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Lead-isotope-based stratigraphic correlations and ages of Proterozoic sediment-hosted Pb–Zn deposits in the Mount Isa Inlier

Lead-isotope model ages of sediment-hosted stratabound Pb–Zn deposits can be calibrated by using zircon U–Pb ages of associated volcanic rocks. The consistency of the calibrated Pb model ages with the expected stratigraphic ages constrains the formation of these deposits, including the Mount Isa Pb–Zn mineralisation (~1650 Ma old), to either during or shortly after sedimentation. In the Eastern Fold Belt of the Mount Isa Inlier (Fig. 1), a zircon age and several Pb-isotope model ages are now available to confirm that at least part of the sedimentary sequence — that hosting Pb–Zn ores (e.g., Pegmont, Cannington, and Fairmile) — accumulated at about the same time as the lower part of cover sequence 3 in the west. Model ages related to Pb–Zn mineralisation in the McNamara Group, hosting Lady Loretta and Century ores, are significantly (~70 Ma) younger than those relating to Pb–Zn mineralisation at Mount Isa, suggesting that the Western Fold Belt was mineralised over a longer period than previously thought.

In this issue:

Introduction

Faulting, deformation, metamorphism, and a paucity in some areas of suitable felsic igneous rocks for zircon dating hamper stratigraphic correlations in the Mount Isa Inlier. The timing of stratabound Pb–Zn mineralisation has been a controversial topic for many years. Three main periods of Pb–Zn mineralisation have been proposed: 1725–1780, ~1650, and ~1500 Ma. In the Eastern Fold Belt (Fig. 1), the Dugald River deposit — a product of the first period — is assumed to be hosted by the Corella Formation, a correlative of the Doherty Formation, which has been dated by zircon at 1725 ± 3 Ma. The host of the Pb–Zn deposits at Pegmont, Fairmile, and Cannington — the Soldiers Cap Group east of the Cloncurry Fault — has been considered to belong to cover sequence 1 or 2 (pre-1725 Ma; e.g., Beardsmore & others 1988: *Precambrian Research* 40/41, 487–508). The second period — at ~1650 Ma — is generally considered to be the most important in the Mount Isa Inlier for sediment-hosted Pb–Zn mineralisation (e.g., Mount Isa ore). As for the third period, W.G. Perkins of MIM has recently proposed that the Pb–Zn deposit in the Mount Isa Group at the Mount Isa mine was introduced at the same time as the Cu deposit, during the D3 deformation of the Isan Orogeny at ~1500 Ma (e.g., Perkins 1993: *Australian Institute of Geoscientists, Bulletin* 14, 39–41).

The purpose of AGSO geochronological work in the Mount Isa region has been to provide a coherent time-framework to underpin stratigraphic, deformational, and igneous processes. In order to better understand these processes and to complement currently active exploration, an effort is being made to date zircons from felsic tuff beds using the SHRIMP ion probe. Since suitable volcanic tuff beds are sparse and commonly difficult to identify in the field, a pragmatic, additional approach to this dating problem is to use Pb-isotope model ages — based on the abundant Pb-isotope data in the literature and in a CSIRO database — to determine approximate ages for the stratabound mineralisation.

Background to Pb model ages

Plotted on a $^{207}Pb/^{204}Pb$-*versus*-$^{206}Pb/^{204}Pb$ diagram, Pb-isotope compositions of major stratabound sediment-hosted and volcanogenic massive sulphide (VMS)

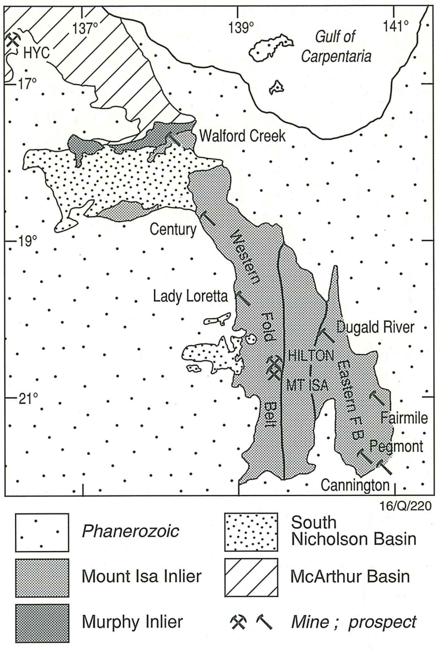

Fig. 1. Locations of stratabound Pb–Zn deposits in the Mount Isa Inlier.

deposits fall on or near a growth curve (Fig. 2), reflecting ^{235}U decay (to ^{207}Pb) and ^{238}U decay (to ^{206}Pb). The position of a sample on the growth curve is determined by both geological age and history of U/Pb in the source regions, expressed in terms of μ value ($^{238}U/^{204}Pb$). Simple models have been proposed to estimate formation ages of major stratabound Pb–Zn deposits throughout the world. With proper radiometric age control points, Pb-isotope model ages often agree well with expected geological ages — to within ~50 Ma.

In essence, Pb-isotope evolution of the Earth started, about 4560 Ma ago, with an initial Pb-isotope composition the same as that measured in iron meteorites. The two-stage Pb-evolution model of Stacey & Kramers (1975: *Earth & Planetary Science Letters*, 26, 207–221) assumes that the second stage commenced at 3700 Ma with increased μ values in response to crustal development. An alternative model, proposed by Cumming & Richards (1975: *Earth & Planetary Science Letters* 28, 155–171), assumes a steady increase of μ values with time since 4509 Ma ago. Cumming & Richards's model is constrained by an age close to 430 Ma assigned

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to Pb–Zn ore at Captains Flat (NSW) as a control point, and yields model ages for Broken Hill and Mount Isa ores ~100 Ma younger than expected from zircon U–Pb ages. Without further reasoning, this young model age (1530 Ma) for the Mount Isa Pb–Zn ore could have been used to support the idea that the Pb–Zn mineralisation was synchronous with the Cu mineralisation, during the D3 deformation (~1500 Ma).

In terms of the 'plumbotectonics' of Zartman & Doe (1981: *Tectonophysics*, 75, 135–162), Pb-isotope studies are complicated by the different geological histories of source rocks with variable μ values — i.e., different types of mantle, lower crust, orogen, and upper crust. In principle, a specific mixing model — involving different source components (e.g., mixing of upper crust and mantle Pb) — can be constructed for a region for which the geology is known in some detail. Even so, a reliable model is difficult to formulate. As a result, Pb-isotope model ages for Phanerozoic stratabound Pb–Zn mineralisation commonly have large uncertainties, and some show discrepancies. For example, VMS deposits associated with the mid-Late Cambrian (500 Ma) Mount Read Volcanics (Tas.) have Pb model ages of ~250 Ma, which are even younger than Silurian VMS deposits in the Lachlan Fold Belt. Likewise, Japanese Miocene (~15 Ma) Kuroko deposits have Pb model ages of 100–250 Ma. In contrast, however, Pb model ages for Archaean to Paleoproterozoic stratabound deposits are reasonably consistent with radiometric age constraints.

Pb-isotope data from northern Australia

The accuracy of Pb model ages can be improved by using zircon U–Pb ages of volcanic rocks in the local stratigraphy as benchmark control points, and determining a suitable Pb-isotope evolution model for the particular area.

In northern Australia, zircon U–Pb ages of 1653 ± 7 Ma and 1640 ± 7 Ma have been determined for volcanics asociated with the Mount Isa and HYC Pb–Zn deposits respectively. According to Figure 2, which is based on a modified Cumming & Richards model, sediment-hosted Pb–Zn deposits in the Eastern Fold Belt — e.g., at Pegmont, Fairmile, and Dugald River — and at Mount Isa have similar Pb model ages. These results support the suggestion that the Eastern Fold Belt deposits are hosted by rocks that are closer in age to the Mount Isa Group than previously thought. This suggestion is also supported by the maximum zircon U–Pb age of 1677 ± 9 Ma reported by Page (1993: *AGSO Research Newsletter* 19, 4–5) for the volcanic precursor of a felsic gneiss in the Soldiers Cap Group. Earlier arguments for a 1740–1780 Ma old period of Pb–Zn mineralisation in the Mount Isa Inlier do not have any geochronological support.

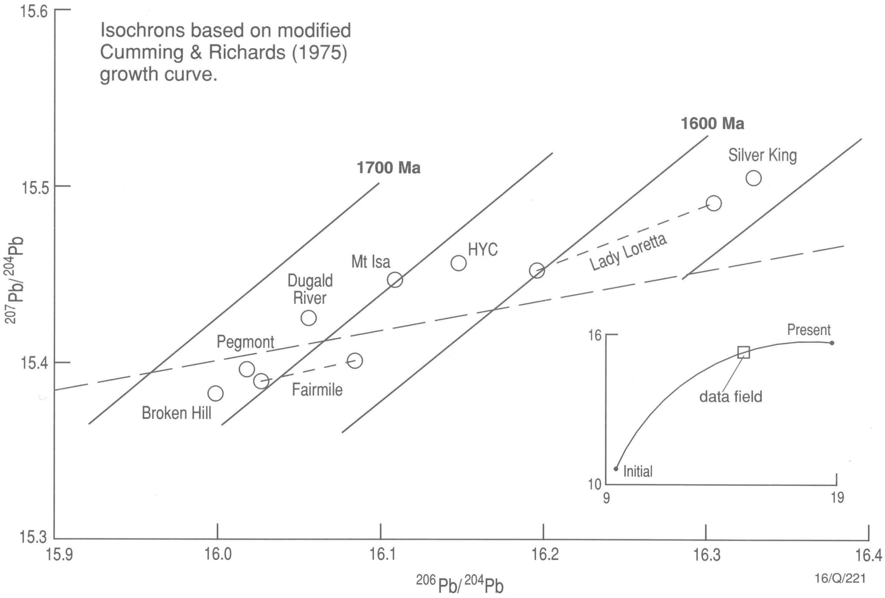


Fig. 2. A $^{207}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ plot for major sediment-hosted Pb–Zn deposits in the Mount Isa Inlier.
The position of these deposits on the Pb-isotope growth curve for stratabound Pb–Zn ores is shown on the inset diagram. Isochrons of 1700, 1650, 1600, and 1550 Ma are shown as straight lines.

Pb isotopes show that the Pb–Zn deposits in the McNamara Group (Lady Loretta, Silver King) are significantly younger (~70 Ma) than the 1640–1680 Ma age for the deposits at Mount Isa, at HYC, at Dugald River, and in the Soldiers Cap Group. This is consistent with a new zircon U–Pb age of 1595 ± 6 Ma for the Century deposit reported by Page et al. (1994: Abstract, *8th International Conference on Geochronology, Cosmochronolgy & Isotope Geology*). A considerable variation in $^{206}Pb/^{204}Pb$ among the Lady Loretta Pb–Zn ore samples might reflect incomplete homogenisation of Pb derived from sources with different μ values and/or a protracted period of mineralisation (i.e., epigenetic); further study is required to resolve this uncertainty.

According to the Pb-isotope model ages, Pb–Zn deposits in the Mount Isa Inlier appear to be confined to sedimentary sequences between ca 1680 and 1590 Ma. However, the possibility that Pb–Zn mineralisation took place at some other period of time cannot be eliminated. In principle, mineralisation may occur as long as favourable ore-forming environments are available.

For the Mount Isa Pb–Zn ore, the consistency between Pb model ages and stratigraphic ages for Proterozoic sediment-hosted Pb–Zn ores supports a syn- to diagenetic origin. Furthermore, Pb-isotope model ages for Cu deposits, which were introduced during D3 deformation (~1500 Ma), are both the same as and younger than the model ages for Pb–Zn ores (Gulson et al. 1983: *Economic Geology*, 78, 1466–1504). This can be explained by the incorporation of only minor amounts of Pb from the diagenetic Pb–Zn ore into the late-metamorphic Cu ores. The relatively wide range of $^{206}Pb/^{204}Pb$ ratios in samples from the Fairmile deposit might also reflect the overprint of metamorphic fluid.

If the assumptions of Stacey & Kramers are applied, the Pb model ages contradict the zircon U–Pb ages determined for the Mount Isa and Broken Hill ores. Zircon ages suggest that the hosts to the Broken Hill ore were formed at 1690 ± 5 Ma, ~40 Ma earlier than the Mount Isa hosts, but two-stage model ages based on Stacey & Kramers (1975) suggest that the Broken Hill ore was formed ~15 Ma later than the Mount Isa ore. In the modified Cumming & Richards model (Fig. 2), the Pb model ages agree more closely with the zircon ages for Palaeoproterozoic Pb–Zn mineralisation, and suggest that the Broken Hill ore is about 15 Ma older than the Mount Isa ore. This modification, however, results in incorrect model ages for Phanerozoic samples.

A major conclusion of this study is that, in order to fine-tune Pb model ages, we should give up the attempt to fit data covering a wide range of ages and from different terranes to a single growth curve. Independent of the choice of an appropriate model (two stages, continuous increase of μ, or multiple-component mixing) it is advisable to have zircon age-control points for each terrane under study. This study is a continuing AGSO–CSIRO cooperative project.

For further information, contact Dr Shen-su Sun or Dr Rod Page (Minerals & Land Use Program) at AGSO, or Dr Graham Carr (Division of Exploration & Mining) at CSIRO, North Ryde (NSW).

Potential for magnetostratigraphy as a correlation tool in the Late Permian coal measures of eastern Australian basins

AGSO and several collaborating agencies are studying the potential use of magnetostratigraphy as an additional tool for correlating drillcores from the Late Permian coal measures of the Sydney, Gunnedah, and Bowen Basins. The project aims to overcome uncertainties commonly experienced in correlating continental successions lithostratigraphically and biostratigraphically. Initial results show that the coal measures postdate the Permo-Carboniferous Reverse Superchron ('Kiaman'), and that reversal sequences in the upper coal measures may be correlatable between the Sydney and Gunnedah Basins. The demonstrated presence of reversal sequences in the lower coal measures, of Kazanian–Djulfian and probably Ufimian age, highlights the need for re-evaluating the early to late Tatarian age commonly concluded for the top of the 'Kiaman' from Late Permian stratotypes in Russia and Tatarstan.

Late Palaeozoic magnetostratigraphy

The late Palaeozoic is characterised by a long interval of reverse polarity of the Earth's magnetic field. Now known as the Permo-Carboniferous Reverse Superchron (PCRS), it was first defined in eastern Australia (Irving & Parry 1963: *Geophysical Journal of the Royal Astronomical Society*, 7, 395–411),

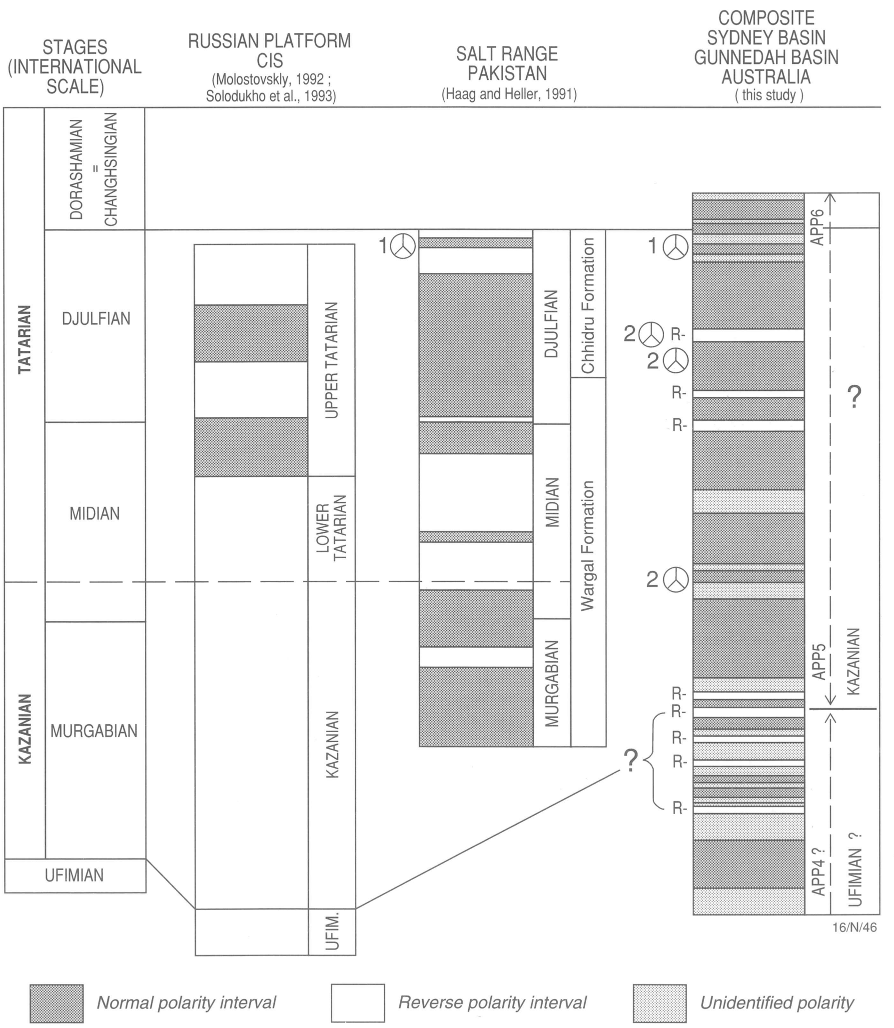


Fig. 3. Tentative global correlation of Late Permian magnetostratigraphic profiles. 1 = *Protohaploxypinus microcorpus* Zone, 2 = *Dulhuntyispora parvithola* Zone (= AAP5).
Reference timescale after Archbold & Dickins (1991: *Bureau of Mineral Resources, Australia, Record* 1989/36), Kapoor (1992: *Permo-Triassic events in the Eastern Tethys*, Cambridge University Press, 21–36), and Kozur (1992: *International Geological Review*, 34, 907–932). Salt Range timescale adapted after Pakistani–Japanese Research Group (1985: *"THE TETHYS": Her paleogeography and paleobiogeography from Paleozoic to Mesozoic*, Tokai University Press, Tokyo, 221–312).

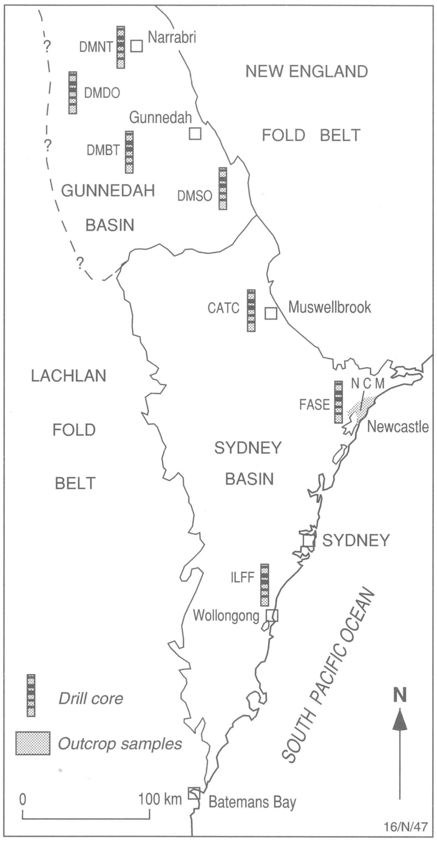


Fig. 4. Overview of drillcore and outcrop sites in the Sydney and Gunnedah Basins.

and called the 'Kiaman Magnetic Interval'. The start of the succeeding Illawarra Superchron of mixed polarity was represented by the 'Illawarra Reversal'. However, this reversal was no better constrained than postdating the 'Upper Marine Latites' (Gerringong Volcanics) and predating the 'Chocolate Shales' of the Narrabeen Group, and remained unlocated within the Late Permian coal measures of the Sydney Basin. This vagueness compromised the use of magnetostratigraphy in the coal measures as a regional correlation tool to complement traditional lithostratigraphic and biostratigraphic correlation methods.

Since the early pioneering studies, little progress has been made in eastern Australia in defining more closely the younger boundary of the PCRS and the magnetostratigraphic pattern of the Illawarra Superchron. Substantial studies overseas on the record of the two Superchrons, however, have produced detailed magnetostratigraphic profiles with good biostratigraphic control for Late Permian, mainly continental stratotypes in Russia and Tatarstan, and for Late Permian marine successions in Sichuan and in the Salt

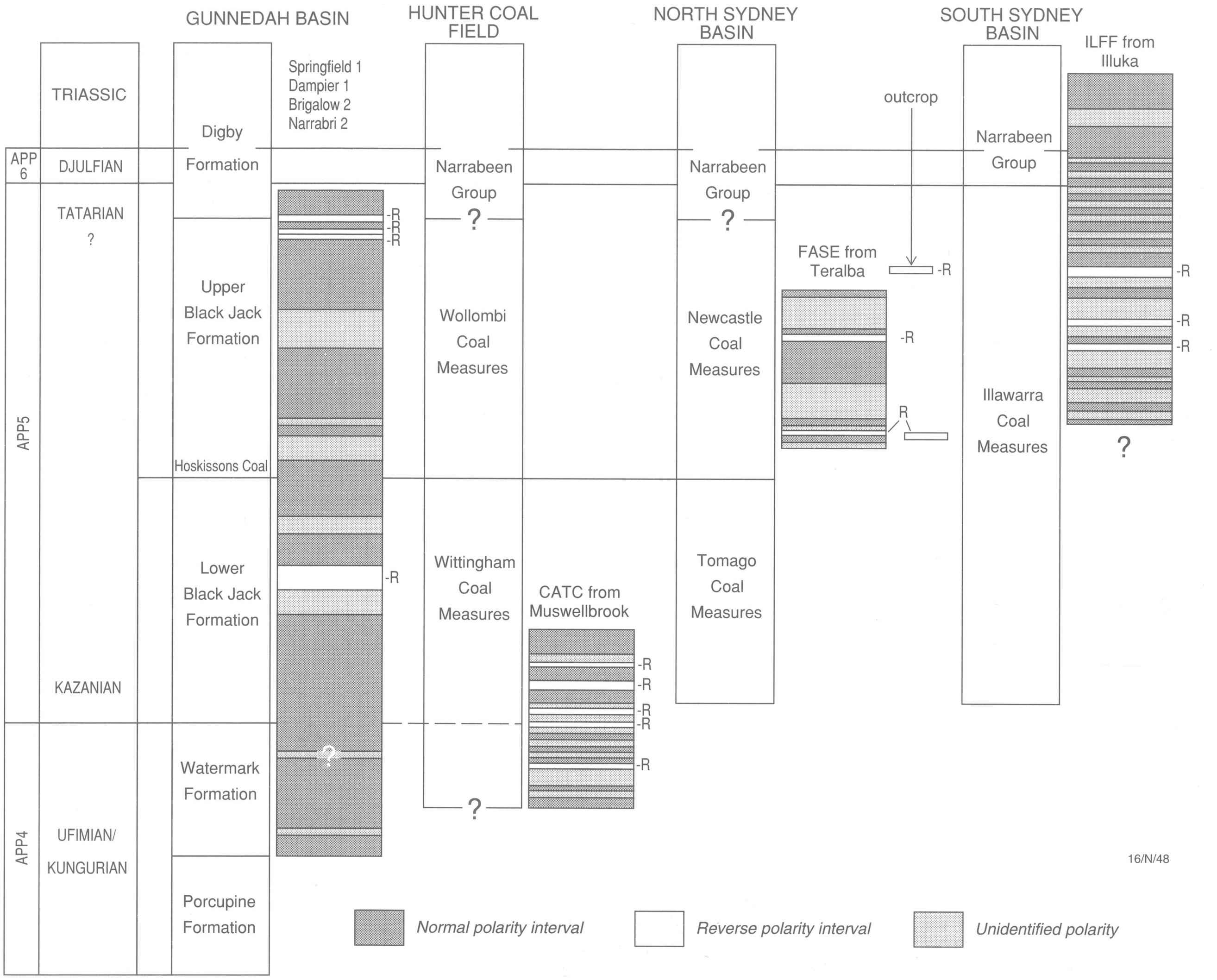


Fig. 5. Tentative magnetostratigraphic correlation of drillcores from the Gunnedah and Sydney Basins and outcrop samples from the Newcastle Coal Measures.

Range of Pakistan. The studies have identified reversal rates for the latest Permian of around two per million years, offering good prospects for magnetostratigraphic correlation and dating. The continental and the marine sections differ, however, on the timing of the start of the Illawarra Superchron: early to late Tatarian (Fig. 3) according to the mainly continental stratotypes of Russia and Tatarstan (e.g., Molostovskiy 1992: *International Geological Review*, 34, 1001–1007; Solodukho et al. 1993: *Occasional Publications ESRI*, 10, 269–303), and Kazanian or older according to the marine succession of the Salt Range (Haag & Heller 1991: *Earth & Planetary Science Letters*, 107, 42–54). This conflict has serious implications for the application of magnetostratigraphy as a regional and global correlation tool, and must be resolved.

Magnetostratigraphic potential of the eastern Australian coal measures

The Late Permian coal measures of the Sydney, Gunnedah, and Bowen Basins provide a unique opportunity to evaluate both the conflicting age constraints on the PCRS–Illawarra Superchron boundary, and the applicability of magnetostratigraphic correlation and dating as a practical tool in coal exploration. The coal measures span the time-interval under dispute, were deposited under a high-sedimentation regime that offers considerable resolution in time, and have been drilled extensively. They probably record magnetic reversals that occurred at a rate of about two per million years. Though palynological control facilitates their direct correlation with the mainly continental Permian stratotypes of Russia and Tatarstan, the paucity of marine intercalations in them might hinder correlation with the marine magnetostratigraphic profiles.

Throughout the coal measures, the widespread occurrence of tuffaceous horizons is a potential bonus, especially if they are suited to the U–Pb (SHRIMP) dating technique, whose application to the Phanerozoic has been pioneered at the Research School of Earth Sciences (Australian National University) and AGSO (*BMR Research Newsletter* 15, 14–16). We thus have the first prospect of accurate chronostratigraphic constraints on the PCRS–Illawarra Superchron bound-

Table 1. Drillcore sample data

Drillhole	*Core*	*Interval (m)*	*Length (m)*	*No. samples*	*Spacing (m, av.)*
ILUKA55	ILFF	381.8–557.4	175.6	153	1.15
FAI DDHN 1968	FASE	11.5–144.2	132.7	69	1.92
DDH 2000-C000	CATC	20.1–345.7	325.6	123	2.65
Springfield DDH1	DMSO	311.6–648.8	337.2	130	2.59
Dampier DDH1	DMDO	595.6–694.9	99.3	46	2.16
Brigalow DDH2	DMBT	448.7–546.3	97.6	46	2.12
Narrabri DDH2	DMNT	497.8–593.5	95.7	45	2.13

ary, and on the reversal sequence of the coal measures. Magnetostratigraphic analysis of the dense network of drillcores through the coal measures might also lead to more reliable and detailed regional correlation and dating of prospective coal seams than can be obtained from lithostratigraphic and biostratigraphic studies alone, demonstrating the potential of magnetostratigraphy as a fast and effective exploration tool.

To this end, AGSO — in collaboration with research groups at the Universities of Newcastle, New South Wales, and Wollongong, the CSIRO, the New South Wales Geological Survey, and the Coal Geology & Petroleum Branch of the New South Wales Department of Mineral Resources — has started a project to detail the magnetostratigraphy of the eastern Australian sedimentary basins near the boundaries of the PCRS. The study described here focusses on the potential for regional and global correlation, and dating of the Late Permian coal measures in the Sydney and Gunnedah Basins.

Sampling

Cylindrical samples were drilled as both oriented cores from surface outcrops and as cores from the centres of seven unoriented drillcores in the Sydney and Gunnedah Basins (Fig. 4). Drillcore samples were taken at intervals of about 1 to 2 m, preferably from tuff horizons and from fine-grained sandstones, siltstones, and mudstones, in order to establish polarity patterns with good stratigraphic control. Drillcore information is summarised in Table 1. The oriented cores were extracted from tuff horizons in the Newcastle Coal Measures — Nobbys Tuff Member of the Shepherds Hill Formation, Reids Mistake Formation, and Awaba Tuff — at coastal outcrops south of Newcastle and in an open-cut coalmine near Teralba (Fig. 4: NCM), and were taken to provide a key to the interpretation of data from the unoriented drillcore samples.

To determine the directions of magnetic remanence present in the samples, about 250 pilot samples were demagnetised by alternating-field and thermal demagnetisation methods. Three magnetisation components were identified: a soft, upward-pointing, normal-polarity component of recent or drilling-induced origin; an intermediate normal-polarity component, probably representing an overprint of Late Cretaceous age which is known to be prevalent along the Tasman seaboard; and a hard normal- and reverse-polarity component interpreted as the primary magnetisation of Late Permian age.

Regional magnetostratigraphic correlation

Compilation of the results we have obtained so far is encouraging. In conjunction with lithostratigraphic and palynological constraints, they show that there is a potential for magnetostratigraphic correlation of drillcores from the coal measures across the Sydney and Gunnedah Basins, and that this work could be confidently extended to the Bowen Basin. Notable observations are the occurrence of a distinctive pattern of three reverse-polarity intervals in the Trinkey Formation of the upper Black Jack Group of the Gunnedah Basin, and a well determined set of five reverse-polarity intervals in the Wittingham Coal Measures (CATC drillcore) of the northwestern Sydney Basin (Fig. 5).

The set of reverse-polarity intervals in the Wittingham Coal Measures is tentatively assigned to palynozones APP4.3 and APP5 of Price (in Draper & others 1990: *Bowen Basin Symposium 1990*, 26–35) from a re-evaluation of correlations shown by McMinn (1987: *Alcheringa*, 11, 151–164). Current evidence suggests that they predate the single reverse-polarity interval observed in the lower Black Jack Group of the Gunnedah Basin. Of two reverse-polarity intervals established in the drillcore (FASE) through the Newcastle Coal Measures at Teralba, the lower one correlates with a reverse-polarity interval in the Nobbys Tuff Member (Fig. 5). The other tuff (Awaba Tuff) sampled in the coastal outcrops of the Newcastle Coal Measures has a third, younger reverse-polarity interval. A tentative correlation of the three reverse-polarity intervals observed so far in the Newcastle Coal Measures of the northeastern Sydney Basin with some observations of reverse-polarity intervals in the lower part of the Illawarra Coal Measures of the southern Sydney Basin is presented in Figure 5, and suggests a linkage for the FASE and ILFF drillcores. Wider correlation of these patterns of three reverse-polarity intervals in the Sydney Basin with the distinctive pattern in the upper Black Jack Group of the Gunnedah Basin (Fig. 5) needs further investigation.

Global magnetostratigraphic correlation

The present results have important implications for correlation of the Late Permian continental successions of eastern Australia with continental and marine stratotypes overseas (Fig. 1). Excluding the unrecognised but possible presence of a blanket Late Cretaceous normal-polarity overprint, the normal polarities observed in the drillcores from the basal parts of the Gunnedah Basin and the Wittingham Coal Measures indicate that these successions must postdate the long-reverse polarity interval of the PCRS. Palynological control of the basal parts indicates that they are Kazanian to probably Ufimian in age (Figs. 3, 5). Such an early age constraint for the top of the PCRS is supported by the well established observations of normal polarity in the Murgabian from the marine Salt Range section (Fig. 3; Haag & Heller 1991, op. cit.).

On the one hand, the top of the PCRS is Kazanian/Ufimian or older according to the continental sections of the eastern Australian basins, and Murgabian or older according to the marine Salt Range section; on the other hand, it is early to late Tatarian according to numerous studies of the mainly continental stratotypes of Russia and Tatarstan (e.g Molostovskiy 1992, op. cit.; Solodukho et al. 1993, op. cit.). This controversy might reflect the unrecognised presence, in the eastern Australian data, of normal-polarity overprints of Late Cretaceous age. However, the mutually supportive interpretations of older-than-expected age constraints for the top of the PCRS from both continental (Sydney and Gunnedah Basins) and marine (Salt Range) sections suggest that the magnetostratigraphic interpretation of the Permian stratotypes in Russia and Tatarstan is the more likely cause of the discrepancy. Resolution of this discrepancy will have significant implications for global correlation schemes. Pending this, it is imperative that the top of the PCRS be determined in eastern Australia with the most detailed magnetostratigraphic, palynological, and U–Pb dating control that can be obtained.

For further information contact Drs Hervé Théveniaut, Chris Klootwijk, John Giddings (Geophysical Observatories & Mapping Program), Clinton Foster, or Russell Korsch (Onshore Sedimentary & Petroleum Geology Program) at AGSO.

New geological and geochronological constraints on volcanogenic massive sulphide prospectivity near Halls Creek (WA)

Exploration for volcanic- and sediment-hosted Cu–Pb–Zn deposits in the Kimberley region of Western Australia has focussed on Palaeoproterozoic rocks of the Lamboo Complex of the Halls Creek Orogen. Volcanogenic massive sulphide (VMS) deposits southwest and north of Halls Creek (Fig. 6) occur within the Koongie Park Formation of deformed and metamorphosed sedimentary and felsic volcanic rocks (Marston 1979: *Geological Survey of Western Australia [GSWA], Mineral Resources Bulletin* 13; Griffin & Tyler 1992: *GSWA Record* 1992/17; Griffin & Tyler in press: Angelo, Western

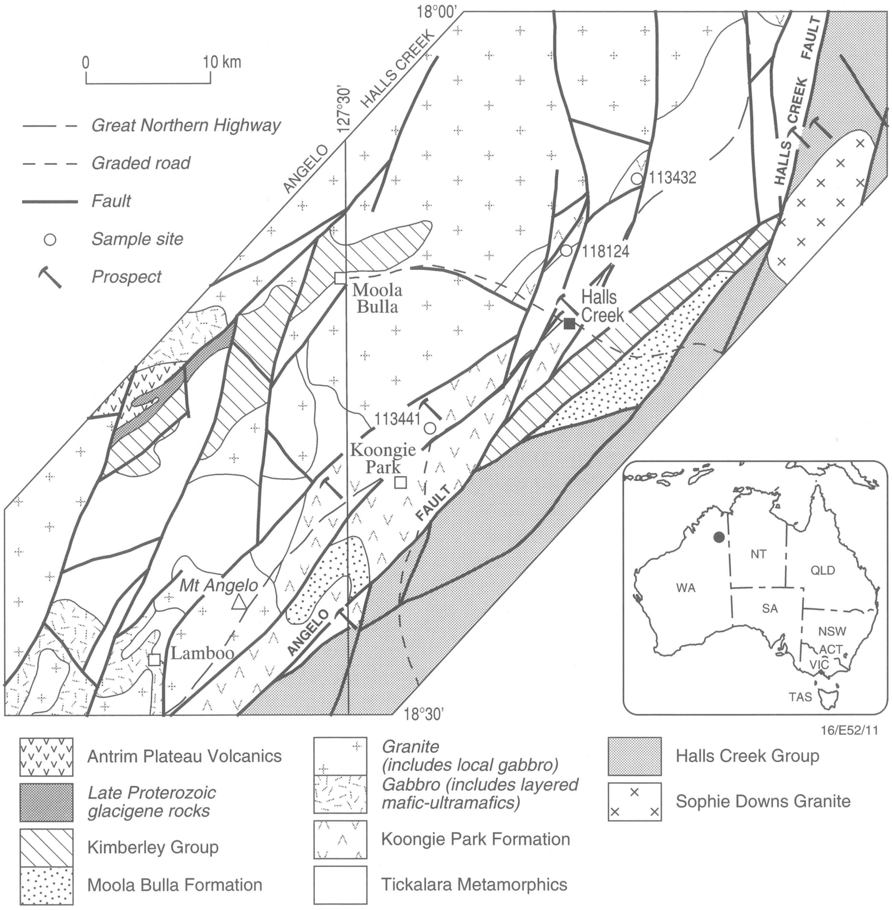


Fig. 6. Simplified geological map, Halls Creek area.

Australia, *GSWA 1:100 000 Geological Map*). Sediment-hosted base-metal deposits northeast of Halls Creek occur in the Biscay Formation.

The Koongie Park Formation crops out in the Angelo and Halls Creek 1:100 000 Sheet areas, remapped recently as part of the joint AGSO–GSWA Kimberley–Arunta National Geoscience Mapping Accord project. The mapping has been supported by a program of U–Pb zircon geochronology using the joint ANU–AGSO SHRIMP (ion-microprobe) facility in Canberra.

Stratigraphic relations

The Koongie Park Formation consists mainly of low- to medium-grade felsic volcanic and volcaniclastic rocks, and includes calcareous and pelitic metasediments, chert, and banded iron formation which host currently subeconomic Cu–Pb–Zn mineral occurrences. It is openly to tightly folded with upright northeasterly trending axial surfaces. The sequence is intruded by both granite and gabbro.

Before the results of the present study were obtained, the Koongie Park Formation was believed to be part of the Biscay Formation of the Palaeoproterozoic Halls Creek Group. This interpreted relationship was based on some lithological similarities to the Biscay Formation, and on the presence of clastic rocks thought to belong to the Olympio Formation (youngest unit of the Halls Creek Group) overlying Koongie Park Formation rocks in the core of a syncline to the east of Mount Angelo (Roberts et al. 1968: *Bureau of Mineral Resources, Australia, Explanatory Notes*, SE/52–9).

Page & Hancock (1988: *Precambrian Research*, 40/41, 447–467) reported a conventional U–Pb zircon age of 1856 ± 5 Ma for a felsic volcanic or subvolcanic rock then assigned to the Biscay Formation (but currently considered to be part of the Olympio Formation), and the Koongie Park Formation was therefore expected to be of similar age. However, outcrops of the Koongie Park Formation are separated from the main area of the Halls Creek Group to the east and southeast (which includes the locality of the 1856 ± 5 Ma Biscay Formation sample) by the major Halls Creek–Angelo Fault (Fig. 6). Correlations of Palaeoproterozoic units across this fault have been conjectural, and include an option canvassed by Griffin & Tyler (1992, p. 12) that the uncertain stratigraphic position of clastic rocks above the Koongie Park Formation may actually place 'no constraints on the position of the Koongie Park Member [sic] within the Halls Creek Group'.

The clastic rocks overlying the Koongie Park Formation are strikingly similar to the Moola Bulla Formation (which may be equivalent to the lower part of the Kimberley Basin succession) exposed to the east of Halls Creek (Fig. 6), and are now considered to correlate with this formation. In its type area the Moola Bulla Formation comprises a basal unit of sandstone and conglomerate (1400 m thick), overlain by argillite and sandstone (600 m), sandstone and conglomerate (500 m), and argillite and sandstone (500 m). It was deposited unconformably on the previously deformed, mainly turbiditic Olympio Formation.

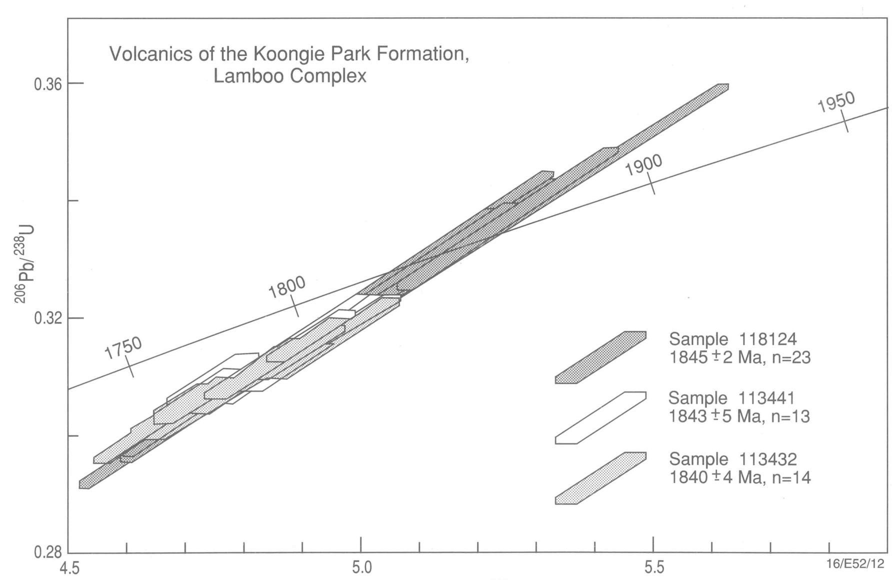


Fig. 7. Concordia plot of zircon U–Pb data for three felsic volcanic rocks from the Koongie Park Formation.

The coherence of the three quoted ages (with 95% confidence limits) is reflected in the fact that the data considerably overlap each other. Each data point is drawn with a 1σ error box, and 'n' is the number of analyses for each sample.

New geochronological results

SHRIMP U–Pb zircon dating has been undertaken on rhyolitic rocks from three sites within the Koongie Park Formation over a strike length of about 25 km (Fig. 6). Two of the rocks are porphyritic lavas which show contorted and ropy flow banding, and the other is probably a fragmental volcanic. All three rocks are variably altered and recrystallised, but the zircons in them are pristine euhedral grains, commonly with delicate igneous zonation.

The U–Pb zircon data from a ferruginised rhyolite lava in the southwest (sample 113441, Fig. 6) are slightly discordant on a $^{206}Pb/^{238}U$ *versus* $^{207}Pb/^{235}U$ concordia plot (Fig. 7), but have a tight clustering in $^{207}Pb/^{206}Pb$ and an indicated age of 1843 ± 5 Ma (95% confidence limits). Zircons from a rhyolite lava to the northeast (113432) are elevated in uranium (350–800 ppm), but the 14 data points closely overlap the data of sample 113441, and have a pooled $^{207}Pb/^{206}Pb$ weighted mean age of 1840 ± 4 Ma. The 23 zircon U–Pb data points from the fragmental volcanic rock (118124), from a locality between the two others, are concordant (lower Th/U and U than the zircon populations in the two other samples) with an indicated $^{207}Pb/^{206}Pb$ age of 1845 ± 2 Ma.

The three measured ages are in good agreement, and allow us to closely define the magmatic age of the felsic volcanics in the Koongie Park Formation. As the three samples appear to be analytically, graphically, and stratigraphically inseparable, it is reasonable to group all the data. All 50 data points are coherent to within experimental expectations, and provide a pooled $^{207}Pb/^{206}Pb$ age of 1843 ± 2 Ma, which is regarded as the best age for volcanism and deposition of the Koongie Park Formation.

Overview

The new geochronological results confirm that the Koongie Park Formation is younger than the Biscay Formation and probably the Olympio Formation (Butchers Gully Member) of the Halls Creek Group, as these units have an age no younger than 1856 ± 5 Ma. Hence the base-metal mineral deposits in the Biscay Formation northeast of Halls Creek are probably older than the Koongie Park VMS deposits. A recalibration of Pb-isotope models relevant to northern Australia gives a model age of ~1820 Ma for Koongie Park galenas, confirming an approximate link between sulphide formation and 1843 ± 2 Ma volcanism/sedimentation in the Koongie Park Formation.

The volcanics in the Koongie Park Formation are probably submarine in origin, and although they are marginally younger than the subaerial Whitewater Volcanics (presently accepted as 1850 ± 5 Ma) exposed to the west and north, they might have been produced by the same thermal/magmatic event. The existence of VMS mineralisation in the Koongie Park Formation might therefore increase the prospectivity of the Whitewater Volcanics. The previously held link in stratigraphy and VMS prospectivity between the Koongie Park Formation and older Halls Creek Group is now discounted.

For further information, contact Rod Page, David Blake, or Shen-su Sun (Minerals & Land Use Program) at AGSO; or Ian Tyler, Tim Griffin, or Alan Thorne at GSWA, Perth.

Revision of Late Triassic biostratigraphy of the North West Shelf

The recovery of age-diagnostic conodont faunas in association with both dinocysts and spore–pollen floras from Upper Triassic rocks of the North West Shelf, intersected in petroleum exploration drillholes and dredged during a recent AGSO cruise aboard RV *Rig Seismic*, has led to a significant revision of the previously interpreted ages of those rocks (Fig. 8; Nicoll & Foster 1994: *AGSO Journal of Australian Geology and Geophysics*, 15(1), 101–118). The resulting investigations have shown that the Late Triassic palynological zones of Helby & others (1987: *Memoirs of the Association of Australasian Palaeontologists* 4: 1–94) are largely confined to the Norian and Rhaetian.

In the Triassic of the North West Shelf, good regional correlations have been established using spore–pollen and dinocyst assemblages (Helby & others 1987, op. cit.), but biochronologic ties with marine faunas from the type Triassic sequences in Europe and western Canada were only poorly established (Dolby & Balme 1976: *Review of Palaeobotany and Palynology* 22, 105–168). The ammonoid faunas, on which the biostratigraphic divisions of the Triassic are principally established, are absent or have not been recovered.

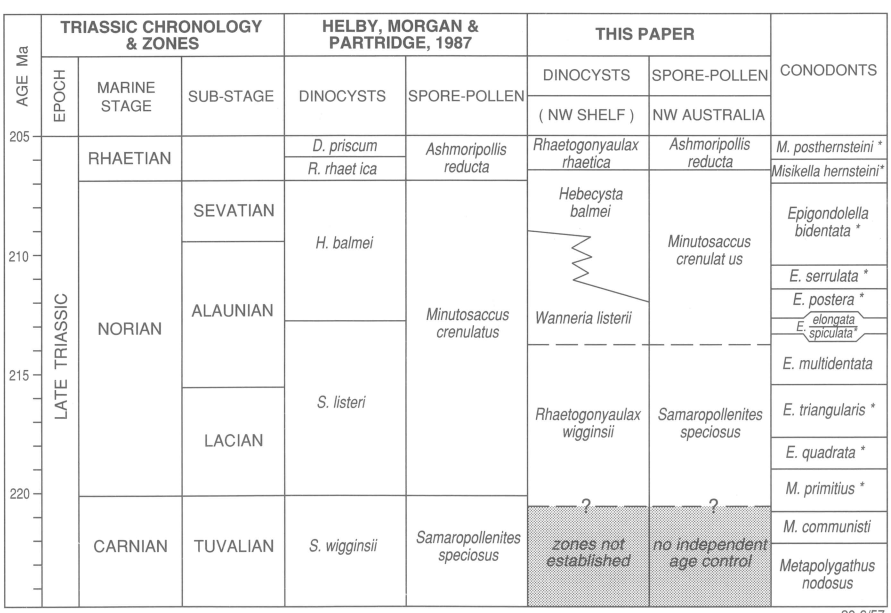


Fig. 8. Revised Late Triassic conodont and palynomorph zonations.
The seven conodont zones identified on the North West Shelf are asterisked.

Conodonts had earlier been used (McTavish 1973: *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, 143, 275–303; Dolby & Balme 1976) to establish tight biochronologic age control on the Early Triassic of the southern part of the North West Shelf in the Carnarvon and Perth Basins, and a single control point for the Late Triassic was provided by Jones & Nicoll (1985: *BMR Journal of Australian Geology & Geophysics*, 9, 361–364) from a sample in the Sahul Shoals 1 well. The conodonts recovered in association with both dinocysts and spore–pollen floras from the North West Shelf are extending this control throughout the Late Triassic, and providing a series of key biochronologic anchor points with the type Triassic.

Seven conodont zones are now known in the Late Triassic (Norian/Rhaetian) sedimentary rocks of the North West Shelf; Carnian rocks have yet to be investigated. Only four of the conodont zones established by Orchard (1983: *Fossils & Strata*, 15, 177–192; 1991a: *Geological Survey of Canada, Paper* 90–10, 173–193; 1991b: *Geological Survey of Canada, Bulletin* 417, 299–335) in the Norian to Rhaetian interval in Cordilleran

Canada have not been recognised on the North West Shelf. According to Orchard (1991c: *Geological Survey of Canada, Bulletin* 417, 1–25), these four zones might reflect local endemic faunas found only in western Canada. This investigation has compressed into the Norian and Rhaetian the palynomorph zones that Helby & others (1987, op. cit.) established for the whole of the Late Triassic. Further studies are proposed to examine additional samples from the North West Shelf, and to extend the study downward from the base of the Norian to the base of the Middle Triassic.

This note summarises some of the findings of Robert S. Nicoll & Clinton B. Foster in their paper contributed to the latest number of the *AGSO Journal of Australian Geology & Geophysics* — volume 15, number 1 — a thematic issue which focusses on the geology of the outer North West Shelf.

For further information, contact Drs Robert Nicoll or Clinton Foster (Onshore Sedimentary & Petroleum Geology Program) at AGSO.

Permian–Carboniferous magmatism in north Queensland

A new perspective

Most of the mineral deposits of north Queensland are associated with Permian–Carboniferous igneous rocks. Geophysical data show that these igneous rocks are not associated with the Permian–Carboniferous continental margin as was previously thought, but are part of a previously unrecognised major intraplate igneous belt extending from Townsville, on the northeast Queensland coast, to Mornington Island, in the Gulf of Carpentaria.

According to existing maps, and gravity and magnetic data in areas of post-Permian cover, exposed and concealed Permian–Carboniferous igneous rocks have an extensive distribution northwest of Townsville (Fig. 9). Most of these rocks can be placed in two groups of contrasting distribution and composition: I- and A-type igneous rocks of the Townsville–Mornington Island Igneous Belt (TMIIB), which are the topic of this paper; and S-type granitoids in the Hodgkinson Province.

The TMIIB is a previously unnamed belt of igneous rocks at the base of Cape York Peninsula. It is 1000 km long, generally 100 km wide, and trends west-northwesterly (Fig. 9). It includes most of the Permian–Carboniferous igneous rocks northwest of Townsville. Outcrops within the belt are Permian–Carboniferous I- and A-type granitoids and volcanics, and a basement of Proterozoic and early Palaeozoic metamorphics and granitoids. Confirmation that the interpreted Permian–Carboniferous rocks extend west-northwestwards to the southern part of the Gulf of Carpentaria is provided by isotopic ages for felsic granitoids at the bases of GSQ Normanton 1 well (at 636 m; Carboniferous SHRIMP date; L.P. Black, AGSO, personal communication 1994) and Mornington Island 1 well (at 836 m; Permian K–Ar date; Delhi Petroleum Ltd; *Geological Survey of Queensland, Library-registered report* CR789).

The central part of the igneous belt is defined by a prominent magnetic high, 50 km wide, 1000 km long, and ~200 nT amplitude (Fig. 10). This magnetic high coincides with a gravity low of ~200 $\mu m\ s^{-2}$ amplitude between Normanton and the Palmerville Fault System, and with a gravity high west of Normanton. The broad magnetic high and gravity low are thought to be due to the concentration of I-type felsic granitoids and volcanics. Many of the exposed Permian–Carboniferous granitoids and volcanics are associated with cauldron structures, and have arcuate margins marked by faults or ring-dykes. The exposed structures generally have several types of characteristic magnetic anomaly, and anomalously low gravity anomaly values; these characteristics have facilitated the interpretation of concealed cauldron structures from geophysical data.

The TMIIB is at a high angle to the inferred Permian–Carboniferous continental margin, and is structurally controlled by a major Proterozoic basement discontinuity. In the west, the belt separates two north-trending collinear geophysical domains of Pro-

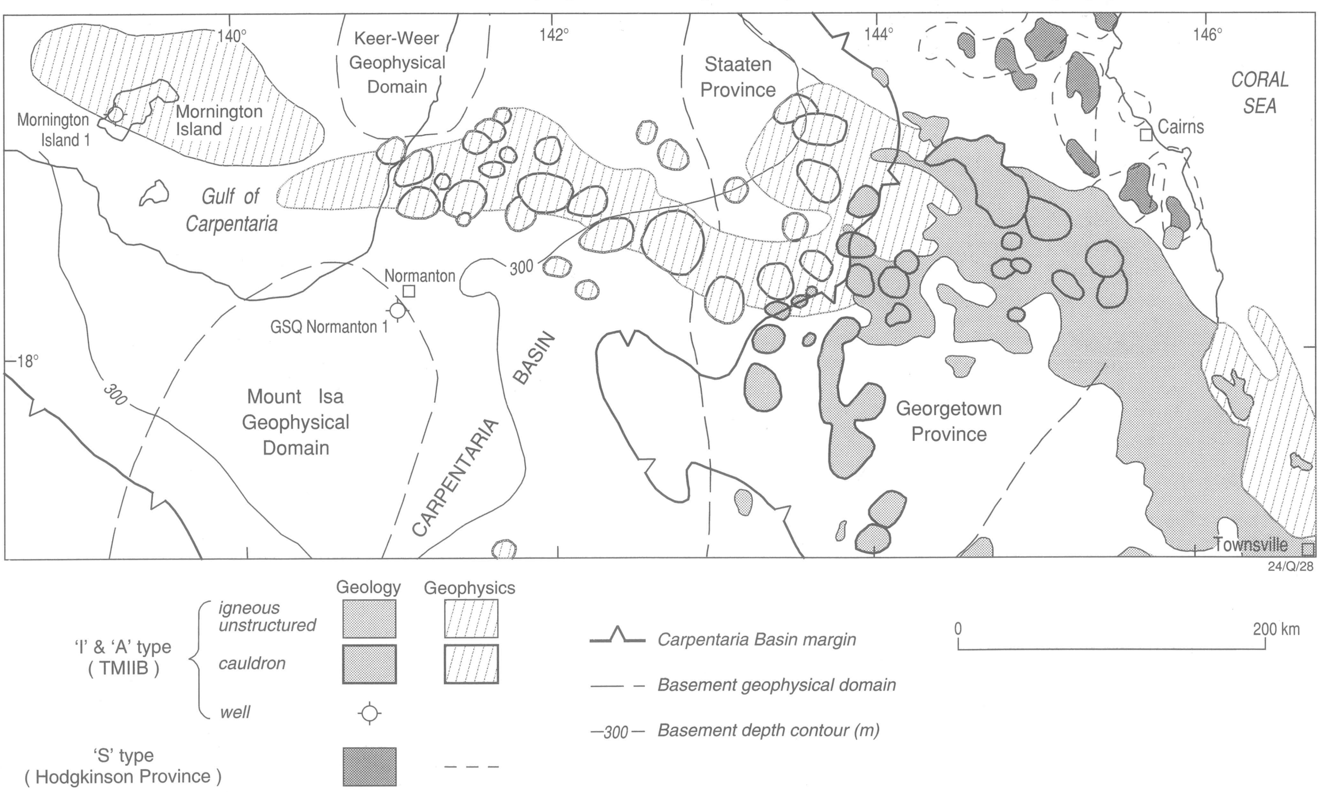


Fig. 9. Distribution of Permian–Carboniferous rocks of the Townsville–Mornington Island Igneous Belt. This belt trends west-northwest, so it is at a high angle to the Australian margin.

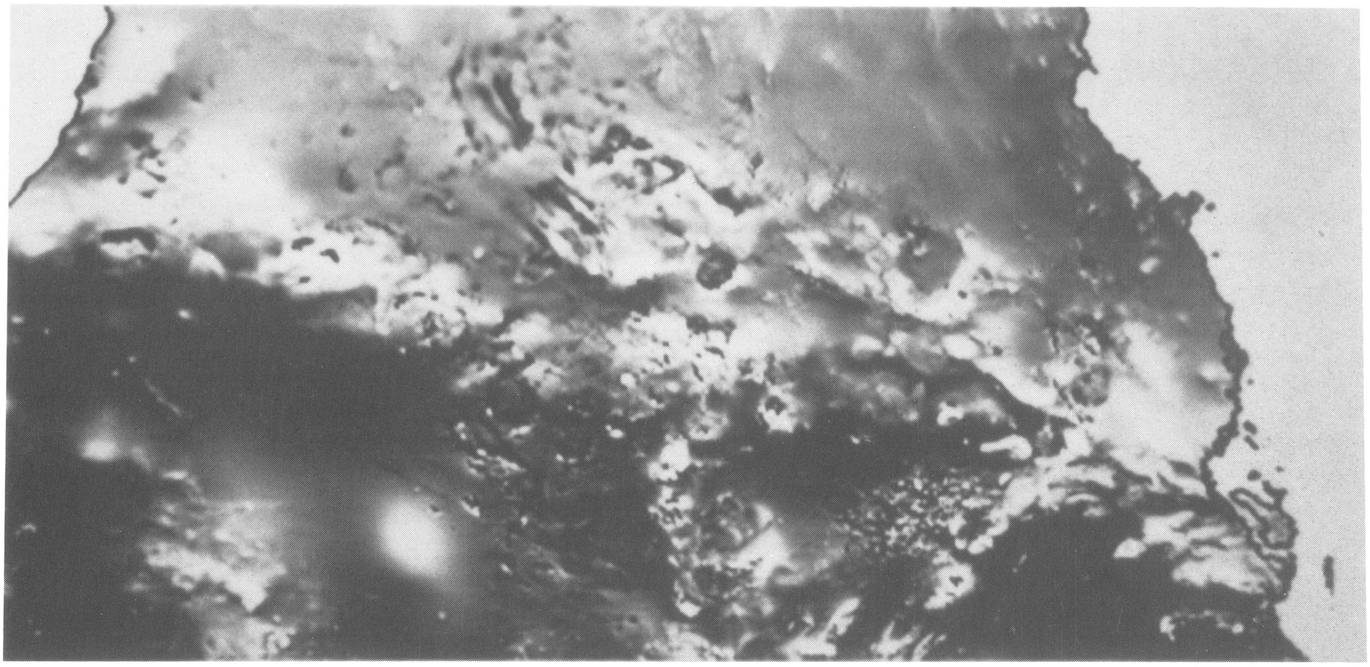


Fig. 10. Total magnetic intensity image showing the west-northwesterly trending broad magnetic high along the axis of the Townsville–Mornington Island Igneous Belt. Magnetic grid from Geophysical Observatories & Mapping Program, AGSO.

terozoic age: the Mount Isa and Keer-Weer Geophysical Domains. In the east, the belt separates two components of the Proterozoic Georgetown–Coen Geophysical Domain: the mainly non-magnetic Georgetown Province, which crops out to the south of the belt, and the non-outcropping, reversely magnetised Staaten Province, immediately to the north of the belt.

The igneous rocks of the outcropping part of the TMIIB have whole-rock and isotopic compositions consistent with their derivation from crustal rocks in an intraplate location: there is no evidence of a direct contribution from Permian–Carboniferous subduction. The distribution and chemistry of the outcropping rocks is best shown by the 'Igneous rocks of north Queensland' geographic information system and atlas packages, which AGSO released early this year. The rocks are mainly I-type granite to granodiorite, and rhyolite to andesite; A-type rocks are mostly rhyolite and granite; and S-type rocks are rare components of the belt.

Most mineral deposits in the belt are associated with I-type rocks, especially those that are fractionated. Magnetic images and outcrop data indicate that the depth of erosion increases east-northeastwards, with the result that volcanic rocks predominate west of longitude 144° and intrusive rocks east of longitude 144°. Recognition of the TMIIB extends the area of highly prospective rocks 500 km westward beneath the Carpentaria Basin. For at least the first 100 km, this cover is less than 300 m thick. AGSO plans further work to define in more detail the TMIIB, and the regional tectonic Permian–Carboniferous tectonic environment and mineral potential.

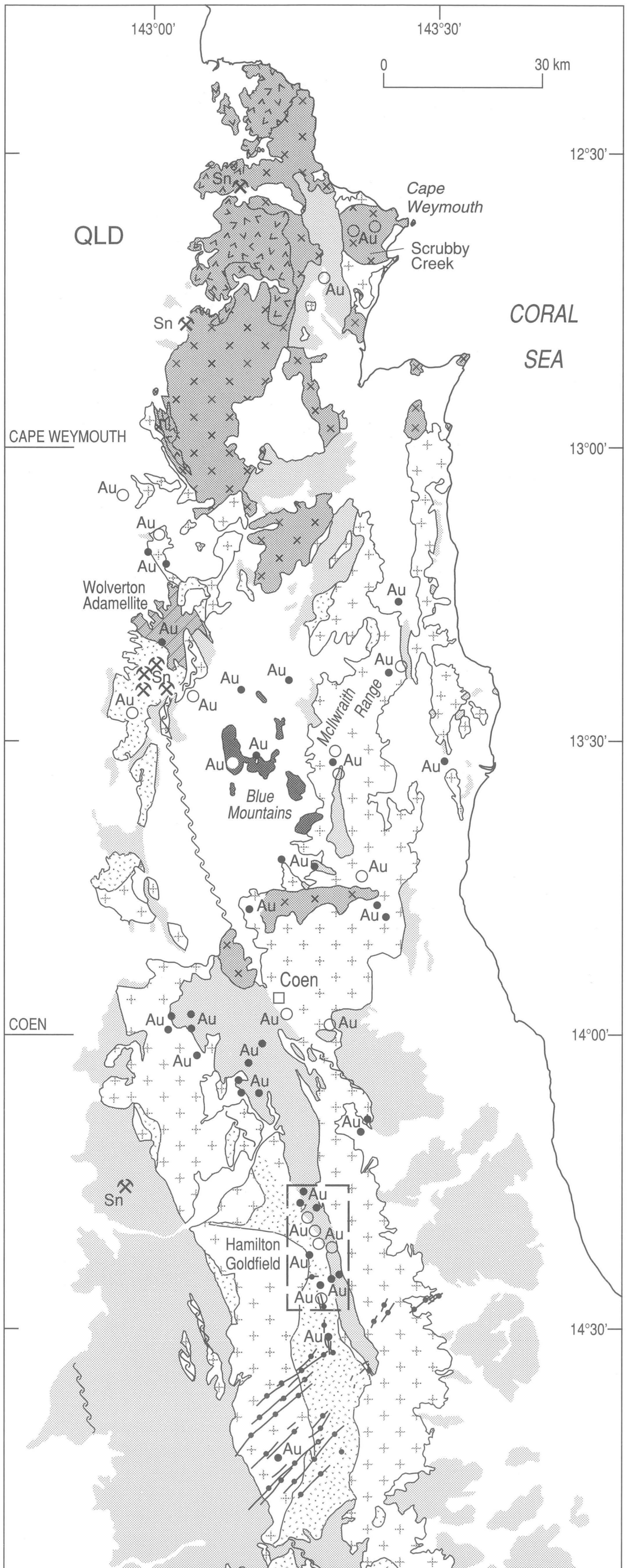
For further information, contact Peter Wellman, Doug Mackenzie, or John Bain (Minerals & Land Use Program) at AGSO.

Mineralisation potential of the granites of the Cape York Peninsula Batholith, Cape Weymouth, Coen, and Ebagoola 1:250 000 Sheet areas

Recent whole-rock and stream-sediment geochemistry in the northern part of the Cape York Peninsula Batholith (CYPB) of the Coen Inlier has identified specific geochemical characteristics in the Siluro-Devonian Blue Mountains and Permo-Carboniferous Wolverton granites, which are associated with Au and Sn mineralisation respectively. Geochemical data show that the I-type Wolverton Adamellite is strongly fractionated and reduced; it has elevated Sn values, which are associated with a pronounced stream-sediment Sn anomaly. In the Blue Mountains area, which has a history of small-scale Au mining, I-type granitic rocks range in composition from granodiorite to leucogranite, and include moderately oxidised types. Broadly similar whole-rock geochemical characteristics are also apparent in the Weymouth Granite, and identify it as one of the more Au-prospective units in the CYPB (see also *AGSO Research Newsletter* 18, May 1993, front page). These geochemical characteristics are generally not associated with the southern CYPB granites, which on the basis of available data appear to have poor potential for Au and Sn.

The CYPB is the major igneous feature of the Coen Inlier, forming a north-northwest-trending belt 400 km long and up to 60 km wide (Fig. 11). It consists of S- and I-type granites of Siluro-Devonian age, and Permo-Carboniferous I-type granites and comagmatic volcanics. The intrusion of Permo-Carboniferous granites into coeval volcanic rocks in the Cape Weymouth area of the northern CYPB attests to their emplacement at high crustal levels. Siluro-Devonian S-type granites are dominant in the central and southern parts of the inlier, where their deeper level of emplacement is indicated by an absence of comagmatic volcanics and their close spatial and temporal association with migmatites and high-grade metamorphic rocks.

Recent geological mapping and analytical studies of the mainly granitic rocks of the



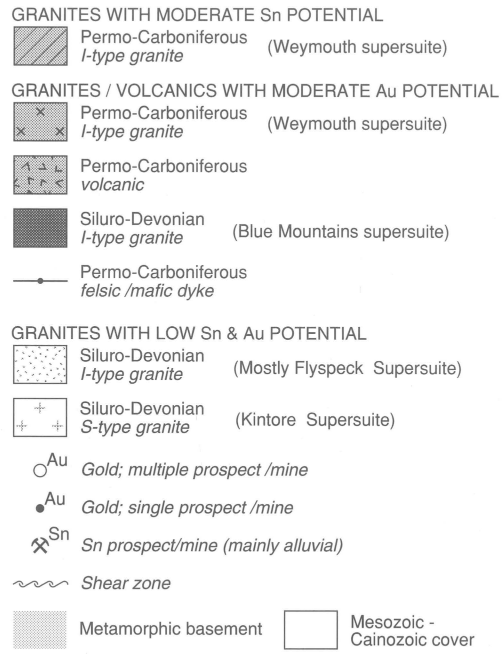


Fig. 11. Simplified geology of the Cape Weymouth, Coen, and Ebagoola 1:250 000 Sheet areas, showing Sn and Au prospects/mines and an assessment of mineral potential for the Cape York Peninsula Batholith. The assessment for the Cape Weymouth and Coen Sheet areas is based on 1967 mapping and only reconnaissance fieldwork in 1990 (whereas the Ebagoola Sheet area was remapped in 1991), and there is limited data for much of these areas. Au prospects/mines in areas identified as having low Au potential (e.g., McIlwraith Range) are possibly controlled by other factors such as the presence of unmapped I-type granites and later shear zones.

CYPB as part of the north Queensland National Geoscience Mapping Accord (NGMA) project, being carried out jointly by AGSO and the Geological Survey of Queensland, have identified four granitic supersuites (I-type Weymouth, Blue Mountains, and Flyspeck, and S-type Kintore) in the Cape Weymouth, Coen, and Ebagoola 1:250 000 Sheet areas. The I-type and S-type supersuites have a similar span of SiO_2 values — from about 60 to 76%.

Fractional crystallisation has been important in the evolution of some of the I-type granites — particularly for those of the Permo-Carboniferous Weymouth and Siluro-Devonian Blue Mountains supersuites, in the northern part of the CYPB, where Rb, Pb, and U show an overall increase in rocks with SiO_2>72%. Similar trends are recognised in other mineral provinces (Ishihara 1981: *Economic Geology, 75th Anniversary Volume*, 458–484; Blevin & Chappell 1992: *Transactions of the Royal Society of Edinburgh*, 83, 305–316; Stuart-Smith et al. 1993: *AGSO Bulletin* 229).

Sn mineralisation

Alluvial Sn is closely associated with the Wolverton Adamellite, one of the more reduced and fractionated units of the Permo-Carboniferous Weymouth supersuite. The Wolverton Adamellite has moderately high Sn values (22 ppm), and might have moderate potential for small vein and greisen Sn deposits. Associated alluvial Sn prospects have a known inferred resource of 4.1 Mm^3 alluvium at 1.13 kg m^{-3} cassiterite (Culpepper et al. 1992: *Queensland Resource Industries, Record* 1992/14). A stream-sediment geochemical Sn anomaly is also centred on the Wolverton Adamellite. A less marked stream-sediment geochemical anomaly to the north in the Cape Weymouth area corresponds to known alluvial Sn prospects, and reflects slightly elevated Sn contents in the Weymouth Granite, also part of the Weymouth supersuite.

Geochemical data indicate that units within the Siluro-Devonian

S-type Kintore Supersuite have low Sn values, and that their compositional variations were largely controlled by restite unmixing. They therefore have little Sn-resource potential.

The Siluro-Devonian Flyspeck I-type granites in the southern part of the area are typically reduced, but most are not highly fractionated, thus limiting their Sn-resource potential. The stream-sediment geochemistry of the area shows no significant Sn anomalies associated with either Kintore or Flyspeck Supersuite granitic rocks.

Au mineralisation

The I-type Blue Mountains supersuite, which hosts Au-bearing quartz veins in the Blue Mountains area north of Coen, includes moderately oxidised felsic to intermediate granitic rocks. Au is also closely associated with intermediate I-type granites near Cape Weymouth in the Scrubby Creek area and to the northeast of Coen. Stream-sediment geochemical data for the Coen and Cape Weymouth Sheet areas reveal significant Au anomalies associated with these mineralised rocks in the Cape Weymouth and Blue Mountains areas, and lesser anomalies in a number of other areas. Unfortunately we have limited detailed data for much of the northeastern part of the CYPB (Fig. 11).

Stream-sediment geochemical data for the Ebagoola Sheet area show that the most conspicuous Au anomalies in the CYPB are associated with the Hamilton Goldfield near the Coen and Ebagoola Shear Zones. Siluro-Devonian I-type granites occur in both the Hamilton and Coen mining areas, where — possibly more significantly — there is evidence of probable Permo-Carboniferous igneous activity (small granitic plutons, and rhyolitic plugs and dykes).

Sn- and Au-resource potential of granitic rocks

The distribution of I- and S-type granites in the areas covered by the Cape Weymouth, Coen, and Ebagoola 1:250 000 Sheet areas is shown in Figure 11, along with an assessment of their Au and Sn potential based on granite type, oxidation state, and relative importance of fractional crystallisation processes. A limitation to this assessment for the Cape Weymouth and Coen Sheet areas is a lack of detailed mapping of individual granitic plutons.

Known Au occurrences and stream-sediment anomalies are associated with the Blue Mountains and Weymouth supersuites. In addition, regional ^{18}O depletion, thought to be associated with epithermal gold mineralisation, has been reported from Permo-Carboniferous volcanic rocks associated with the Weymouth Granite in the northern Coen Inlier (Ewers & Cruikshank, 1993: *AGSO Research Newsletter* 18, 1–2).

In summary, the I-type Blue Mountains and Weymouth supersuites in the northern part of the Coen Inlier are generally considered to have a greater ore-mineral potential than the S-type granites. In particular, the Wolverton Adamellite is clearly an Sn-rich granite, and might have moderate potential as a host to small Sn deposits. In contrast, detailed mapping and whole-rock geochemistry in the extension of the CYPB to the south, in the Ebagoola 1:250 000 Sheet area, has shown a scarcity of trends indicating prolonged fractional crystallisation and a general absence of oxidised I-type granites. These granites are therefore regarded as unfavourable for Sn and Au deposits.

For more information, contact Dr Jan Knutson (granite geochemistry) or Dr Bruce Cruikshank (stream-sediment geochemistry) at AGSO (Minerals & Land Use Program).

Implications of Pb-isotope data for tectonostratigraphic correlations in the Proterozoic of central Australia

Almost identical Pb model ages have been determined for samples from the Central and Northern Provinces of the Arunta Block and Tennant Creek Block. They suggest that the units from which they were collected are essentially time-stratigraphic equivalents, and are believed to reflect sedimentary accumulation on a sialic basement during the same tectonostratigraphic episode, probably in an extensional environment, between about 1820 and 1800 Ma. Further, they indicate that a substantial part of the Central Province of the Arunta Block is younger than was previously suspected, which has implications for palinspastic reconstructions.

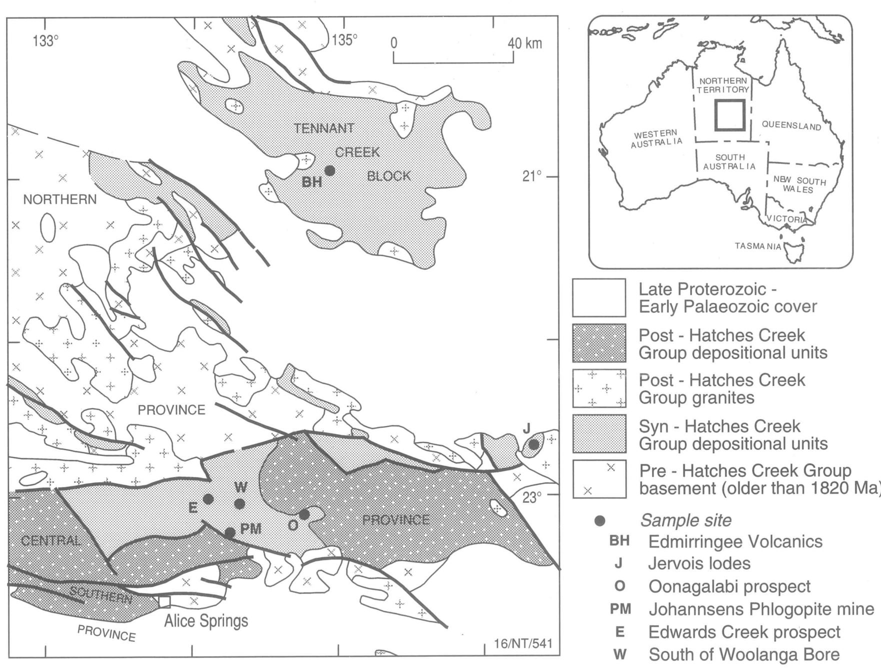


Fig. 12. Map of the Arunta Block and southern Tennant Creek Block showing locations from which samples were analysed.

AGSO contributes to a Geological Survey of Canada study

Radioactive decay causes the isotopic composition of lead to change with time. Moreover, the Pb-isotope composition of any sample is a mixture derived from sources specific to its geological environment; some sources provide greater proportions of radioactive decay products than others. A study in progress at the Geological Survey of Canada (GSC) aims to characterise the various sources in samples of Proterozoic rocks, and to assess the contribution from each source to the isotopic signature of each sample.

Following a request from GSC, AGSO's predecessor (BMR) donated to their study a collection of samples containing lead minerals from base-metal deposits in central Australia. The request was prompted by a paper, by BMR scientists, on the probable volcanogenic origin of several base-metal deposits in the Strangways Metamorphic Complex (Warren & Shaw 1985: *Journal of Metamor-*

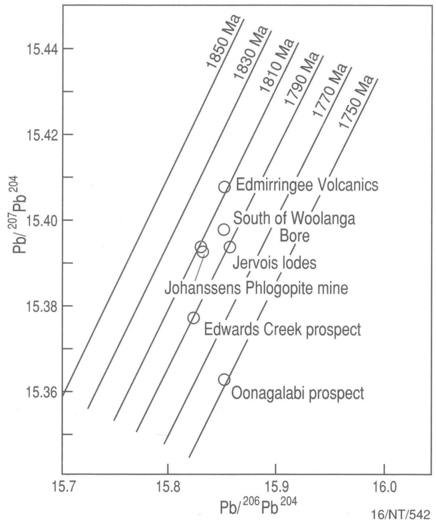


Fig. 13. Plot of the Pb-isotope data in relation to isochrons based on the source mixing that is considered to be most probable for central Australian Proterozoic lead.
Data from Warren et al. (in preparation). The analyses were carried out as part of a study of the characteristics of lead-isotope evolution at the Geological Survey of Canada.

Table 2. Analytical data and model Pb ages for samples used in the study of Pb-isotope compositions

Deposit, occurrence	*Formation, major unit*	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	*Model age (Ma)*
Galena in vesicles	Edmirringee Volcanics, lower Hatches Creek Group	15.852[a]	15.408	35.496	1811
Jervois lodes	Bonya Metamorphics	15.857[a]	15.394	35.492	1790
Edwards Creek prospect	Yambah granulite, Strangways Metamorphic Complex	15.823[b]	15.378	35.438	1792
Johannsens Phlogopite mine	Erontonga granulite, Strangways Metamorphic Complex	15.832[b] 15.830[b]	15.393 15.394	35.485 35.464	1807
Woolanga Bore	Cadney metamorphics, upper Strangways Metamorphic Complex	15.851[a]	15.398	35.481	1799
Oonagalabi prospect	Bungitina metamorphics, Strangways Metamorphic Complex	15.852[a]	15.363	35.469	1752

[a] Analysis by Geological Survey Consultants, Canada.
[b] Analysis by Geospec Consultants, Canada.

phic Geology, 3, 481–499).

Knowing the source characteristics, and the way that these are likely to have varied with time, has enabled GSC to estimate the Pb model ages of their samples. Any other available geochronological data help to constrain both the mixing models that are used to derive the model Pb ages, and the interpreted ages (see also the contribution by Sun et al. in this number of the *AGSO Research Newsletter*, pp. 1–2). The model ages for several of the central Australian samples, and their significance, are presented herein. Uncertainties in the Pb model ages — due to analytical limits, the accuracy of decay constants, etc. — are estimated at about 15 Ma (for details, see Warren et al. in preparation: *AGSO Journal of Australian Geology & Geophysics*).

The central Australian samples, and their model Pb ages

The lead-bearing samples sent to GSC and discussed herein were collected from the stratabound Jervois lodes in the Bonya Metamorphics, from four deposits in the Strangways Metamorphic Complex, and from the Edmirringee Volcanics (with galena-filled vesicles) in the lower Hatches Creek Group (Table 2, Fig. 12).

From a conventional zircon age of 1813 ± 5 Ma for the Treasure Volcanics, a unit stratigraphically above the Edmirringee Volcanics, Blake & Page (1988: *Precambrian Research*, 40/41, 329–340) estimated the depositional age of the Hatches Creek Group to be in the range 1820–1810 Ma. This zircon age serves as the control for the mixing model used to derive the model Pb age for galena from the Edmirringee Volcanics, which in turn is extrapolated to provide model ages for the lead from the other deposits (Fig. 13, Table 2).

The Bonya Metamorphics, in the northeast Arunta Block, are host to the stratabound Jervois lodes. Textures reminiscent of volcanic breccias in drillcore from the lode-bearing stratigraphic layer suggest that the lodes were produced by volcanic exhalative processes. The isotopic sample from the Jervois lodes has Pb-isotope ratios and model Pb age (1790 ± 15 Ma) similar to those of the Hatches Creek Group sample (model age of 1811 ± 15 Ma), indicating near-simultaneous deposition for the lower Hatches Creek Group and the Bonya Metamorphics precursors.

The mineralised host rocks at the Edwards Creek prospect, Johannsens Phlogopite mine, and Oonagalabi prospect are interpreted as metamorphosed exhalative-volcanogenic deposits, and their country rocks (units in the lower Strangways Metamorphic Complex, see Table 2) as bimodal volcanic suites (Warren & Shaw 1985, op. cit.). An isolated outcrop of galena-bearing forsterite marble south of Woolanga Bore has been mapped as part of the upper Cadney metamorphics, part of the upper Strangways Metamorphic Complex. Samples from the Edwards Creek prospect, Johannsens Phlogopite mine, and the prospect south of Woolanga Bore have model ages (1792 ± 15, 1807 ± 15 Ma, and 1799 ± 15 Ma) which

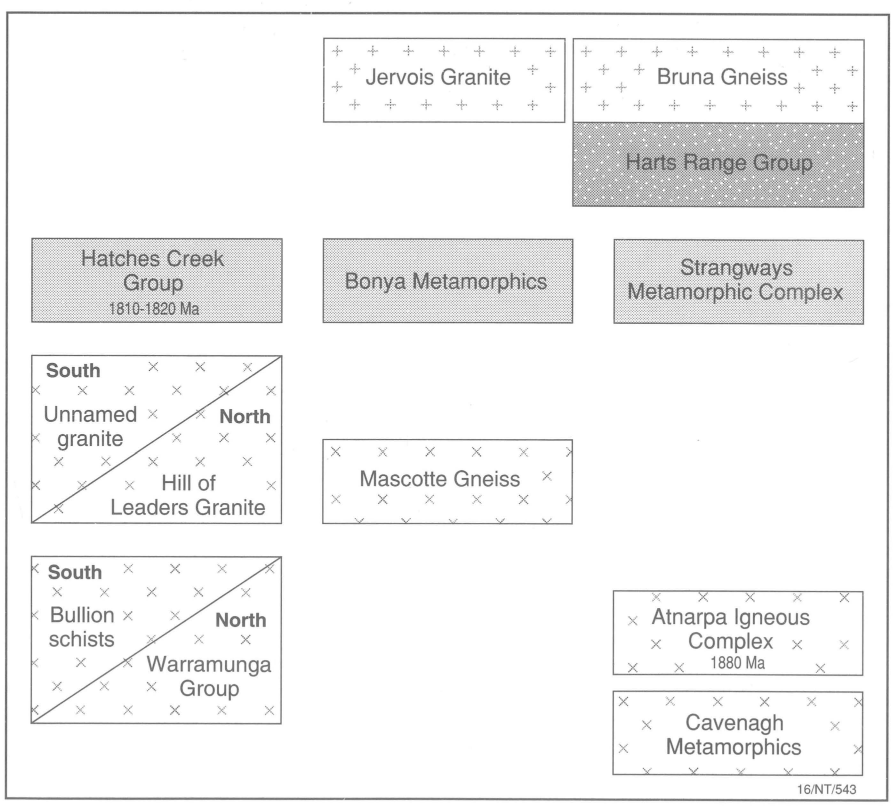


Fig. 14. Stratigraphic correlation chart for the Tennant Creek Block and part of the Arunta Block, based in large part on the results of the Pb-isotope study.
The age of the Atnarpa Igneous Complex is from Zhao & Cooper (1992, op. cit.).

show that their host formations are only marginally younger than the Hatches Creek Group. Thus the depositional age of the Strangways Metamorphic Complex is essentially coincident with that of the Hatches Creek Group.

The sample from Oonagalabi, however, has a model age which appears to be younger than the main cluster (Fig. 13). The shift from the cluster is due to the addition of radiogenic Pb, possibly during the hydration and retrogression that produced the gedrite assemblages so characteristic of the Oonagalabi prospect. The model Pb age is improbably young for the known constraints on the age of the host rocks.

Significance of the Pb model ages

The foregoing implies that the Bonya Metamorphics and the Strangways Metamorphic Complex are essentially time-stratigraphic equivalents of the Hatches Creek Group (Fig. 14), formed during the same tectonostratigraphic episode at about 1820–1800 Ma. The precursors of all three units are considered to have accumulated on a sialic basement, probably in an extensional environment.

A good case can be made for deposition of the Strangways Metamorphic Complex and Bonya Metamorphics in extensional ensialic basins, similar to the Hatches Creek Group. This is in keeping with the regime proposed by Shaw et al. (1984a: *Australian Journal of Earth Sciences*, 31, 457–484), who considered that the Arunta Block evolved by repeated extensional and compressional events.

The Hatches Creek Group was deposited on a sialic basement (Warramunga Group and granite). Its lithological succession is consistent with a rift-and-sag model of basin development. In the early (rift) stage, rapid sedimentation was accompanied by abundant felsic and mafic volcanism (including the Edmirringee and Treasure Volcanics); some of the clastic sediments were externally derived, whereas others were locally derived volcanic detritus. The upper (sag-stage) Hatches Creek Group is mainly sedimentary, with subordinate volcanics (Blake & Page 1988, op. cit.; Blake et al. 1987: *Bureau of Mineral Resources, Australia, Bulletin* 226).

The precursors of the Bonya Metamorphics were probably deposited in an ensialic rift-like environment. In the Northern Province of the Arunta Block, pre-Bonya sialic crust extended at least as far east as the Jervois region, where the Mascotte Gneiss formed older basement to the west of the Metamorphics (e.g., Shaw et al. 1984b: *Bureau of Mineral Resources, Australia, Record* 1984/3). Though little is known of the geochronology of the poorly exposed far-eastern Arunta Block, sialic crust of the Mount Isa Inlier, farther east, predates the Bonya Metamorphics. The internal stratigraphy for the Bonya Metamorphics has been mapped only by lithology, but this fits rift-and-sag deposition. The sequence evolved from early felsic and mafic volcanic rocks to mainly sedimentary rocks, including calc-silicate rocks, at the top in the core of the syncline in the Bonya Hills (Shaw et al. 1984b, op. cit.). Early downwarping outpaced deposition sufficently to create deep-water conditions suited to the formation of volcanogenic base-metal deposits.

In the Central Province, sialic crust south of the Strangways Metamorphic Complex existed well before 1820 Ma, as it was intruded by the Atnarpa Igneous Complex at 1880 Ma (Zhao & Cooper 1992: *Precambrian Research*, 56, 227–253). However, the depositional age of 1820–1800 Ma interpreted for the Strangways Metamorphic Complex now distinguishes this unit and an overlying one as younger parts of the Central Province. The early (rift) stage of the lower Strangways Metamorphic Complex, whose northern margin coincides with the southern edge of the Northern Province, consists mainly of metavolcanic units (e.g., the Yamba granulite, host to the Edwards Creek prospect). The mainly sedimentary Cadney metamorphics represent the late (sag) stage. Again, early downwarping outstripped deposition to allow volcanogenic sulphide deposits to form.

Clearly, more data in the form of ion-microprobe zircon ages are required to test the correlations and to improve interpretation of the Pb-isotopic composition for Oonagalabi. Additional testing can be made through detailed geochemical studies of units in the Bonya Metamorphics and Strangways Metamorphic Complex, and comparison with the Hatches Creek Group.

For more information, consult Dr Gladys Warren (Minerals & Land Use Program) at AGSO or Dr Ralph Thorpe at the Geological Survey of Canada.

Benthic chamber technology and the sea-floor of Port Phillip Bay, Melbourne

AGSO and colleagues from the University of Southern California, and the Marine Science Laboratories of the Victorian Department of Conservation at Queenscliff, recently conducted experiments on the sediments of Port Phillip Bay. Benthic chambers were deployed for the first time in Australia, as part of the Port Phillip Bay Environmental Study, to assess the role that the sediments play in regulating the composition of the sea water, and hence the 'health' of the bay. The data showed evidence of intense microbial activity on the sea-floor. This observation has already resulted in a reassessment of the area, and indicates that the bay is considerably more productive — through the growth of marine plants — than initially believed. The sediments are irrigated by the organisms on the sea-floor, and the biogeochemical reactions in the sediments are important for regulating the growth of marine organisms in the water column.

Port Phillip Bay is a semi-enclosed body of water which receives anthropogenic discharge from the surrounding catchment, and also from the Werribee Treatment Complex in the western part of the bay. The predicted population increases in the greater Melbourne area over the next twenty years or so prompted the Melbourne Water Corporation to commission an environmental study, being managed by CSIRO, to assess the capacity of Port Phillip Bay to accommodate possible increases in nutrients (nitrogen and phosphorus) and other materials that might be toxic to marine organisms and threaten the 'health' of the bay. The data, gathered from a variety of surveys, will be used to assess the need to build new sewage treatment plants or to upgrade existing facilities. One outcome of a review already completed has highlighted the role of the sea-floor as an unknown component in maintaining nutrient balance in the bay.

To address this, specially designed benthic chambers, built at the University of Southern California (USA) and used worldwide to examine seafloor processes, were applied for the first time in Australia to measure microbial activity on the sea-floor, and the rates of transfer of materials between the sediments and the overlying water. The chambers, which are about 30 cm in diameter, capture a parcel of water overlying the sediments. Sensitive instruments in the chamber continuously monitor — over about 18-hour periods — the concentrations of metabolites, which vary as a result of both physical transport (benthic irrigation and groundwater recharge) of and microbial activity within the sediments. Ten stations were occupied in strategic locations in Port Phillip Bay — including those offshore of the Werribee Treatment Complex, the Yarra River, Corio Bay (Geelong), and the central deep-water zone of the bay.

All of the deployments indicated that oxygen from the overlying water is consumed rapidly in the sediments. Associated with oxygen consumption is the release of essential nutrients — ammonia, nitrate, phosphorus, and silicate. Internal tracers are added to the chamber to evaluate mixing processes in the sediments, and radon (which is produced in sediments) is also measured to evaluate exchange parameters between the sediments and overlying water. The data gathered indicate that the sediments receive a considerable input of organic matter, significantly higher than initially believed, and are actively bioturbated, being mixed to depths of about 30 cm by the benthic-dwelling organisms. The intense microbial activity within the interfacial sediments results in a vigorous exchange of materials between the sediments and the overlying water. This activity is an important control on the chemistry of the water column, and hence on the 'health' of the bay. Key reactions that were identified limit the concentrations of nitrogen species available to marine organisms in the overlying water, and hence control the marine productivity of the bay. These key reactions might be utilised to develop environmental monitoring strategies for Port Phillip Bay.

The benthic chambers have a wide variety of applications, particularly as the sea-floor is increasingly recognised as an important repository of waste materials introduced into the coastal zone, and processes occurring there are important for developing environmental monitoring and management strategies.

For further information, call Dr David Heggie (Marine Geoscience & Petroleum Geology Program) at AGSO.

Landscape evolution in the East Kimberley region, Western Australia

The landscape in the East Kimberley region south of the Dixon Range (usually known as the Bungle Bungle Ranges) and east of Halls Creek (Fig. 15) has evolved from an ancient (Sturt) palaeoplain with southward drainage. Regional tilting caused local ponding of drainage and enhanced headward erosion of the ancestral (north-flowing) Ord drainage system. Stream capture of the ancestral (south-flowing) Sturt drainage system by the Ord system was followed by incision of the captured streams into resistant units of bedrock. The Bay of Biscay Hills formed as the drainage was incised within the Sturt palaeoplain, cutting steep-sided channels and making gorges in resistant units within the Olympio Formation.

Five stages in the evolution of the present landscape can be recognised:

1. **A landscape with low relief and south-flowing drainage (ancestral Sturt Creek system)**

The earliest identifiable well preserved element in the East Kimberley landscape is the the high-level plain (Sturt palaeoplain) of the Sturt Plateau. Sloping gently southward, the palaeoplain was drained by the ancestral Sturt Creek and its tributaries. Today, Sturt Creek — intermittently flowing in braided channels weaving across a broad river course — drains the Sturt Plateau. Ferruginous deep-weathering profiles are preserved in the southern Sturt Plateau, unlike the northern Sturt Plateau, where outcropping limestone and basalt outcrops have a cover of black soil. The highest part of the continuous Sturt Plateau — north of Marella Yard — is free of ferruginous deep weathering; it represents the northern, upland area of the Sturt palaeoplain, where the profile was never developed. Sparsely distributed low flat-topped ridges of resistant rocks, mostly sandstone, rose above the level of the palaeoplain, the relics of an even older plain.

2. **Possible slight tilt to the south**

Incision of south-flowing drainage into the ferruginous profile near Marella Gorge — possibly induced by slight uplift to the north — preceded deposition of the Lawford beds (possibly in the mid-Tertiary). This caused inversion of topography, so that laterite formed low rises above shallow stream valleys.

3. **Major tilt to the north (Fig. 16a, b)**

The next major stage in landscape evolution followed a tilt to the north. This had two effects. Firstly, it caused the ponding of drainage in the upper Sturt drainage system. Limestone (Lawford beds) infilled stream channels, and spread across the slightly dissected landscape of stage 2. This created the landscape, preserved along the Duncan Highway between Calico Creek and Nicholson homestead, of low rises covered in ferruginous pisolites above a flat plain of black soil over limestone (Fig. 16b detail). Minor local silicification of the limestone created a resistant carapace against later erosion.

Secondly, a lowered base-level to the north activated headwards erosion in the ancestral Ord drainage system. This selectively removed shale units in the Ord Basin, and captured the headwaters of the Sturt drainage system. Thin resistant units — for example, the sandstones in the Albert Edward Range (already ridges rising above the Sturt palaeoplain) and the Headleys Limestone — now remain exposed as dipping layers. Traversing the thicker resistant unit of the Antrim Plateau Volcanics, most of the captured streams were incised as gorges. The Sturt palaeoplain formerly continued west of the Albert Edward Range, where its remnants now form the bevelled crests of the Bay of Biscay Hills; continuous relics of it survive east of Mount Coughlin.

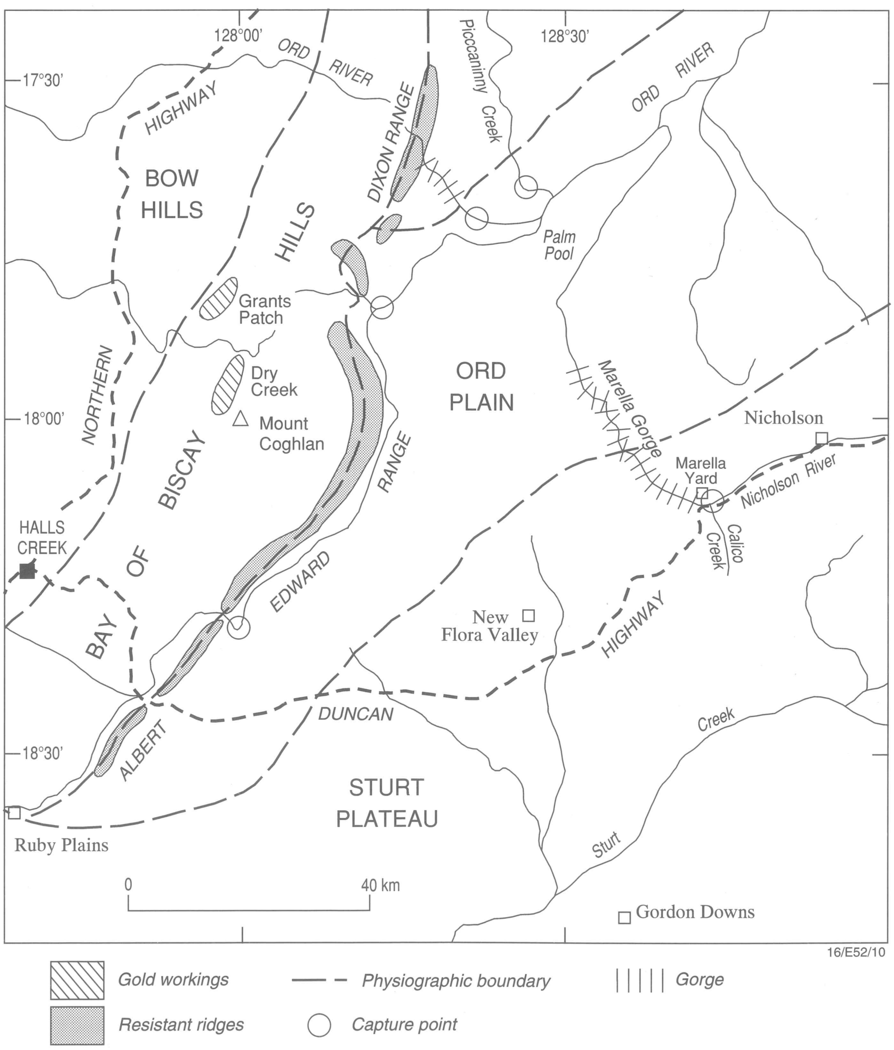


Fig. 15. Map of the area east of Halls Creek.

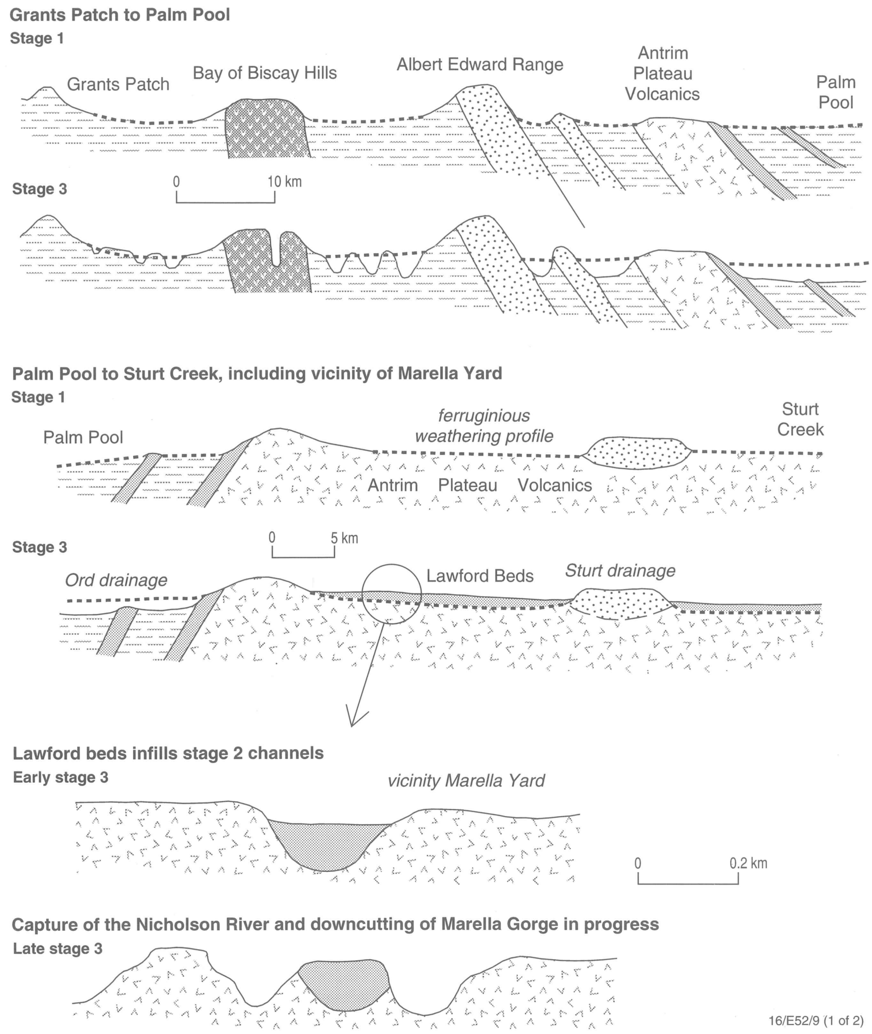


Fig. 16. Topographic profiles (exaggerated vertically) showing the effects of landscape evolution stage 3 superimposed on stage 1.
See Fig. 17 for explanation of symbols.

Capture of the Nicholson River and the incision of Marella Gorge were initiated during this stage, as a small stream etching into the Antrim Plateau Volcanics captured side streams and eventually the main channel of a major tributary of Sturt Creek; these processes continue today. Evidence of two cycles in the downcutting of the gorge to the Ord Plain can be seen near Marella Yard. The first caused downcutting of about 20 m to a level just below the base of the deep weathering profile, where resistant fresh rock is being exposed. Modern streams tend to be cut into the weathering profile, leaving the channel fills of Lawford beds as topographic highs clearly visible on satellite imagery. The second cycle of downcutting is marked by (usually) dry waterfalls at the head of Marella Gorge and in side streams. The level of Marella Gorge falls only a few metres from the head of the gorge to its mouth. Benches along the eastern edge of the Albert Edward Range indicate an early cycle in this area also. The capture of the Sturt Creek headwaters by the Ord drainage is continuing in the area northeast of Ruby Plains homestead, where poorly defined southeast-flowing streams are about to be taken over by sharply incised northeast-flowing streams.

4. **Transient tilt to the south (Fig. 17)**

East of the Albert Edward Range, a thin flat-lying veneer, probably of clay, accumulated over the Ord Plain, and lapped round low rises of the Linnekar Limestone. The veneer is exposed at the top of low cliffs adjacent to the major channels, where it has a distinctive, largely unvegetated, cream-coloured, badlands texture on aerial photographs. For the most part, the veneer supports grasslands described as black soil plains. In places it overlies a red-toned palaeosol or incipent weathering profile. This veneer of sediments is interpreted as the result of a short-lived lacustrine interlude that interrupted erosion by the Ord drainage system, perhaps as minor tilt to the south ponded the north-draining system for a short time.

Southward tilting also affected the remnants of the Sturt drainage system in the northern Sturt palaeoplain, creating a lowered base-level to the south and rejuvenating south-flowing tributaries of Sturt Creek. Some streams cut through the thin limestone of the Lawford beds to expose the Antrim Plateau Volcanics. This erosion produced a downs-type landscape of broad rolling hills over the black soil plains. The best development of this is north of the Duncan Highway near New Flora Valley homestead.

5. **Renewed downcutting in the Ord system**

South of the Dixon Range, the channels of the Ord and its tributaries are deeply incised into the Ord Plain, cutting down through the clay veneer and underlying palaeosol to expose bedrock (Ord Basin succession). Only the main streams are incised; minor side streams descend steeply to reach the main channel. The steep banks, absence of slip-off slopes, and sharply descending

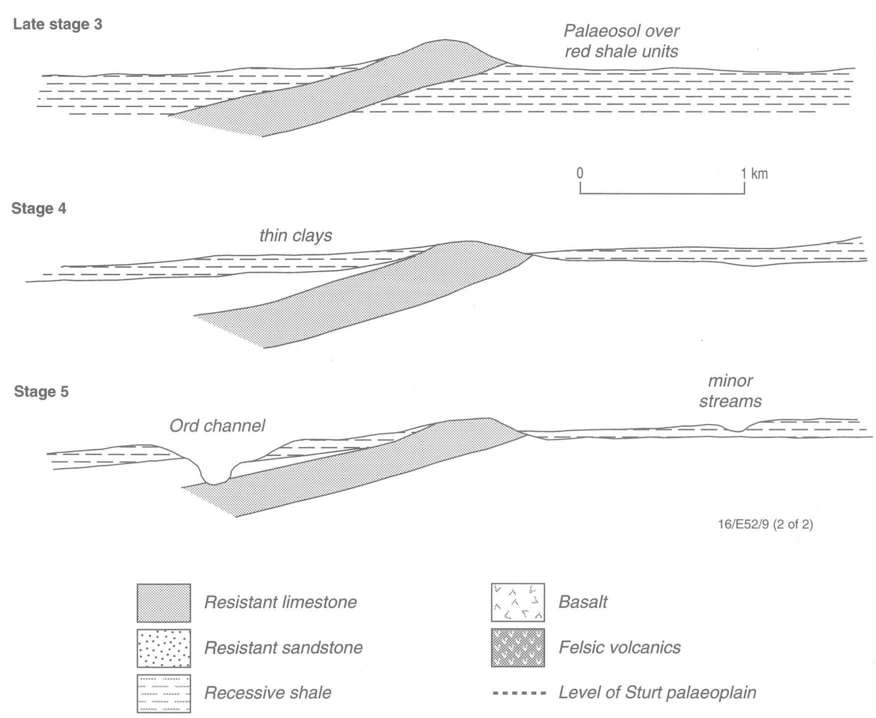


Fig. 17. Topographic profile (exaggerated vertically) in the vicinity of Palm Pool, showing the effects of landscape evolution stages 3, 4, and 5.

side streams all suggest that this stage began recently.

Consequences

The incision of the Ord system has created some spectacular scenery in the Albert Edward Range, much of it inaccessible. The Dixon Range appears to be equivalent to the hills (resistant sandstone-ridge relics of the plain predating the Sturt palaeoplain) that rise above the Sturt Plateau, and Piccaninny Creek, which drains south from Dixon Range, is one of the tributaries of Sturt Creek usurped by the Ord system (Fig. 15). The plains that surround the Dixon Range are partly erosional and partly infilled by clastic sediment, but can be traced southwest into the bevelled hilltops of the Bay of Biscay Hills, and so correlated with the Sturt Plateau.

The rejuvenated drainage that was superimposed on mature plains, and sculptured the Bay of Biscay Hills, has left a legacy of alluvial gold and secondary gold — freed from sulphides — that continue to support small mining operations. The Dry Creek alluvial field, within the deeply disected Bay of Biscay Hills, has benefited from both secondary enrichment and concentration into lag deposits as the old land surface was eroded. The primary sulphide zone, penetrated in shafts at Grants Patch, has so far proved uneconomic.

For more information, consult Dr Gladys Warren (Minerals & Land Use Program) at AGSO.

Mapping large-scale hydrothermal systems using coincident magnetic and gamma-ray spectrometric anomalies

In areas of outcropping basement, the pattern of gamma-ray spectrometric and magnetic anomalies primarily reflects the original lithology. A recent AGSO study has shown that these anomalies can also disclose a superimposed pattern of large-scale (10-km wavelength) changes in chemistry, which are interpreted as the effects of hydrothermal systems within reactive lithologies (metabasalt, limestone, and chert). This study suggests that regional geophysical data sets elsewhere could be analysed for hydrothermal system information.

Coincident geophysical anomalies and chemical variation in the Hodgkinson Fold Belt

During 1986–1989, the Geological Survey of Queensland remapped the Maytown and Laura 1:100 000 Sheet areas, and showed that the rock types of the lower Palaeozoic Mulgrave and Chillagoe Formations form north-striking, steeply dipping, semicontinuous bands. In 1991, AGSO obtained airborne magnetic and gamma-ray spectrometric data along flight lines 400 m apart over these outcropping units. The derived spectrometric image shows relatively high concentrations of uranium, potassium, and thorium over one group of rocks (greywacke, greywacke/mudstone, and quartzose arenite); and low thorium, and high potassium or high uranium, over a second group of rocks (metabasalt, chert, and limestone). Boundaries on the spectrometric image and on the geological map, show a close coinci-

Fig. 18. Correlated gamma-ray spectrometric and magnetic anomalies in parts of the Hodgkinson Fold Belt, indicating chemical remobilisation — probably by Permo-Carboniferous hydrothermal solutions.

dence, demonstrating the accuracy of the lithological mapping.

On a spectrometric image of potassium as red, thorium as green, and uranium as blue, the second group of rocks (metabasalt, chert, and limestone) can be divided along-strike (Fig. 18) into areas of relatively high potassium (displayed as either red and magenta, or red and black), and areas of relatively high uranium (displayed as either magenta, or magenta and blue); the magenta is red and blue, without green. Along-strike variation in potassium and uranium correlates roughly with along-strike variations in magnetic anomalies. Each area of relatively high potassium correlates with an area containing both high-amplitude magnetic anomalies (commonly over 100 nT) with wavelengths of 1 km, and a negative anomaly with wavelength of 5–10 km (Fig. 18). Each area of high uranium correlates with an area containing both low-amplitude anomalies (commonly less than 100 nT) with wavelengths of 1 km, and a positive anomaly with wavelength of 5–10 km.

In the Laura Sheet area, the areas of relatively high potassium or uranium (dashed lines in Fig. 18) extend from the Chillagoe Formation into the Mulgrave Formation and adjacent Permian sedimentary rocks, but with lower amplitude. In the Maytown Sheet area, an area of slightly higher potassium (dashed lines of Fig. 18) associated with a broad magnetic-anomaly *high* and subdued short-wavelength anomalies extends toward the western edge of the Sheet area at 144°E, and includes the high-potassium Dalkum Microgranite of Permo-Carboniferous age. Because the plumes of potassium and uranium extend from the lower Palaeozoic rocks into the Permo-Carboniferous rocks, these elements are thought to have been mobile in the Permo-Carboniferous.

Geophysical/chemical correlations elsewhere

The alteration types in the Chillagoe and Mulgrave Formations may be similar to the alteration types in the Eastern Creek Volcanics of the Mount Isa area as described by Wyborn (1987: *Geological Society of London, Special Publication* 33, 425–434). Wyborn's albite–actinolite type, which has high potassium and high magnetic susceptibility, would correlate with areas of high potassium and high-amplitude magnetic anomalies having wavelengths of 1 km. Her calcite–magnetite type, which has lower potassium and is associated with uranium deposits, would correlate with high uranium and high-amplitude magnetic anomalies having wavelengths of 5–10 km; these anomalies would reflect the creation of new magnetite.

Chemical remobilisation can also be recognised in other regional geophysical data sets. In the Kakadu area (NT), the hydrothermal system that generated Au–Pt–Pd–U mineralisation between El Sherana and Coronation Hill (Wyborn 1992: *BMR Research Newsletter* 16, 1–3) is associated with an along-strike decrease in magnetisation, local decreases in potassium and uranium, and increases in thorium. Also in the Kakadu area, the Cullen Granite is bounded in the northeast by two bands of rock: an inner band, 2 km wide, in which local increases in potassium and magnetisation are apparent; and an outer band, 0.5 km wide, in which the magnetisation of the rocks decreases.

Conclusions

The spectrometric and magnetic images that were studied over parts of the Hodgkinson Fold Belt reflect both lithological layering, and along-strike variation in properties due to chemical mobilisation by hydrothermal fluids. The coincidence of along-strike variations in magnetisation and U–Th–K ratio supports the applicability of regional geophysical data sets for mapping residues of chemical mobilisation.

For further information, contact Dr Peter Wellman (Minerals & Land Use Program) at AGSO.

The 'Keith–Kilkenny Lineament': fault or fiction?

As part of its contribution to the Eastern Goldfields National Geoscience Mapping Accord project, AGSO recently acquired semi-detailed aeromagnetic data (along flight-lines 400 m apart) and made ground observations (mostly based on approximately 1:28 000-scale colour aerial photographs) over the central sector of the 'Keith–Kilkenny Lineament' (Yerilla, Minerie, Leonora, Weebo, and Wildara 1:100 000 Sheet areas, WA; Fig. 19). The new data strongly suggest that the 'Keith–Kilkenny Lineament' does not constitute a single, simple, continuous fault, but, rather, is an artefact made up of separate, genetically unrelated — or only very tenuously related — segments interpreted from old reconnaissance data.

The 'Keith–Kilkenny Lineament' of Williams (1974: *Geological Survey of Western Australia, Annual Report for 1973, Perth*, 53–89) has been recognised with varying degrees of assurance for a distance of almost 500 km in the eastern half of the Eastern Goldfields district of Western Australia. It has been conventionally interpreted as the manifestation of a single major fault zone along the eastern edge of a corridor of intensely deformed rock, the Keith–Kilkenny Tectonic Zone of Hallberg (1985: *Geology and mineral deposits of the Leonora–Laverton area, Yilgarn Block, Western Australia*, Hesperian Press, Carlisle, WA). More recently it was nominated as a probable terrane boundary (Swager & others 1992: *University of Western Australia, Geology Department and University Extension, Publication* 22, 107–122).

Historically, recognition of the 'Keith–Kilkenny Lineament' almost entirely depended on the presence of a regional reconnaissance-scale (1500 m flight-line spacing) aeromagnetic low in the vicinity of Mount Kilkenny, about 40 km southeast of Leonora (Williams & others 1976: *BMR Explanatory Notes*, SH/51–6). This geophysical feature was quite reasonably equated with a major concealed fault on the basis of conspicuous structural and apparent stratigraphic discordances at Mount Kilkenny, and nearby conglomerates (to the northwest) marking the poorly exposed Pig Well Graben. The Mount Kilkenny Fault was extrapolated northwards using a variety of geophysical and geological features into the Mount Keith area, about 200 km north-northwest of Leonora.

The new data show that aeromagnetic trends along strike from the established Mount Kilkenny Fault change direction from northwest to slightly more northerly in the northeastern Leonora to southeastern Weebo 1:100 000 Sheet areas, before being lost in a tract of late-stage intrusive granitoids. In the opposite direction, the Mount Kilkenny Fault can be interpreted, but less convincingly than at Mount Kilkenny, across the southeastern Yerilla Sheet area.

In the northeastern Wildara 1:100 000 Sheet area, the 'Keith–Kilkenny Lineament' corresponds to a ductile fault zone collinear with the Perseverance Fault (or a combined Mount Keith–Perseverance Fault?), as delineated to the south of Mount Keith by, for example, Hill & Barnes (1990: *in University of Western Australia, Geology Department and University Extension, Publication*, 21). The ductile fault zone can be traced on aeromagnetic images, and on the ground through very sparse outcrops, south-southeast into the northwestern Weebo 1:100 000 Sheet area. There, it comes into contact with an apparent greenstone–whitestone sequence which enters the main high-strain corridor of the Keith–Kilkenny Tectonic Zone as a 'tributary' from the north-northeast; the old Goanna Patch group of mines lies near the mouth of this greenstone–whitestone 'tributary'.

Aeromagnetic trends parallel to the Mount Keith–Perseverance Fault do not cut southeastwards (i.e., towards the northern end of the Mount Kilkenny Fault) across the trends delineating the mouth of the Goanna Patch greenstone–whitestone 'tributary'. Instead, they turn south-southwest to merge with tributary trends, and into alignment with aeromagnetic trends and exposed structures marking the northern Minatichi Fault of Barnes & others (1974: *Western Australian Geological Survey, Annual Report for 1973, Perth*, 59–70). Farther south, the most conspicuous trends swing again — south-southeastward into the Clifford Fault of Barnes & others (1974, op. cit.). Together, these aeromagnetic trends and fault sectors follow a sinuous course obliquely across the Keith–Kilkenny Tectonic Zone to at least as far south as the east-central Leonora 1:100 000 Sheet area.

None of these faults (including the Mount Kilkenny Fault) seems to substantially disrupt local greenstone–whitestone sections (cf. Hill & Barnes 1990, op. cit.).

As previously perceived, the 'Keith–Kilkenny Lineament' was evidently an artefact of reconnaissance-scale data sets, and is thus revealed as a fictional entity on that basis alone. More importantly, we see no geophysical (neither magnetic nor gravity), stratigraphic, or structural evidence for a terrane boundary along the eastern edge of, or within, the Keith–Kilkenny Tectonic Zone. Geophysical data analysis and mapping to be undertaken in 1994 by AGSO and the Geological Survey of Western Australia in the Leinster–Mount Keith area will reveal the detailed aeromagnetic signature of the 'Keith–Kilkenny Lineament' in that area also; relationships between geophysical features and the local structure and stratigraphy should be clarified as a result.

For more information, contact Brian Oversby or Alan Whitaker (Minerals & Land Use Program) at AGSO.

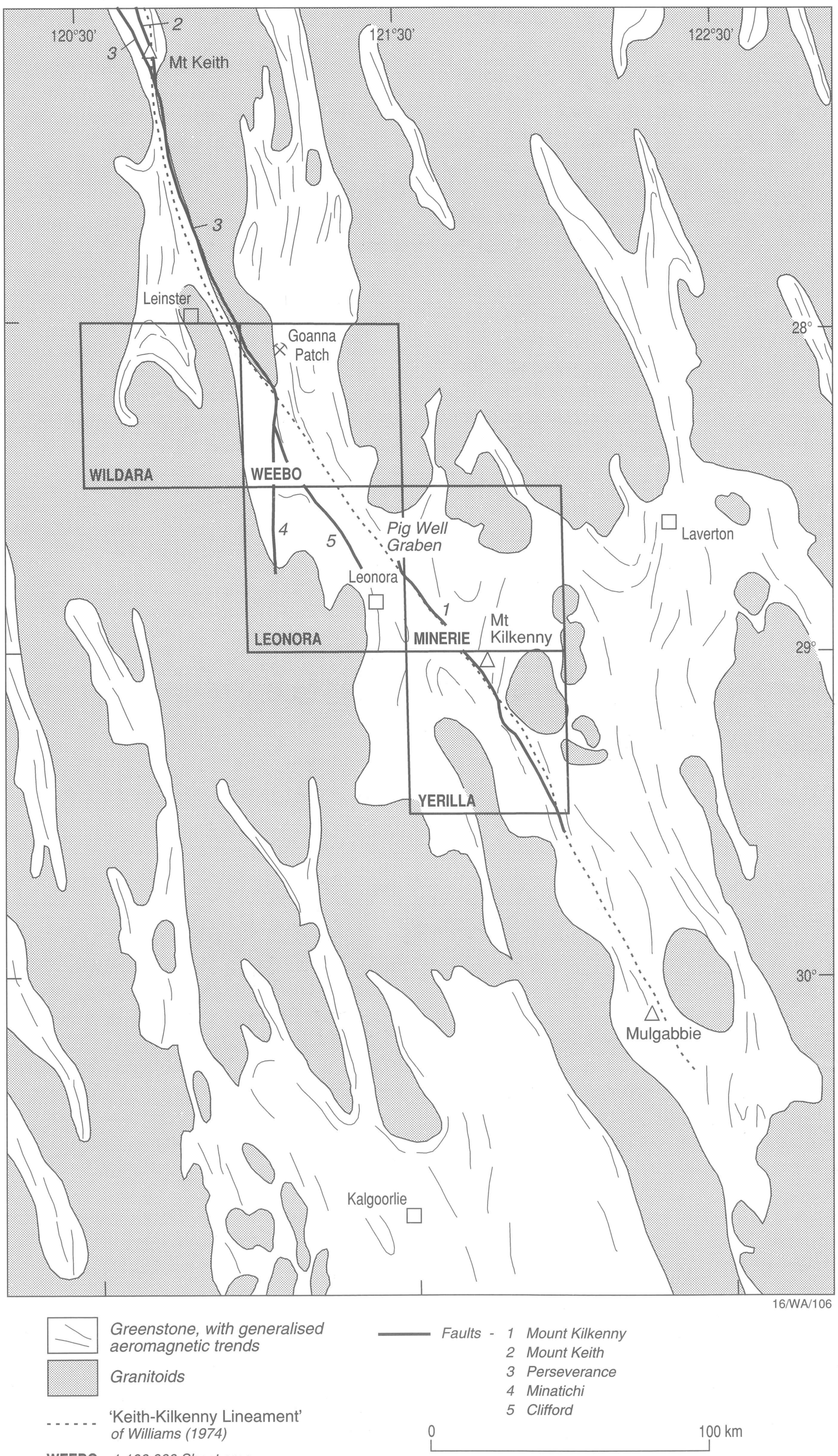


Fig. 19. Simplified locality and geological map of the central sector of the 'Keith–Kilkenny Lineament'.

A milestone in geomagnetic processing

AGSO's Geomagnetism Section operates a network of magnetic observatories, which are located at Canberra (ACT), Gnangara (WA), Charters Towers (Qld), Learmonth (WA), and Alice Springs (NT) on the Australian continent, and on Macquarie Island and at Mawson in Antarctica. A new observatory is planned for Kakadu (NT). Digital data from these sites are telemetered to AGSO in Canberra or to the Mundaring office near Perth (WA), where they are processed, distributed, and archived.

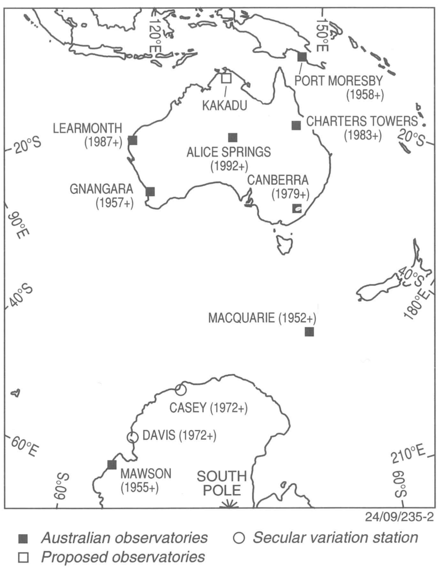


Fig. 20. AGSO magnetic observatory network.

Data from the observatories, and from the approximately 5-yearly first-order magnetic survey of the continent, are used in the formulation of the Australian Geomagnetic Reference Field (AGRF) model, and contribute to the international (IGRF) model. Data are also provided to the World Data Center in Boulder (USA).

Having been initially produced for the processing of the first digital observatory data from the Canberra observatory, a software package — now called *magobs*, which performs virtually all the observatory data manipulations — has been recently ported to the Section's Sun SPARCstation, and its capabilities have been greatly enhanced.

Magobs now processes data from all the magnetic observatories operated by AGSO, and from the first-order survey. Its capabilities include:

- the acceptance of raw 1-minute observatory data and their archival into monthly files;
- the production of daily (either in local or universal time) magnetograms;
- the calculation of mean hourly values, and their display as monthly tables, plots, and IAGA (International Association of Geomagnetism & Aeronomy) format files;
- the production of 1-minute value files in World Data Center format or NGIC INTERMAGNET format;
- the application of algorithms to produce geomagnetic K-indices;
- the filing and retrieval of geomagnetic 'international quiet and disturbed' days;
- the calculation of ranges of magnetic variations over selected intervals;
- the calculation of geomagnetic components and increments from a subset of the same; and
- numerous 'house-keeping' functions.

The source code for the program comprises several subroutine libraries — about 22 000 lines of code — and the executable module is around 760 kbytes. Although the program will probably continue to be modified as needs arise, a milestone in its evolution has now been achieved with its successful transfer to and improvements on the new platform.

For further information, contact Peter Hopgood (Geophysical Observatories & Mapping Program) at AGSO.

Continued from p. 20

Quiet Zone. Even so, the crust over most of the eastern part of the area is considered to have formed during an episode of spreading following the breakup of India and Australia at 132–118 Ma (e.g., Fullerton et al. 1989: *Journal of Geophysical Research*, 94B, 2937–2953), and magnetic anomaly MO (118 Ma) was identified in the southeast (Fig. 21). The crust in the west was formed much later, in the Late Cretaceous (about 80–70 Ma; Veevers & Li 1991: *Australian Journal of Earth Science*, 38, 391–408). Though magnetic lineations of the younger generation (84–50 Ma) were identified only in the westernmost part of the area (e.g., 34b; Fig. 21), we suggest that northerly trending fracture zones, observed farther east, represent transform faults developed during this period.

A number of previous workers have assumed that the pattern of spreading which developed in the Early Cretaceous persisted up to the beginning of the Late Cretaceous (96 Ma). Powell (1988: *Tectonophysics*, 155, 261–284) predicted the position of the spreading ridge, which became extinct at 96 Ma, and we believe that its axis trends north-northeasterly, coinciding with a bathymetric high (part of the western seamount chain) on the southern Christmas Island Rise (Fig. 21). Similar trends are apparent in the northern part of the Rise, most of the seamounts being slightly elongate in this direction. For this reason we suspect that the Christmas Island Rise is the remnant of a mid-ocean ridge which was abandoned at 96 Ma.

An accurate position of the boundary between the Early and Late Cretaceous crustal provinces cannot be established without a better interpretation of magnetic anomalies or additional drilling. We suggest that it lies immediately northwest of the Christmas Island Rise (as shown in Fig. 21), which means that almost all seamounts lie within crust that is 100–96 Ma old. Our conclusion is based on the clear evidence that northwesterly trending fracture zones of the Early Cretaceous system cut through the Christmas Island Rise, but cannot be traced beyond its western boundary.

Plate-tectonic history post-96 Ma

Our study suggests that the plate-tectonic history of the area following the cessation of spreading at the Early Cretaceous mid-ocean ridge (96 Ma) can be presented as follows. High volcanic edifices, some of them emerging above sea level, were formed about 15 Ma after spreading ceased. Intensive volcanic activity, which might have lasted a few million years, was associated with a new spreading centre that started to propagate from the west. The new plate boundary was formed very close to the position of the former spreading axis, but the spreading direction changed by almost 45°. It cut off parts of the former spreading ridge, which were carried away to the north. Propagation of the new spreading centre through the old rigid lithosphere caused volcanic activity at places with weakened crust, mostly at intersections with old fracture zones. A thermal anomaly associated with the extinct spreading ridge contributed to both the general elevation of the area and the intensity of volcanism.

The Eocene volcanism (about 35–40 Ma) in the Christmas Island area follows an important stage in the evolution of the Indian Ocean — collision of Greater India with Eurasia, and cessation of spreading in the Wharton Basin (50 Ma), when the Indo-Australian plate started to subside directly beneath Eurasia. The Eocene volcanism may have been caused by intraplate stress associated with those changes.

The most recent volcanic activity on Christmas Island (about 3–5 Ma) was probably also caused by intraplate stress and reactivation of fracture zones, reflecting lithospheric flexure and fault reactivation as the area approached the Java Trench.

More detailed information is available in the recently released *AGSO Record* 1994/2: 'Seafloor morphology and tectonics of the Christmas Island area, Indian Ocean' by Irina Borissova.

For further information, contact Dr Irina Borissova or Dr Neville Exon (Marine Geoscience & Petroleum Geology Program) at AGSO.

Plate tectonics of the Christmas Island region, northeast Indian Ocean

In February 1992, RV *Rig Seismic* carried out a detailed geological and geophysical survey of a 200-mile Australian Fisheries Zone around Christmas Island (*AGSO Research Newsletter* 18, p. 12; Exon et al. 1993: *AGSO Record* 1993/6). The resulting data, together with seismic and bathymetric data collected earlier, provide good coverage of the zone. Since then a new bathymetric map (to be published in AGSO's *1:1 000 000 Offshore Resources Map Series*) and sediment thickness map have been compiled (Borissova 1994: *AGSO Record* 1994/2). The new bathymetric map contains a lot more detail on the complex bathymetry of the area, allows the tracing of prominent lineaments, and presents a better picture of seamount distribution. The sediment thickness map reveals patterns of sediment distribution within different tectonic settings. A regional synthesis based on the bathymetric and seismic data is presented herein; it provides important constraints on the plate tectonic evolution of the area, and outlines the main ideas of the new tectonic interpretation.

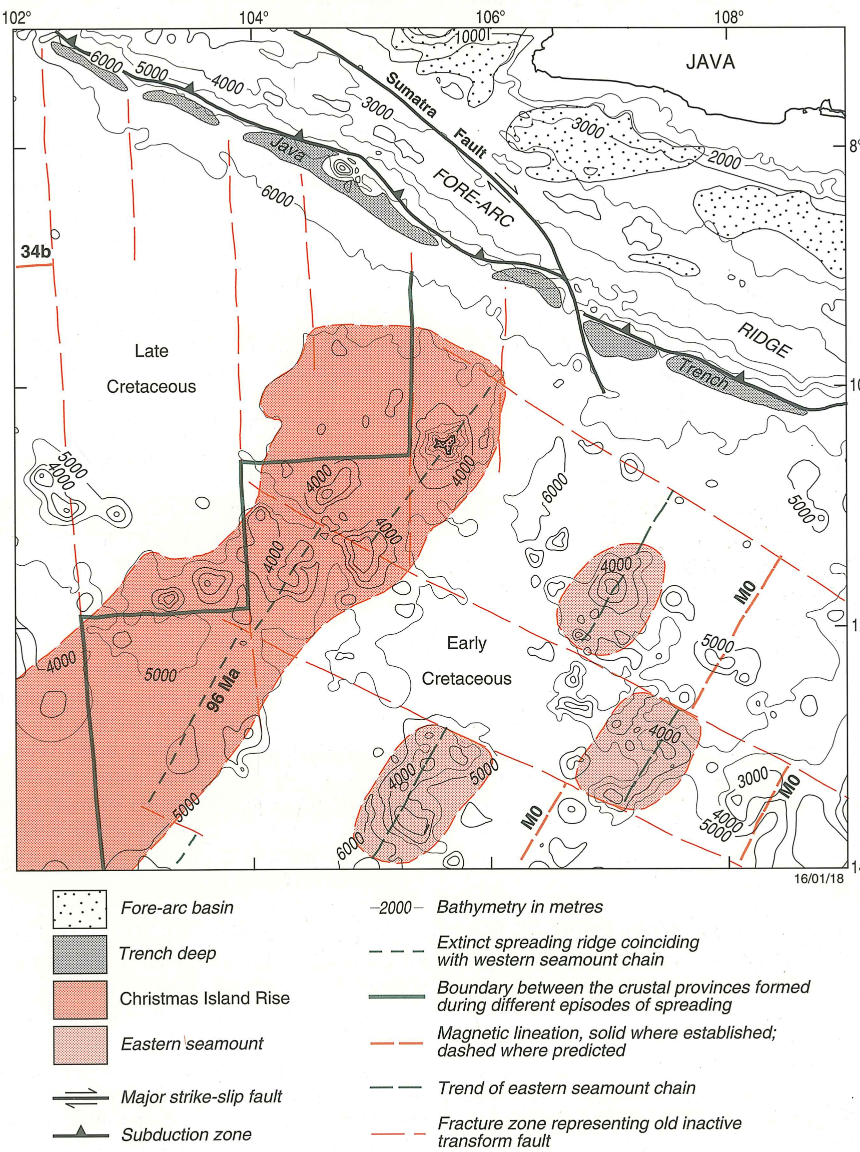


Fig. 21. Tectonic map of the Christmas Island area.

Seamount chains

Christmas Island is located about 300 km south of the Java Trench, a major tectonic boundary dividing the Indian plate from the island-arc complexes of Indonesia. In this area (Fig. 21), the Indian Ocean floor (northeast Wharton Basin) is sliding roughly northward beneath Java at a velocity of 7.0–8.0 cm y^{-1}. Its most striking bathymetric feature is the abundance of large seamounts — sites of Late Cretaceous and, for some, Eocene volcanism — aligned along two broad northeasterly trending chains of contrasting morphology.

The western chain comprises closely spaced large seamounts superimposed on a large uplifted block (Christmas Island Rise) rising 800–1000 m above the rest of the abyssal plain. Fracture zones in two directions (N–S and NW–SE) are expressed in the bathymetry as steep slopes or deep gulfs encroaching on the Rise. The strike of the seamounts seems to be displaced along the northwesterly oriented fracture zones.

The eastern chain is not in an uplifted area. Its seamounts are smaller, and their summits usually lie at about 3000 m. Clear northwesterly oriented fracture zones are collinear with those intersecting the western chain, but northerly oriented fracture zones are absent. The chain seems to be displaced along the two most prominent fracture zones (Fig. 21).

These observations allow us to suggest that both seamount chains evolved before or during the period when the northwesterly fracture zones were active. However, apparently later tectonism, associated with the northerly fracture zones, affected only the western chain.

One of the most intriguing questions is the origin of the seamounts. Intraplate volcanism, which formed them, occurs in three possible tectonic settings: (1) along fracture zones; (2) in zones of intraplate stress; and (3) in the vicinity of a hotspot. We consider that the volcanism of the studied seamounts was associated with the reactivation of old fracture zones during periods of major plate reorganisation, accompanied by increased intraplate stress.

Early and Late Cretaceous crustal provinces

The age of the crust in the northeast Wharton Basin is hard to determine, because most of this area lies in the Cretaceous Magnetic

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