evident, leading to the conclusion that these correction factors probably vary with time. For this survey a new set of correction factors, based on the intervals between the four gravity control points, were calculated. Typically these scale-factor corrections are several parts in 10^4. Applying these new scale factors enabled the results from the five good meters to be combined and readjusted together; after a rigorous culling of inconsistent readings — amounting to 20 per cent of the original data — a definitive set of values was determined for all the stations. The SD of the adjustments for the new Victorian network is 0.10 μ ms^{-2}, and the maximum adjustment is 0.22 μ ms^{-2}. These values will change slightly when the network is reworked as new relative and absolute measurements are made, but the values are guaranteed to be accurate to ±0.25 μ ms^{-2}, and are probably accurate to better than ±0.10 μ ms^{-2}.

A complete report on this survey will be published as an *AGSO Record* in 1995, and an analysis of the behaviour of the gravimeter scale factors will be the subject of further investigation.

[1] AGSO Division of Geophysical Observatories & Mapping, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9264, fax (06) 249 9986.

Reworked Ordovician conodonts lead to an enhanced mineral and hydrocarbon potential in the southern Petrel Sub-basin, Western Australia

Robert S. Nicoll[1]

An enhanced mineral and hydrocarbon potential on the southwest margin of the southern part of the Petrel Sub-basin (Bonaparte Basin) has resulted from the recognition of reworked Ordovician conodonts (Table 1). These faunas have been recovered from three localities (Fig. 12) in the northern part of the onshore Bonaparte Basin. One sample, from the Late Devonian Westwood Member of the Hargreaves Formation (formerly 'Cockatoo Formation'), contains an Early Ordovician (Tremadoc) fauna (Fig. 13) whose age is equivalent to that of the Pander Greensand fauna previously known from studies in the basin (Jones 1971: *BMR (AGSO) Bulletin* 117). The second sample, from the Carboniferous Utting Calcarenite, contains a fauna with *Phragmodus*, indicating a Middle Ordovician (Llanvirn or younger) age. Ordovician sedimentary rocks of this age previously have not been reported from northern Australia in the onshore Bonaparte and Daly River Basins (Jones 1971: *op. cit.*) or from the offshore Arafura Basin (Bradshaw et al. 1990: *The APEA Journal* 30(1), 107–127). The third sample is from the Keep Inlet Formation (formerly 'Keep Inlet Beds') of Early Permian age. This sample contains a single element whose identification cannot be conclusively determined, but which appears to be of Ordovician age.

Structural and depositional history

The recovery of reworked conodont faunas indicates that sediments of the source age were exposed to erosion contemporaneously with deposition of the sediments in which they were reincorporated. This means that — in the Late Devonian (Frasnian), Early Carboniferous (Visean), and Early Permian (Asselian) — exposed Ordovician rocks, probably on the southwest margin of the Petrel Sub-basin, were shedding sediments into adjacent marine or glacial depositional environments. This revelation places some limits on the extent of the onlap of Devonian and younger sediments on the margins of the basin. It also demonstrates the presence of rocks of an age (Middle Ordovician) not previously recognised in the basin. The youngest Ordovician rocks previously identified in the basin belong to the Pander Greensand, to which Jones (1971: *op. cit.*) ascribed an Early Ordovician (Tremadoc) age according to conodonts recovered from outcrop sections in the Pretlove Hills.

Onshore exposures of Late Cambrian and Ordovician rocks of the southern Petrel Sub-basin are limited (Fig. 12) to the southwest margin of the basin, extending from Cambridge Gulf to near Tarrara Bar on the Ord River (Mory & Beere 1988: *Geological Survey of Western Australia, Bulletin* 134). Cambrian rocks are also exposed to the south in a number of structurally controlled outliers and in the Ord Basin. No exposures of Ordovician rocks have been identified on the southeast margin of the Petrel Sub-basin, in the area northeast of Kununurra. There is some suggestion that right-lateral strike-slip movement along the faults of the Halls Creek Mobile Zone displaced the eastern end of the Cambro–Ordovician outcrops of the Petrel Sub-basin southward a distance of over 200 km where they are now recognised as the Ord Basin. A similar right-lateral strike-slip fault may also control the western truncation of the Cambro–Ordovician outcrop in the Cambridge Gulf area. Displacement along this second fault may also be as much as 100 km. Walter & Gorter (1994) refer to this zone of structural accommodation between a compressional regime to the east and an extensional regime to the west as the Lasseter Shear (Fig. 14). The late Middle Devonian re-initiation of sedimentation in the Bonaparte and Canning Basins constrains the movement along the shear as being no later than the Middle Devonian (Kennard et al. 1994: *In* Purcell & Purcell (Editors), 'The sedimentary basins of Western Australia', *Petroleum Exploration Society of Australia, Perth,* 657–676; Mory 1988: *In* Purcell & Purcell (Editors), 'The North West Shelf, Australia', *Petroleum Exploration Society of Australia, Perth,* 287–309; Mory & Beere 1988: *op. cit.*)

Reworked conodont faunas

Westwood Creek locality, Hargreaves Formation, Cockatoo Group (Fig. 12, loc. 1)

In a sample of the Westwood Member of the Hargreaves Formation collected by Druce (1969: *BMR (AGSO) Bulletin* 98) from a locality adjacent to Westwood Creek, a conodont fauna incorporates both Upper Devonian and

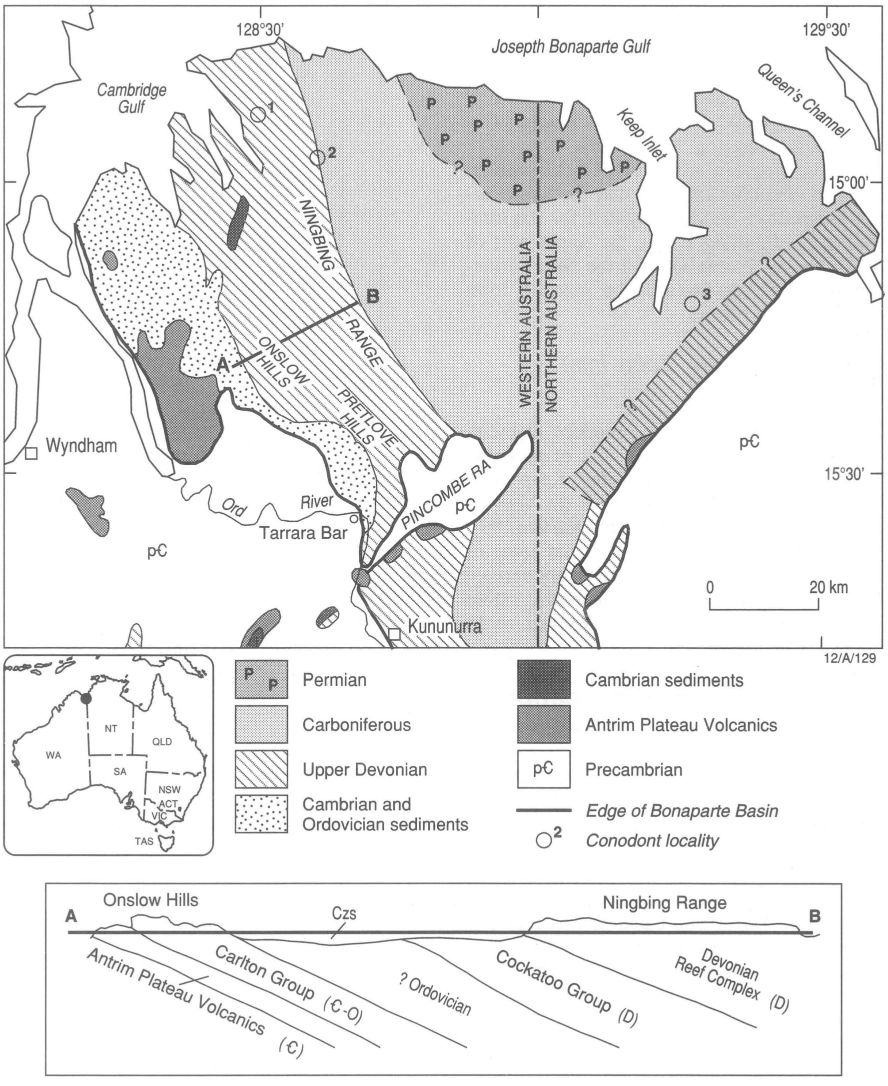

Fig. 12. Locality map and cross-section.

Early Ordovician elements. The Ordovician elements of the fauna include specimens of *Cordylodus angulatus* and of *Chosonodina herfurthi*, a species not reported by Jones (1971) from outcrop samples but now known from samples of the Pander Greensand in localities from exposures in the Pretlove Hills area.

Utting Gap locality, Utting Calcarenite (Fig. 12, loc. 2)

Two samples of the Utting Calcarenite (Tournaisian–Visean, Early Carboniferous) from a measured section in the Utting Gap area of the Ningbing Range (Fig. 12) contain both Carboniferous and reworked Ordovician conodonts. The recovery of seven elements of the genus *Phragmodus*, a conodont of Llanvirn age (Middle Ordovician) from the Utting Calcarenite, is important for two reasons. Firstly, it is another example of the reworking of conodonts that were probably derived from the southwest margin of the basin, which must have been exposed to erosion in Carboniferous (Visean) time. Secondly, and of more importance, is the fact that Ordovician rocks of this age are not known from outcrop within the basin, nor have rocks of similar age been identified in the subsurface of the Petrel Sub-basin. This reworked conodont fauna is the first, and thus far the only, indication of Middle Ordovician sedimentation in this part of northern Australia. Rocks of equivalent age are known in both the Georgina Basin (Carlo Sandstone and Mithaka Formation) and Canning Basin (upper Goldwyer and Nita Formations; Nicoll et al. 1993: *AGSO Journal of Australian Geology & Geophysics,* 14, 65–76).

The economic implication of this reworked Llanvirn conodont fauna is that the hydrocarbon-prospective section targeted for exploration in the Canning Basin, the upper part of the Goldwyer Formation and the Nita Formation, has been assumed to be missing from the Bonaparte Basin.

Keep Inlet locality, Keep Inlet Formation (Fig. 12, loc. 3)

The recovery of a single conodont element, genus, and species unknown, but of probable Ordovician age, in the Permian Keep Inlet Formation was reported by Jones (*in* Veevers & Roberts 1968: *BMR (AGSO) Bulletin* 97). This conodont element indicates that some of the sediment of this unit was probably derived from the southwest part of the basin, rather than the southeast, where no Ordovician rocks have been recorded.

Interpretation and implications

The results of petroleum and mineral exploration in the southern Petrel Sub-basin have led to the general assumption that a depositional hiatus separates the outcropping Early Ordovician (Tremadoc) Pander Greensand and the Late Devonian Cockatoo Group. This presumed hiatus has also influenced an interpretation of the age of an evaporite interval in the offshore Petrel Sub-basin as possibly Devonian (Mory & Beere 1988: *op. cit.*), rather than Late Ordovician as for the probably equivalent bedded evaporite deposits in the Canning Basin (Nicoll et al. 1994: *AGSO Journal of Australian Geology & Geophysics,* 15, 247–255; Romine et al. 1994: *In* Purcell & Purcell (Editors), 'The sedimentary basins of Western Australia', *Petroleum Exploration Society of Australia, Perth,* 677–696).

Recognition of Middle Ordovician rocks in the basin has prompted a significant revision to its geohistory, and provided alternative exploration targets, for both minerals and hydrocarbons, in areas along its southwest margin. The Middle Ordovician section in the Canning Basin, the Goldwyer and Nita Formations, is an interval of proven hydrocarbon source potential (Scott 1994: *In* Purcell & Purcell (Editors), 'The sedimentary basins of Western Australia', *Petroleum Exploration Society of Australia, Perth,* 141–145), and is also known to have served as a trap for Mississippi Valley-type lead–zinc deposits (Etminan et al. 1995: *In* Leach & Goldhaber (Editors), 'Extended abstracts: international field conference on carbonate hosted lead–zinc deposits', *Society of Economic Geologists, Colorado*). Similar deposits could be expected in the similar depositional and structural settings of the Middle Ordovician sequence in the Petrel Sub-basin. Areas for exploration include parts of the basin where Devonian and younger rocks are absent or are moderately thin. These include the section below the Ningbing Range, where the Ordovician section would be expected to be hydrocarbon mature, and the adjacent area extending from the Ningbing Range west to Cambridge Gulf. Though mapping in the poorly exposed sections of this western onshore portion of the basin has not identified a post-Tremadoc Ordovician section, rocks of this age could be concealed beneath a Cainozoic cover, or have been inadequately sampled for age determination.

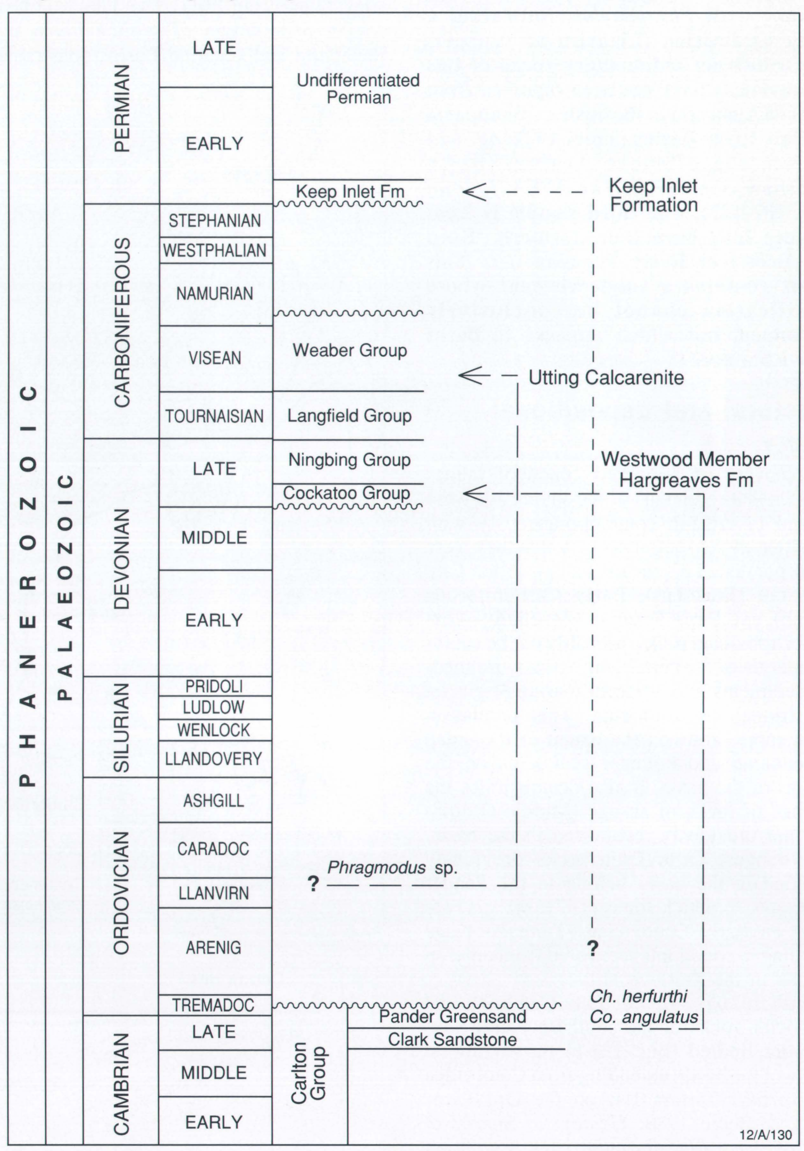

Fig. 13. Stratigraphic column showing ages of previously identified stratigraphic units in the Bonaparte Basin and the reworking of conodonts.

Table 1. Reworked Ordovician conodonts, Bonaparte Basin

Hargreaves Formation, Westwood Member (Frasnian, Upper Devonian)

Section 459 of Druce (1969: *op. cit.*); lat.14.52°S, long. 128.30°E

BGB 459/ 150 — 25 elements:

Chosonodina herfurthi (1)
Cordylodus angulatus (5)
Acanthodus sp.

Age of reworked fauna: *Chosonodina herfurthi–Cordylodus angulatus* Zone, Tremadoc, Ordovician

Utting Calcarenite (Tournaisian–Visean, Early Carboniferous)

Type section at Utting Gap (section 108) of Veevers & Roberts (1968: *op. cit.*); lat.14.58°S, long. 128.56°E; Utting Gap section remeasured and collected by Nicoll as BGB 620 in 1980

BGB 620/ 23 — 1 element:

genus & sp. indet. (1)

BGB 620/ 38 — 7 elements:

Phragmodus sp. (7)

Age of reworked fauna: *Phragmodus–Plectodina* Zone, Llanvirn, Ordovician

Keep Inlet Formation (Late Carboniferous–Early Permian)

Type section of the 'Keep Inlet Beds' of Veevers & Roberts (1968: *op. cit.*); lat. 15.03°S, 128.58° E

V&R 22/6 — 1 element:

genus & sp. indet. (1)

Age of reworked fauna: ?Ordovician

[1] AGSO Division of Marine, Petroleum & Sedimentary Resources, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9415, fax (06) 249 9983.

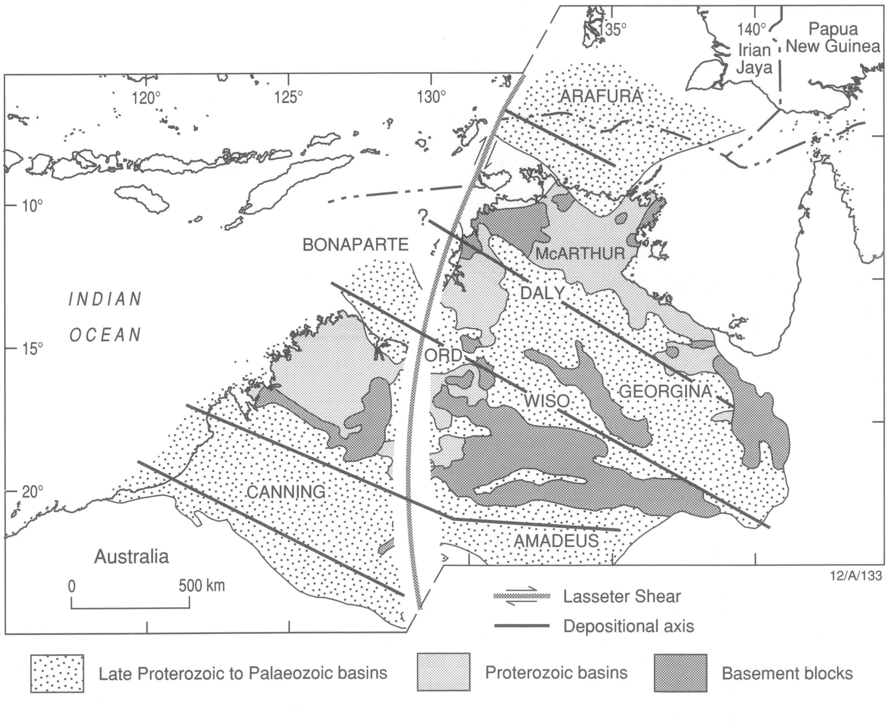

Fig. 14. Map showing the lineal axis of Cambro-Ordovician basins in northern Australia before movement along the Lasseter Shear.

Broken Hill Exploration Initiative

Continued from p. 16

It involves the acquisition of a new generation of high-resolution airborne geophysical data, and their interpretation in association with a detailed study of structure, rock properties, ore genesis, tectonic history, landforms, and regolith. A new generation of maps, a thematic geographic information system (GIS), and a new understanding of the structure, stratigraphy, and mineral potential within the project area (Fig. 15) will issue from the initiative. These outputs and outcomes will enhance the prospectivity of the project area, and enable explorers to focus their exploration dollars into areas that warrant new and further appraisal. They are expected to promote more effective exploration.

Mapping by Barnes (1989: Broken Hill Block southwest, 1:50 000 metallogenic map, *Geological Survey of New South Wales, Sydney*) and Bartholomaeus et al. (1995: Broken Hill Block southeast, 1:50 000 metallogenic map, *Geological Survey of New South Wales, Sydney*)* has revealed that the known mineral deposits are restricted to outcrop. An important objective of the BHEI, therefore, is to stimulate exploration of the concealed prospective units by mapping their distribution from detailed regolith, structural, and solid-geology interpretations facilitated by the new high-resolution airborne data.

The search for other commodities, as well as lead–zinc, is continuing, and is encouraged by recent gold–copper strikes in the project area. Drilling by Platinum Search and Savage Resources on the Mundi Mundi Plain 50 km northwest of Broken Hill has provided a new incentive for explorers. It was directed at a deflection or splay on a linear magnetic trend evident over several kilometres, and clearly visible in images generated from the newly acquired airborne magnetic data. The target underlay thick cover; the intersection started at 337.6 m downhole, and persisted for 1.8 m in a magnetite-rich ironstone, which assayed 7.4% Cu, 6.2 g/t Au, and 6.1 g/t Ag. Aberfoyle, too, recently drilled in an area 20 km northeast of Broken Hill, and intersected high-grade (12% Zn) intersections.

* For explanatory texts referring to these two maps, consult Barnes (1988: *Geological Survey of New South Wales, Bulletin* 32, parts 1 and 2) and Burton (1994: *Geological Survey of New South Wales, Bulletin* 32, part 3) respectively

Initial work

AGSO is committed to acquiring more than 290 000 km of magnetic and gamma-ray spectrometric data during the early part of the initiative, and had already flown 225 000 km by September 1995. The State collaborators had flown 160 800 km before September 1995: MESA had acquired 72 600 km, and NSWDMR 88 200 km. MESA and NSWDMR have also commissioned high-resolution gravity surveys in which station spacing will be as little as 500 x 500 m in some places.

The BHEI has brought together geoscientists from MESA and NSWDMR who have worked in the project area on opposite sides of the border for many years. This interface is providing the incentive to develop an integrated cross-border GIS that contains information previously only accessible to well-resourced and experienced explorers. The GIS will enable geoscientists to access a regional database for minimal cost. Its major components include mineral deposits, drillholes, tenements, geophysical surveys, summary of geology, magnetic and gravity data, and interpreted solid geology and tectonics of the project area.

MESA has compiled thirteen 1:25 000 outcrop geology maps for the Olary area from the results of previous company, university, and MESA mapping. It has started a program of detailed geological mapping of all the Willyama Supergroup outcrop in South Australia; the initial focus is on the Mingary area (adjacent to the NSW border).

Preliminary 1:500 000 maps of pre-Mesozoic basement geology and of the regolith are in preparation. The part of the regolith map on the New South Wales side of the BHEI project area is presently being compiled jointly by AGSO and the Cooperative Research Centre for Landscape Evolution & Mineral Exploration; it is based on an interpretation of Landsat V Thematic Mapper (TM) and SPOT images and limited field mapping. Compilation of the South Australian part of the regolith map is scheduled for September–October. The map should be ready for release in December 1995.

Other early outputs from the initiative will include solid-geology maps. Based on the high-resolution airborne magnetic and gamma-ray spectrometric data, these maps will extend outcrop to areas of subcrop and under cover. NSWDMR has released seventeen 1:25 000 outcrop geology maps; eight more are being finalised. The BHEI team intends to update as many of these released maps as appropriate, to extend the mapped outcrop geology and prospective units into covered areas, and to present a structural and stratigraphic interpretation that will assist exploration geologists.

[1] AGSO Division of Regional Geology & Minerals, GPO Box 378, Canberra, ACT 2601; tel. (06) 249 9586, fax (06) 249 9983.
[2] Geological Survey of New South Wales, 32 Sulphide Street, Broken Hill, NSW 2880; tel. (080) 880 229, fax (080) 880 227.
[3] MESA, PO Box 151, Eastwood, SA 5063; tel. (08) 274 7621, fax (08) 272 7597.

The Broken Hill Exploration Initiative — seeking renewed prospectivity in an historically prospective area of New South Wales and South Australia

Richard Haren[1], Barney Stevens[2], & Stuart Robertson[3]

The Broken Hill Exploration Initiative (BHEI) is a recently commenced collaborative National Geoscience Mapping Accord (NGMA) project between AGSO, the NSW Department of Mineral Resources (NSWDMR), and Mines and Energy South Australia (MESA).

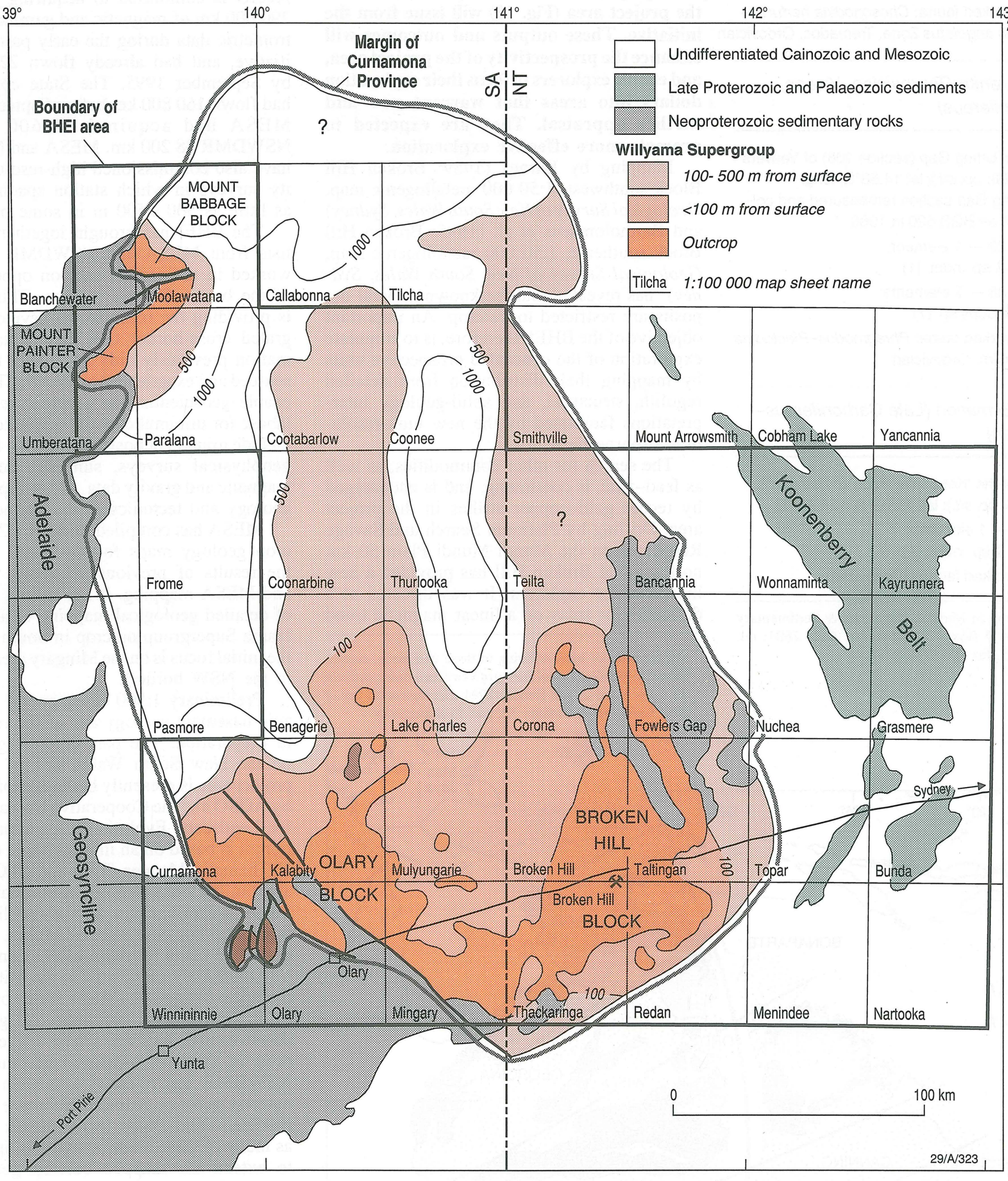

Fig. 15. The Broken Hill Exploration Initiative project area.

Continued on p. 15

AGSO

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

The *AGSO Research Newsletter* is published twice a year, in May and November. For further information please contact AGSO Marketing & Information Section, tel. (06) 249 9623, fax 249 9982. Correspondence relating to the *AGSO Research Newsletter* should be addressed to Geoff Bladon, Editor, *AGSO Research Newsletter*, Australian Geological Survey Organisation, GPO Box 378, Canberra ACT 2601; tel. (06) 249 9111, extn 9249; fax (06) 249 9990.

 ISSN 1039-091X A62085

PP255003/00266