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Potential applications of palaeomagnetism to mineral exploration in the Proterozoic of northern Australia

For the Proterozoic of northern Australia, palaeomagnetism offers a relative timescale of great potential for tracking the plumbing systems of known mineralising events, and for correlating metallogenically important but volcanic-poor sedimentary packages which host many of these deposits. Investigation of the apparent polar-wander path (APWP) for the period 1700–1500 Ma has elicited several distinct regional magnetic overprints, which we believe are related to regional-scale alteration events associated with significant Proterozoic metallogenic episodes. As with biostratigraphic zonations that are widely used in oil exploration in Phanerozoic basins, calibration of the APWP on an absolute timescale, although advantageous, is not considered essential for meaningful applications of palaeomagnetism to minerals exploration.

The Proterozoic APWP

AGSO has just completed a major contribution to the definition of the Proterozoic APWP for Australia (Idnurm et al. in press: *Precambrian Research*; Giddings & Idnurm in press: *Exploration Geophysics*; Tanaka & Idnurm in press: *Precambrian Research*). In the southeast McArthur Basin, about 1800 volcanic, clastic, and carbonate rock samples were analysed to define in detail the APWP (Fig. 1) for the period 1700–1500 Ma, and to develop a Proterozoic reversal stratigraphy for correlation and dating. From this study, 12 palaeomagnetic poles were interpreted as primary, including two that are preliminary. Another 10 poles record three or possibly four periods of magnetic overprinting (OP1–OP4, Fig. 1). The study also produced one of the oldest reversal records reported so far. The results suggest that the APWP offers great potential to the minerals exploration industry as a new and exciting tool for determining the relative ages of both non-volcanic sequences and alteration events, and for mapping the extent of these events around major mineral deposits.

Application of palaeomagnetism to correlating non-volcanic sequences

Few indisputable primary volcanic rocks 1700 to 1500 Ma old occur in sedimentary basins, so that the depositional ages of many contemporary non-volcanic sequences have yet to be determined. A recently completed palaeomagnetic study of such sequences by AGSO has successfully established a relative magnetic chronology in mainly *dolomitic lithologies* of the McArthur Basin. Up to now, dating of these Proterozoic sequences has had to rely on U–Pb zircon determinations of local 'tuff' beds, some of which are highly altered. The successful (but labour intensive) attempt at magnetostratigraphy by Idnurm et al. (in press) is promising, and offers further hope for correlating and/or dating other carbonate-rich sequences of uncertain age, several of which have been only tentatively correlated with sequences hosting major sedimentary base-metal deposits.

Palaeomagnetism as a means of dating Proterozoic regional alteration events

Between Katherine and Mount Isa, many igneous rocks dated between 1870 and 1500 Ma are extensively altered. On a district scale, most Proterozoic ore deposits are surrounded by alteration halos which are readily detected in igneous rocks by whole-rock geochemistry and fluid-inclusion studies. Although these halos extend up to 5 km from the known mineralised areas, they tend to be concentrated along major fault systems and in zones up to 1 km wide around structures known to control the mineral deposits (e.g., Coronation Hill — Wyborn & others 1989: *BMR Research Symposium*; Mount Isa copper — Bain & others 1992: AGSO *Bulletin* 243, 125–136).

In the Katherine to Mount Isa region, the chemical composition of altered rocks close to mineral deposits is in many ways similar to that in regional-scale alteration zones, many of which are remote from known mineral deposits. Deciding whether regional alteration zones are associated with the plumbing systems of undiscovered mineral deposits remains a challenge. Bulk chemistry alone cannot prove a metallogenic connection between a source rock and depositional processes. What is required is a way of determining the age or some other identifable characteristic of regional alteration zones, so that we may then relate a package of altered rocks to known deposits of equivalent age and characteristics, and thus perhaps detect the plumbing system of a hidden orebody. None of the available isotopic techniques is sufficiently established to unambiguously and accurately date alteration events, so any alternative method to constrain absolute or relative ages of alteration would be beneficial.

By defining and dating alteration overprints in the McArthur Basin, AGSO's studies have shown the potential of palaeomagnetism to identify the spatial extent of mineralising plumbing systems. Palaeomagnetism can successfully date these alteration events because, regardless of their style or type, one of the most common mineralogical changes is in the proportions of the magnetic remanence carriers — hematite and magnetite. The mix of these minerals changes consistently in response to common chemical alteration processes such as carbonation and oxidation. By its capacity to date hematite and magnetite formation, the palaeomagnetic method can specifically distinguish overprinting or alteration events, which are common in the Proterozoic of northern Australia. Hematite and magnetite cannot be easily dated by isotopic techniques.

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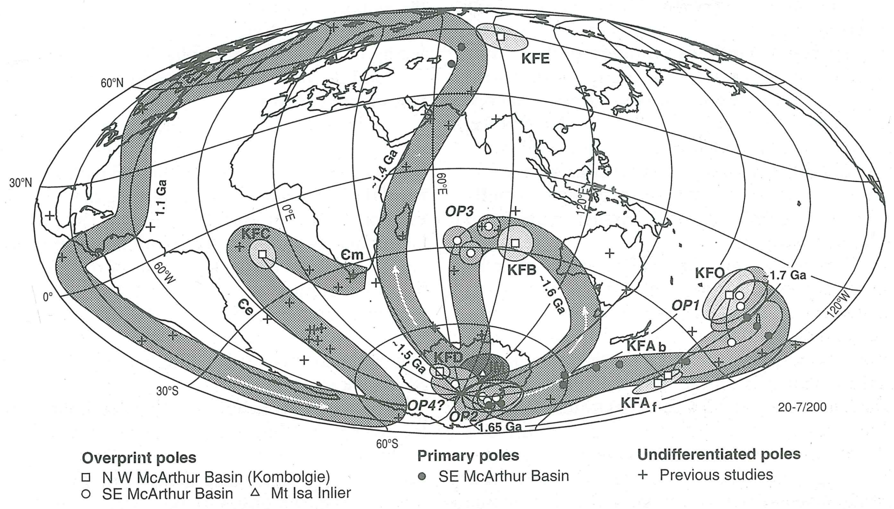

Fig. 1. 1800-Ma–Middle Cambrian APWP for Australia showing the locations of primary poles (black symbols) from the southeast McArthur Basin, and overprint poles (white symbols) from the northwest and southeast McArthur Basin and the Mount Isa Inlier. Circles around symbols represent the 95% confidence zones.

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Correlating regional alteration events with mineralising episodes

The pervasive hematite alteration of nearly all the 1700–1670-Ma volcanics in the Katherine to Mount Isa region has been attributed to various causes, including modern regolith formation. The new palaeomagnetic results of Idnurm & others (in press) show that a hematite overprint (OP1) in the Redbank area occurred soon after volcanism. The timing probably explains why the volcanics are so pervasively altered, and invites more detailed work to determine if the alteration might be associated with the copper mineralisation in the nearby Redbank breccia pipes, which formed at low temperature in the presence of liquid hydrocarbon (Wall & Heinrich 1990: 'Mount Isa Inlier geology conference', Abstracts, *Monash University*, 47–48). The location of OP1 on the APWP (Fig. 1) shows that this overprint predates the deposition of the Barney Creek Formation, which hosts the major HYC Pb–Zn deposit; hence OP1 cannot be a regional expression of the hydrothermal processes that formed this major base-metal deposit.

A second overprint — OP2, documented at about 1650 Ma — is more restricted geographically, and was found only near a prominent north- to northwest-trending fault system in the Abner Range area, 70 km south-southeast of the HYC deposit. OP2 affects units in and below the Umbolooga Subgroup of the McArthur Group, which also contains the Barney Creek Formation. If HYC Pb–Zn deposition was contemporaneous with sedimentation, OP2 could be a regional expression of this major hydrothermal event.

A prominent third overprint — OP3 at 1600–1550 Ma, restricted to dolomite units in the southeast McArthur Basin — has no known local metallogenic expression, though major uranium deposits were formed at this time in the Alligator Rivers Uranium Field, on the northwest edge of the McArthur Basin (Maas 1989: *Economic Geology*, 84, 64–90). Overprint KFB is pervasive throughout sampled areas of the Kombolgie Formation in the northwest McArthur Basin; it is similar in direction to OP3, and probably relates to the formation of the uranium deposits.

A fourth possible overprint, OP4 (Fig. 1), immediately below the McArthur/Tawallah Group unconformity was tentatively identified at 1550–1500 Ma. Similar overprints in the northwest McArthur Basin (KFD, Fig. 1; Giddings & Idnurm in press) and Mount Isa Inlier (IM; Tanaka & Idnurm in press) demonstrate the widespread influence of this alteration event. The Mount Isa Inlier at this time was metamorphosed, deformed, and intruded by granite, and the Mount Isa copper deposit is interpreted to have formed towards the end of this period (Heinrich 1993: *AGSO Research Newsletter*, 18, 9–11). All notable copper deposits (>20 tonnes contained metal) in the Mount Isa Inlier occur in rocks of greenschist or higher metamorphic grade (Jagodzinski & others, 1993: 'Mount Isa metallogenic atlas', AGSO *Metallogenic Atlas Series*, 1). As no equivalent upper-greenschist- to amphibolite-grade regional metamorphism is recorded in the southeast McArthur Basin at 1550–1500 Ma, it is unlikely that the local temperatures would have been high enough to mobilise significant Cu. Instead, the lower temperatures prevailing in this area during OP4 alteration would have been more likely to favour migration of Zn and Pb.

In a palaeomagnetic study of the Kombolgie Formation along the northwest edge of the McArthur Basin, Giddings & Idnurm (in press) identified many more hydrothermal events than previously suggested from isotopic dating. They distinguished overprints at 590, ~1300–1400, 1500–1550, 1600, 1680–1690, and 1700 Ma ($KFA_{b,f}$–KFE, KFO; Fig. 1), of which some are pervasive and others local.

Conclusions

AGSO's palaeomagnetic studies show that palaeomagnetism offers a new tool for mineral exploration in the Proterozoic of northern Australia, not only for stratigraphic correlation but also for tracking the regional plumbing systems of alteration events. They also highlight how widespread some of these events are. Significantly, the palaeomagnetic work can detect events of lower-temperature than can currently be detected by conventional isotopic methods. The threshold lower temperatures make the technique especially relevant in the Proterozoic of northern Australia, where the likely temperature of sediment-hosted base-metal deposition was <250°C. Most of the low-temperature chemical-alteration overprints in northern Australia contain hematite, which for palaeomagnetic work can have a high natural thermal stability — sometimes requiring exposure to temperatures >600°C for hundreds of millions of years before its magnetic remanence is thermally reset (Idnurm & Heinrich, 1993: *Australian Journal of Earth Sciences*, 40, 87–101).

An advantage of palaeomagnetic work is that it does not require an absolute time calibration of the APWP. All that needs to be done is to determine the remanence direction in the alteration zone associated with a mineral deposit, and then to track the plumbing system by identifying those rocks that have a similar remanence direction. Use of the Proterozoic APWP for dating is analogous to other relative dating methods, such as those based on palynological and dinoflagellate zonations which are widely used in the oil exploration industry for stratigraphic correlation.

AGSO will further test the palaeomagnetic technique for mineral exploration following the 1993 field season of sampling breccia pipes in the Redbank–Wollogorang area. Samples will also be collected to define more precisely APWP segments at 1700 Ma and 1650 Ma, when overprints OP1 and OP2 were acquired. Reconnaissance work will also be carried out on the Roper Group to improve the definition of the APWP at the time this unit accumulated, and to check for alteration events. Possible future extensions include sampling of the alteration zones enclosing the uranium deposits of the Alligator Rivers Uranium Field.

For further information, contact Drs Lesley Wyborn (Minerals & Land Use Program), Mart Idnurm, or John Giddings (Geophysical Observatories & Mapping Program) at AGSO.

Geology and geological processes of Australian national parks

In Australia, as elsewhere, a wide variety of places has been set aside for the conservation of the natural environment. These areas include national parks in the formal sense, administered at either Commonwealth or State level; and a variety of faunal and floral reserves, recreational parks, forest reserves, and other places of conservation importance. Some have achieved the rank of internationally recognised symbols of Australia, and come under great tourist pressure; others, usually remote of access, survive as almost undamaged wilderness areas.

Common to the majority of these reserved areas, however, is the fact that the underlying character of the park is determined by its geological framework. This is no less true for the low-lying, flood-prone plains of the northern part of Kakadu than it is for the stark monolith of Uluru. The landscape and the natural environment are the direct result of the interaction of geology and climate with time. The underlying geology determines the landform and soils; climate determines rainfall and erosion; and all these factors combine to provide the range of habitats that support the fauna and flora in all their diversity. Even the Great Barrier Reef is a product of rock-forming organisms.

And yet it is the understanding of this fundamental facet of our parks that is most neglected, both as a tool for better management and as a focus for public education programs. The 'poor-relation' status of geology in park activities is in contrast to the emphasis on biology. This is surprising when one considers that the criteria for World Heritage listing of natural areas emphasise geological history and its value in understanding processes of landscape evolution.

AGSO established 'The geology of Australian national parks' project in 1989 in an endeavour to raise the awareness of the public and park managers of the importance of understanding the geological foundations of Australian parks. The project has drawn heavily on information gathered by AGSO scientists during the course of routine geological mapping activities, and has benefited greatly from cooperation with the Australian Nature Conservation Agency (formerly the Australian National Parks & Wildlife Service) and from State park services.

The recent publication of a popular booklet on the geology of Uluru and Kata Tjuta is a landmark in the project's history. This full-colour publication describes, in language accessible to an educated public, the origin of both Uluru and Kata Tjuta (formerly known as Ayers Rock and the Olgas) from the time of deposition of their constituent strata, to the present phase of erosion and weathering; it includes accounts of the early interpretations of these startling features by European explorers, and has a section dealing with the geological features exposed along the recommended walks. This publication is not the only contribution that AGSO (and its predecessor, BMR) has made to the understanding of this important park; it follows a survey of groundwater resources there published in 1989 as *BMR Bulletin* 230.

Other project publications relate to Kakadu, and include posters on southern Kakadu and on the sandstone outliers and their role in the conservation of rock art. The production of notes on the geology of three walking trails is under way: that on the Jim Jim Falls trail was recently produced as *AGSO Record* 1992/80; others on Ubirr/Nourlangie and Little Rockhole/Bukbukluk are in draft.

Other products include annotated and illustrated maps of the geology of Jervis Bay; a recently published educational booklet on the volcanic features of the Warrumbungles in New South Wales; and a brochure on the geology of the Iron Range National Park, north Queensland.

Until now, in this early phase of the project, most attention has been directed towards the educational aspects of national park geology. For the future, there is a need to consider what role such reserves will play as sites for monitoring environmental change, and what kinds of geological information will be required as baseline data against which changes can be measured.

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

Empirical observations on granite-associated gold ± base-metal mineral deposits in the Proterozoic of Australia

Delineating exploration criteria

In the Proterozoic of Australia, hydrothermal vein- and breccia-hosted Au ± base-metal mineral deposits are rarely hosted by granites[1] (their supposed sources), and commonly occur in country rocks up to 5 km from the nearest pluton boundary. A review of field, petrographic, and geochemical characteristics of both granites and host rocks associated with such deposits shows many common features. The granites are all chemically fractionated and have specific geochemical characteristics, and the Au host rocks usually contain a reductant such as carbonaceous matter, sulphides, or magnetite. The granites and host rocks of such deposits are distinct from those usually associated with porphyry Cu ± Au ± Mo and carbonate-rich skarn deposits.

The granite factor: is a specific granite type important?

As more exploration in the Proterozoic focusses on hydrothermal Au ± base-metal deposits, granites are increasingly seen by many to be an important component of the mineralising system. Yet the occurrence of such deposits up to 5 km from a granite body has stimulated debate about the role of granite and/or granite-related processes in their formation. These deposits also contrast markedly with those ascribed to normal conceptual models of granite-related mineralisation — e.g., porphyry copper deposits, which are either hosted by or lie above the associated intrusive; or skarn deposits, which are usually hosted by carbonate-rich rocks immediately adjacent to granite. An Australia-wide compilation shows that Proterozoic granites with hydrothermal Au ± base-metal deposits within 5 km of their contacts have many field, petrographic, and chemical characteristics in common. This empirical observation suggests that granite intrusions are an essential ingredient in the style of mineralisation that generated such deposits.

Characteristics of the ore-related granites

1) Field characteristics. Although granite plutons associated with Au ± base-metal deposits show complex mineralogical and chemical variations, both within and between plutons (e.g., Telfer area, Paterson Province — Goellnicht et al. 1991: *Precambrian Research*, 51, 375–391; Williams Batholith, Mount Isa Inlier — Wyborn 1992: *BMR Research Newsletter* 16, 12–16; Cullen Batholith, Pine Creek Inlier — Stuart-Smith et al. 1993: *AGSO Bulletin* 229), overall they share many field and petrographic features, including:

- commonly circular outcrop;
- some composed entirely of leucogranite with >74 wt% SiO_2;
- common association of pegmatites, aplites, and greisens, indicating later magmatic fluid saturation;
- some strongly zoned;
- magnetite and hornblende in more-mafic varieties;
- usually compositionally distinct comagmatic felsic volcanics (where mapped);
- distinct and mappable contact aureoles up to 3 km wide;
- commonly upper-amphibolite-grade contact metamorphism, indicating considerable thermal disequilibrium between granite and country rock at the time of intrusion;
- distinct mineralogical and chemical features compared with other coeval plutons in the batholith; and
- common association with major shear zones.

2) Geophysical characteristics and expressions. The *magnetic signature* of plutons can be extremely variable: leucogranite bodies are poorly magnetised, and concentrically zoned plutons can have a strong positive magnetic signature on the outer rim. The conversion of pyrite in rocks in the aureole to pyrrhotite or magnetite, due to contact-metamorphic desulphidation, can result in the formation of magnetically distinct ring-shaped bands around individual plutons.

The *gamma-ray spectrometric* signature can also be extremely variable, though the more fractionated plutons usually have distinct and uniform high U, K, and/or total-count signatures. The zoned plutons have distinct concentric zoning.

3) Chemical classification. The granites are I-type, characterised by magnetite and hornblende in the more mafic phases, and I-(granodiorite) type on the classification of Chappell & Stephens (1988: *Transactions of the Royal Society of Edinburgh, Earth Sciences*, 79, 71–86). Typical of I-(granodiorite) types, Proterozoic granites associated with Au base-metal deposits have SiO_2 ranging from 58 to 78 wt% (mostly 70–75 wt%). In contrast, M-types and I-(tonalite) types, which are associated with Phanerozoic subduction zones in island arcs and continental margins respectively, are more mafic (SiO_2 = 48–70 wt%; Chappell & Stephens 1988). Most Phanerozoic porphyry Cu ± Au ± Mo deposits are associated with more mafic M-types or I-(tonalite) types; these types are rare in the Proterozoic of Australia (Wyborn et al. 1992: *Transactions of the Royal Society of Edinburgh*, 83, 201–209), where unequivocal porphyry deposits have not been found.

4) Specific chemical signatures. The ore-related I-(granodiorite) types have several common geochemical characteristics:

- wide range in SiO_2 content (58–78 wt%);
- high values of Rb (>250 ppm), U (>15 ppm), and, in some, Y (>40 ppm) and Li increasing exponentially with increasing SiO_2;
- decreasing K/Rb ratio with increasing SiO_2;
- alumina saturation index (ASI; Zen 1986: *Journal of Petrology*, 27, 1095–1117) <1.1 in the more mafic end-members, and >1.1 in some of the more fractionated members; and
- Fe_2O_3/FeO ratio decreasing as ASI increases >1.1; vein Sn and W mineralisation are common in regions where this happens.

The above signatures are illustrated in Wyborn & Stuart-Smith (this newsletter, pp. 5–8), and are typical of fractionated I-type granites (Chappell & White 1992: *Transactions of the Royal Society of Edinburgh*, 83, 1–26). Such granites have considerable potential for mineralisation, as fractionation provides a mechanism for concentrating elements, particularly metals of economic importance. Fractionated granites therefore may be an essential ingredient of hydrothermal mineralisation.

Which granites have the specific chemical signatures?

A review of ROCKCHEM, AGSO's whole-rock geochemical database of over 8000 analyses from Proterozoic provinces in Australia, shows that granites from the following areas have these signatures:

- Tennant Creek Block — several unnamed porphyries;
- Davenport Block — Elkedra Granite, Devils Marbles Granite;
- The Granites–Tanami Inlier — Lewis Granite, Winnecke Granophyre;
- Murphy Inlier — Nicholson Granite Complex;
- Paterson Province — Mount Crofton Granite;
- Pine Creek Inlier — Cullen Batholith;
- Mount Isa Inlier — Ewen Granite (limited data), Williams and Naraku Batholiths;
- Gascoyne Block — Minnie Creek Batholith (limited data); and
- Stuart Shelf — various granites of the Olympic Dam region.

Not all these provinces have known Au ± base-metal deposits, for a number of reasons — including lack of focussed exploration, and, where the granites constitute basement, limited exposure of the intruded rocks (e.g., Nicholson Granite Complex, Ewen Granite). Vein Sn, W, Cu, and/or U deposits do occur in some of these provinces, and are usually hosted by the granite. However, if the Cullen Batholith can be taken as a model, Sn, W, and U vein-style mineralisation apparently occurs only where fractionation proceeds to the point at which the I-type magma becomes distinctly peraluminous and has an ASI >1.1 (Wyborn & Stuart-Smith, this newsletter).

The host rock factor: are specific mineral compositions necessary?

Au, Cu, Pb, and Zn commonly occur in country rock, not always near granite, in contrast to Phanerozoic porphyry and skarn deposits. Empirical observations indicate the following compositional controls (e.g., Stuart-Smith et al. 1993; Wyborn & Heinrich 1993: *AIG Bulletin* 14, 51–54). Carbonate-rich but carbon-poor rocks commonly host Pb and Zn deposits; rarely, if ever, do they host Au or Cu deposits. Au deposits are hosted mainly by reduced (C- or Fe^{2+}-rich) rocks such as:

- banded iron formations;
- mafic volcanics;
- magnetite-bearing felsic volcanics;
- earlier, more-mafic magnetite-bearing phases of the granite (rare);
- carbon-bearing rocks;
- sulphide-bearing shales; and
- magnetite-bearing skarns which replace silicate but not carbonate rocks.

These mineral assemblages are products of either primary, metamorphic, or alteration processes; indeed, alteration can enhance the magnetite content of a rock.

The preferences that mineralising processes show for specific rock types might reflect vapour/brine separation. Thus, components such as Au and Cu, which can be preferentially carried in a sulphur-enriched vapour phase, will precipitate in reductant-bearing units (e.g., those that are rich in carbon, magnetite, or sulphide). In contrast, Pb and Zn are carried in a chloride-enriched brine, which will preferentially interact with carbonate hosts (Heinrich et al. 1992: *BMR Research Newsletter* 16, 12–13; Wyborn & Stuart-Smith, this newsletter).

Exploration criteria

The data accumulated so far suggest that exploration for granite-related hydrothermal deposits in the Proterozoic of Australia should focus on identifying, firstly, granites with the specific geochemical and field characteristics described above, and, secondly, appropriate host rocks for the precipitation of the relevant commodity. Searching for Au or Cu deposits in carbonate-hosted skarns adjacent to an intrusion is empirically unsupported. Cu (with minor Au) occurrences in the Proterozoic are typically more closely associated with contacts of granite plutons,

[1] 'Granite' herein covers the broad spectrum of granitic rocks, including diorite, granodiorite, adamellite, and granite (*sensu stricto*).

but still lack the typical morphology of modern porphyry Cu (± Au ± Mo) deposits. It is unclear if the absence of narrow subvolcanic porphyry plugs in the Proterozoic simply relates to the higher SiO_2 content, and hence higher viscosity, of even the most mafic Proterozoic granites, or if the different chemical composition of the Proterozoic granites is the main cause for the different style of mineralisation. An interesting corollary to the observation that Proterozoic Au-only deposits occur up to 5 km away from a granite contact, possibly because Au can be carried in a sulphide-enriched low-viscosity vapour phase (Wyborn & Heinrich 1993), is that Au-only deposits might occur several kilometres away from known Phanerozoic porphyry Cu deposits (e.g., Carlin-type Au deposits?).

Is age a valid exploration criterion for this style of mineralisation?

Proterozoic granites associated with Au ± base-metal mineralisation have a considerable range in age — from 690 (Telfer area; Goellnicht et al. 1991) to 1830 Ma (Cullen Batholith; Stuart-Smith et al. 1993). Granites with similar chemical characteristics also occur in the late Archaean of the Yilgarn Block (Wyborn 1993: *Ore Geology Reviews*, 8, 125–140; Champion & Sheraton 1993: *in AGSO Record* 1993/54). Host rocks for this style of mineralisation also show a large variation in age. Therefore, base geochemical and mineralogical features of source granites and depositional host rocks, rather than age criteria, should be used for exploration area selection.

Can we determine areas that have low potential?

In contrast to the variability shown by the mineralised granite suites, the non-mineralised suites of the Proterozoic are very uniform. For example, Wyborn & Page (1983: *BMR Journal of Australian Geology & Geophysics*, 8, 53–69) showed that the Kalkadoon Batholith and its comagmatic volcanics in the Mount Isa Inlier vary little chemically over 4500 km^2. Similar uniform granites are found throughout northern Australia (Wyborn 1988: *Precambrian Research*, 40/41, 39–60), and include the Nimbuwah Granite of the Pine Creek Inlier, and many of the Kimberley granites. Compositionally and geographically distinct plutons (e.g., leucogranites, zoned plutons) are hard to identify in these granites, which are compositionally similar to their comagmatic volcanics where exposed. Not only are pegmatite, greisen, aplite, and other indicators of late-stage magmatic processes uncommon, but these granites lack well developed contact aureoles. The chemical trends for these granites are linear, and — unlike the granite suites that are fractionated — Rb, U, Y, and Li, etc., do not increase exponentially, neither does the K/Rb ratio decrease, with increasing SiO_2.

According to Chappell et al. (1987: *Journal of Petrology*, 28, 1111–1138), these more uniform suites are dominated by abundant xenocrysts or restite, and the crystallisation process is one of the restite (hornblende, biotite, calcic plagioclase) unmixing from a minimum melt dominated by quartz, K-feldspar, and albite components. Restite unmixing precludes these granites from becoming enriched in any trace-metal component beyond its concentration in the initial melt plus restite. Moreover, restite-rich granites will generally not evolve a magmatic fluid phase, nor do they impart any significant heat into the local environment.

For further information, contact Dr Lesley Wyborn or Dr Chris Heinrich (Minerals & Land Use Program) at AGSO.

Geochronological results from the Eastern Fold Belt, Mount Isa Inlier

New depositional and metamorphic ages

The paucity of suitable dating material, high grades of metamorphism, and fault-bounded major geological contacts have precluded meaningful isotopic dating of supracrustal sequences in the Eastern Fold Belt of the Mount Isa Inlier (Fig. 2). Hence, stratigraphic connections between these rocks, the rest of the Inlier, and other Palaeoproterozoic terranes such as the Georgetown and Broken Hill inliers have been matters of great conjecture. This article presents new U–Pb zircon ages from the Eastern Fold Belt, and the results facilitate more definitive correlations with parts of the Western Fold Belt.

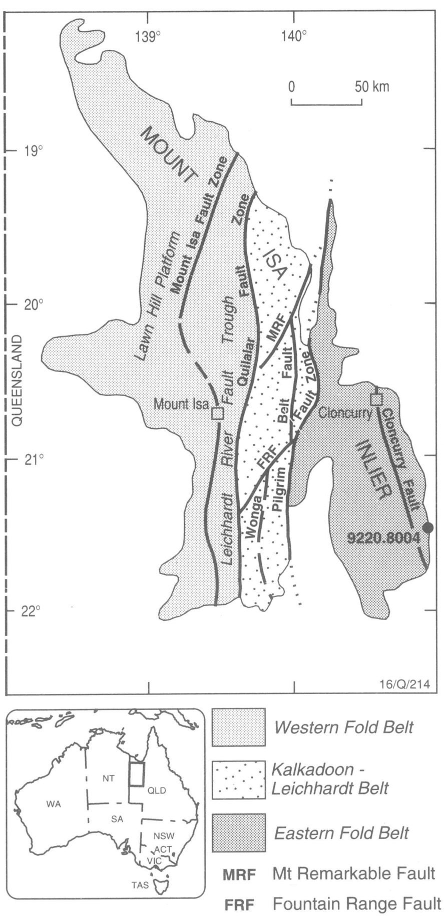


Fig. 2. Location of the Eastern Fold Belt, Mount Isa Inlier.

The dated rock (sample 92208004) belongs to the Maronan Supergroup of Beardsmore et al. (1988: *Precambrian Research*, 40/41, 487–507), who considered that this unit belongs to cover sequence 1 of Blake (1987: 'Geology of the Mount Isa Inlier and environs', *BMR 1:500 000 map*) and therefore between 1810 and 1880 Ma old. Blake, however, considered that many of the rocks of the Maronan Supergroup (e.g., Soldiers Cap Group) probably belong to a cover sequence 2 package, 1780–1800 Ma old. Derrick (1976: *BMR Journal of Australian Geology & Geophysics*, 1, 251), Blake et al. (1984: *BMR Bulletin* 219), and Laing & Beardsmore (1986: *Geological Society of Australia, Abstracts*, 15, 114–115) drew lithostratigraphic comparisons between parts of the Eastern Fold Belt and parts of the Willyama Supergroup near Broken Hill, now dated at 1690 ± 5 Ma (Page & Laing 1992: *Economic Geology*, 87, 2138–2168). In short, the rocks of the Eastern Fold Belt have had few firm age constraints, and have a possible age range from 1500 to 1880 Ma, or perhaps even older.

The first results from the current study come from a felsic gneiss in the southeast (Fig. 2), which belongs to the Gandry Dam Gneiss (Fullarton River Group) of Beardsmore et al (1988), and was mapped as undivided Soldiers Cap Group by Blake (1987). The lithology reported on here is a porphyroblastic garnetiferous felsic gneiss exposed near Marramungee Creek in the Mount Angelay 1:100 000 Sheet area at GR 497200E, 7623000N. The rock contains 67% SiO_2, 8.1% K_2O, 0.8% Na_2O, 0.2% MnO, and 1345 ppm Ba. This is similar to the analysis in Blake et al. (1984), who suggested that this gneiss might have been derived from a felsic volcanic precursor.

U–Pb zircon ages, and their significance

Zircons in this rock are morphologically and isotopically complex (Fig. 3). Of the 53 analyses undertaken (using both SHRIMP I and II ion-microprobes), about 10 per cent clearly reflect inheritance between 2320 and 2550 Ma old. Another grain is 1830 Ma old. These are either xenocrysts in an original felsic magma, or detrital components in a greywacke-type metasediment.

Most of the zircon U–Pb data straddle the concordia curve between 1670 and 1750 Ma (Fig. 4). Euhedral to subhedral zoned and cracked grains have ages that generally fall on the older side of this grouping, and they form a population that defines a $^{207}Pb/^{206}Pb$ age of 1734 ± 6 Ma. This is interpreted as dating a provenance terrain of the same general age as granites in the Wonga Belt in the central part of the Mount Isa Inlier.

Of most interest is a younger group of grains with U contents similar to that of the 1734-Ma population (200–600 ppm), but with generally higher Th/U (0.8–1.6, except in grain 14). A further difference is that the younger grains are clear and

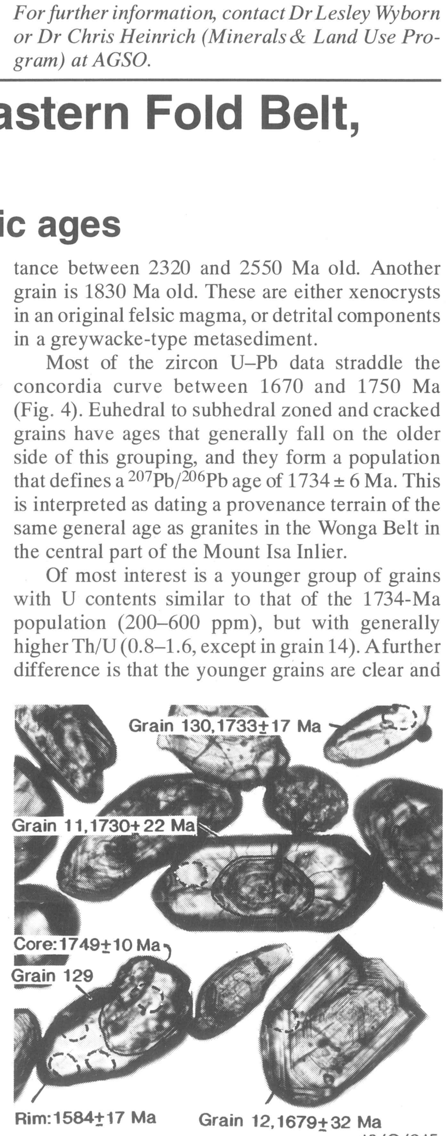


Fig. 3. Photomicrograph, in transmitted light, of zircons from felsic gneiss sample 92208004. The annotated subcircular areas, about 25 x 18 microns, are analytical target areas of the SHRIMP II primary ion beam. Most of the grains in this field of view belong to inherited populations. Grain 12 is part of the higher Th/U zircon suite 1677±9 Ma old. The irregular selvedge on grain 129 has exceedingly low Th/U, and defines a metamorphic age more than 160 Ma younger than its core.

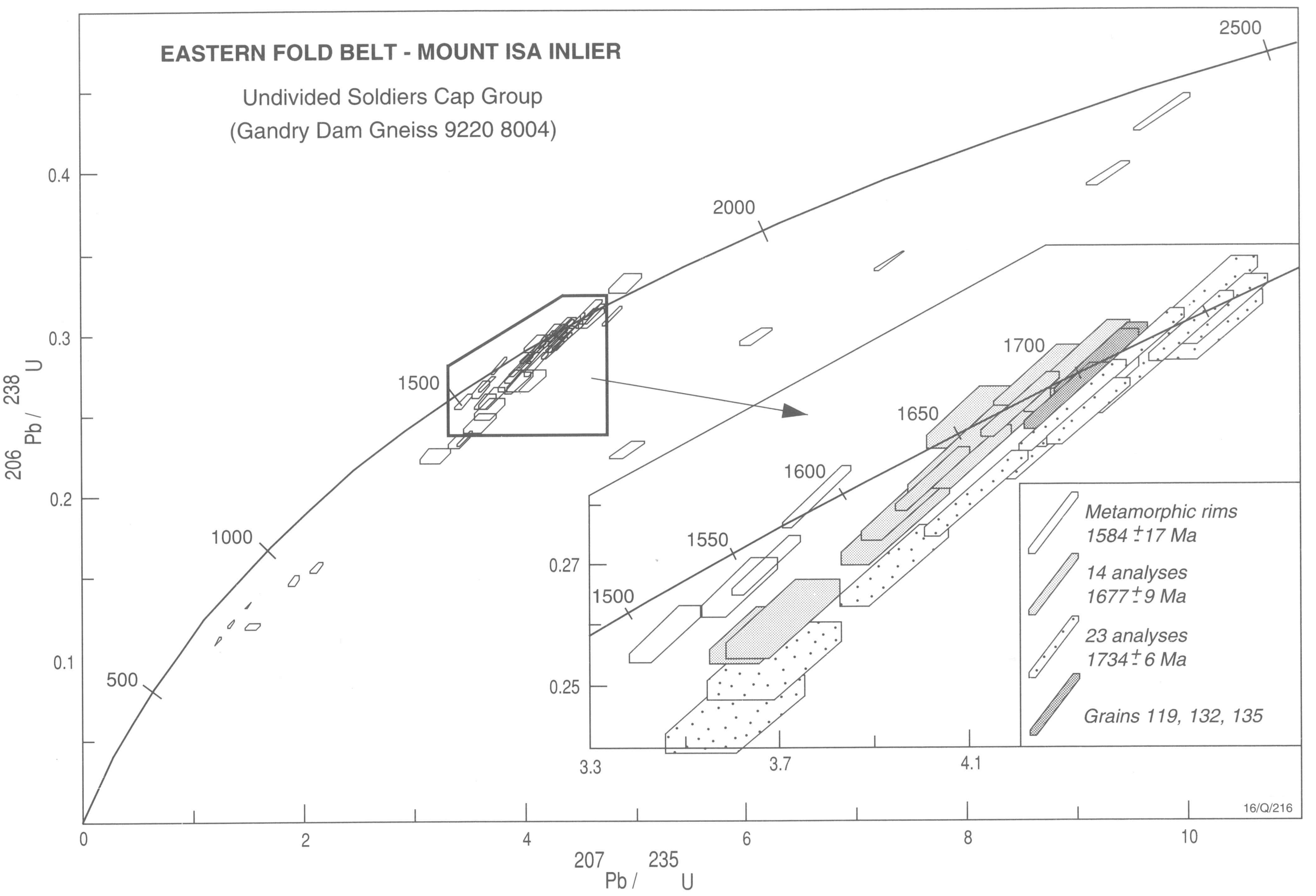


Fig. 4. Concordia plot of zircon U–Pb data from felsic gneiss 92208004. The 1677 ± 9-Ma group has generally high Th/U, and is thought to represent the gneiss's precursor volcaniclastic component, contemporary with the rock's depositional age. Most of the other grains in the gneiss are inherited, and older than this (e.g., 23 analyses at 1734 ± 6 Ma), but a few high-uranium overgrowths are metamorphic in origin, and have a clearly younger isotopic age of 1584 ± 17 Ma.

euhedral. This group of data is coherent in $^{207}Pb/^{206}Pb$, and has an age of 1677 ± 9 Ma. This probably represents the age of a volcaniclastic component contemporary with the depositional age, or it might represent the age of an immature detrital component if the rock is a paragneiss. This cannot be determined from the present petrological or geochronological information.

The 1677 ± 9-Ma result provides a maximum depositional age for this part of the sequence, and indicates that the metamorphosed rocks in the Eastern Fold Belt might be much younger than hitherto considered. At least this part of the Eastern Fold Belt is similar in age to cover sequence 3 in the Western Fold Belt, which includes the Mount Isa Group — host to the Cu and Pb–Ag–Zn orebodies at the Isa and Hilton mines. The 1677 ± 9-Ma age is also indistinguishable from the age of the Broken Hill Pb–Zn deposit (Page & Laing 1992).

The stratigraphic relationship between the Soldiers Cap Group and adjacent Doherty Formation has been uncertain, but the favoured interpretation (Blake et al. 1984) has been that the Soldiers Cap Group is overlain unconformably by and locally interfingers with the Doherty Formation. However, the Doherty Formation has been dated at ca 1725 Ma, and hence is stratigraphically below 1677 ± 9-Ma Soldiers Cap Group rocks. A corollary is that the Cloncurry Fault, which generally separates the two units, might be a normal fault, rather than a thrust as previously thought.

A minimum age for these gneisses has been derived from a few high-uranium metamorphic overgrowths that are present as thin selvedges around some grains. All such overgrowths are finely zoned; advanced overgrowths have produced ovoid grains. The distinctive Th/U in these overgrowths (0.004–0.04) is more than ten times lower than in the cores. Some of the rim analyses are discordant and/or contain high common Pb, but four that are subconcordant form a group defining an age of 1584 ± 17 Ma. This is considered to date the time of zircon overgrowth, and therefore provides an age for the high-grade metamorphism in this region. It is consistent with age constraints for major deformation/metamorphism determined farther west in the Inlier, and also with the local constraint that these rocks are part of a suite that is intruded by the post-tectonic Williams Batholith (ca. 1500 Ma).

The interest, collaboration, and logistic support of a number of mineral exploration companies and the James Cook University of North Queensland have contributed to the determination of these results, which provide the best evidence so far for understanding and correlating the stratigraphy and metamorphism of the Eastern Fold Belt.

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

The relationship between granite composition, host rock types, and Au ± base-metal mineralisation in the Cullen Mineral Field, Pine Creek Inlier

The Cullen Mineral Field, southern Pine Creek Inlier, has been a major centre of metal production, mainly for Au, Ag, Pb, Cu, Sn, W, and Fe. It is underlain mainly by the Cullen Batholith, and a magmatic source for some of the metals is indicated, particularly fractionated leucogranites. Chemical analyses show that U, Sn, and W deposits are more common near the most fractionated leucogranites, whereas the precipitation of Au, Cu, Ag, Pb, and Zn is influenced by the presence of specific host rocks up to 3 km from a pluton boundary.

Broad variations in granite[1] composition in the Cullen Mineral Field

The Cullen Batholith comprises three broad granite groups (Fig. 5):

- leucogranite-dominated plutons;
- granite-dominated plutons; and
- concentrically zoned transitional granite- to leucogranite-dominated plutons.

Chemical variation within the plutons is controlled by the mineral phases present, particularly hornblende, biotite, muscovite, apatite, zircon, and allanite. Relative abundances of these minerals change systematically with progressive fractionation. Each zoned or granite-dominated pluton has its own chemical characteristics, which for some are strikingly dissimilar to any other pluton in the Batholith.

[1] 'Granite' herein covers the broad spectrum of granitic rocks, including diorite, granodiorite, adamellite, and granite (*sensu stricto*).

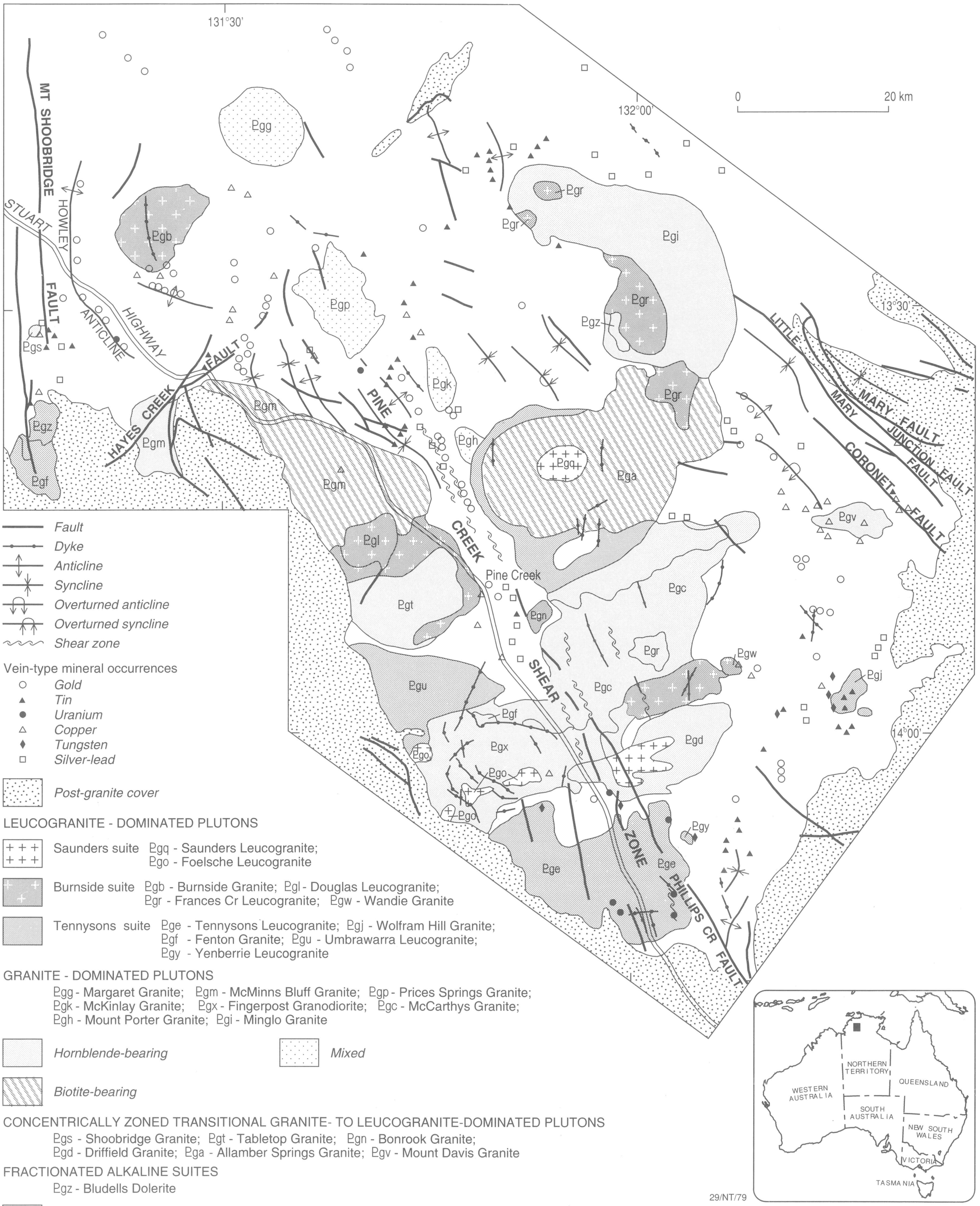


Fig. 5. Geographical distribution of mineral deposits relative to granite type for plutons in the Cullen Batholith, and major structures (after Stuart-Smith & others, 1993: AGSO *Bulletin* 229).

The chemistry of each sample can also be affected by alteration, which is apparent in all samples and probably responsible for the scatter in most of the geochemical plots (Fig. 6). This ubiquitous alteration is not necessarily a product of hydrothermal reaction resulting from magmatic processes, as many samples that were analysed and/or dated were both highly deformed and metamorphosed. Deformed samples in the dominant Pine Creek Shear Zone (Fig. 5) have a definite chlorite-grade overprint related to deformation, whereas samples near the Hayes Creek Fault have a biotite-grade overprint.

Chemical characteristics of the main groups

Leucogranite-dominated plutons are chemically characterised by having >70 wt% SiO_2. Three suites can be identified (Fig. 5) according to the degree of fractionation with increasing SiO_2:

- ***Saunders suite***
  - — relatively small increases in Rb (<240 ppm), Li (<28 ppm), U (<13 ppm), and Y (<26 ppm), and no sign of decreasing K/Rb, with increasing SiO_2;
  - — alumina saturation index (ASI; Zen 1986: *Journal of Petrology*, 27, 1095–1117) = <1.1; $Fe_2O_3/(FeO + Fe_2O_3)$ = >0.24 (Fig. 6);

— no associated vein mineralisation; one nearby alluvial tin occurrence.

- ***Burnside suite***
  — exponentially increasing Rb (<390 ppm), Li (<102 ppm), U (<35 ppm), and Y (<70 ppm), and decreasing K/Rb, with increasing SiO_2;
  — ASI = mostly <1.1; Fe_2O_3/ ($FeO + Fe_2O_3$) ranges from about 0.3 to 0.1 (Fig. 6);
  — one associated vein molybdenite occurrence in granite; numerous vein Au, Cu, Sn, Ag–Pb occurrences and deposits in surrounding contact aureoles.
- ***Tennysons suite***
  — exponentially increasing Rb (<392 ppm), U (<20 ppm), Y (<64 ppm), and Li (<90 ppm), and decreasing K/Rb, with increasing SiO_2;
  — ASI = >1.1; Fe_2O_3/ ($FeO + Fe_2O_3$) is generally <0.24 (Fig. 6);
  — hosts many vein U, Sn, W, topaz, fluorite, and monazite occurrences.

Granite-dominated plutons can be divided into hornblende-dominant and biotite-dominant varieties in the more mafic samples; as it increases, the SiO_2 content at which hornblende disappears facilitates further subdivision. The two distinct chemical end-members are represented by the hornblende-dominated Fingerpost Granodiorite, which has hornblende present up to 69 wt% SiO_2, and the biotite-dominated eastern pluton of the McMinns Bluff Granite, in which hornblende is present only up to 64 wt% SiO_2. For a given SiO_2 value, the hornblende-dominated plutons are enriched in MgO, CaO, Na_2O, Ni, and Cu, and depleted in K_2O, total Fe, TiO_2, Al_2O_3, Li, Zn, and F relative to the more biotite-enriched plutons. Accessory minerals also affect the compositions of the plutons. The early hornblende-rich plutons are low in Zr and P_2O_5, presumably because zircon and apatite crystallise late from the melt. La and Ce are high in those samples that have allanite, which appears to be more common in the biotite-rich coarse granite samples with ASI <1.1.

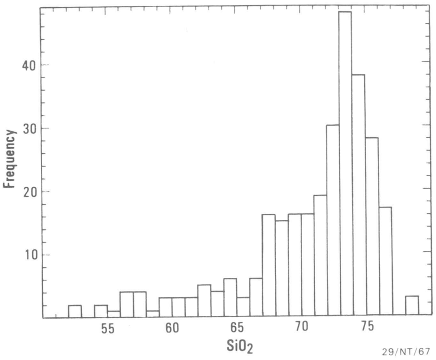


Fig. 7. Histogram of SiO_2 variation in the Cullen Batholith.

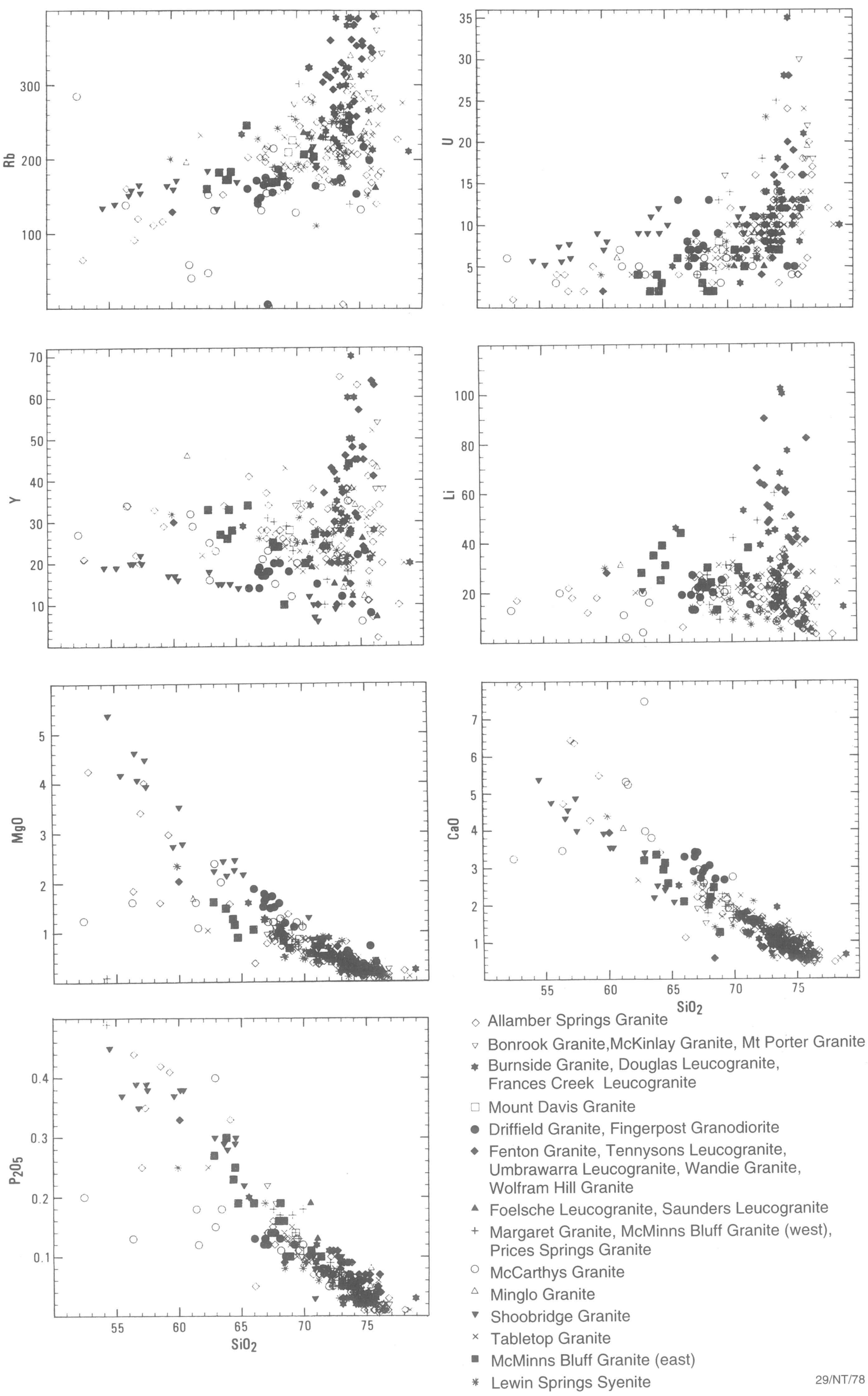


Fig. 6. Harker variation diagrams for the various plutons of the Cullen Batholith.

Concentrically zoned transitional granite- to leucogranite-dominated plutons contain a wide range of SiO_2 contents. The mafic end-members show similarities to either the hornblende- or biotite-dominated suites, whilst the more felsic end-members show characteristics of at least one of the leucogranite suites.

Metallogenic implications of fractionation in the Cullen Batholith

High, exponentially increasing Rb, U, Li, and Y, and decreasing K/Rb ratios, as SiO_2 increases characterise chemically fractionated I-type granitic suites. Fractionation in the Cullen Batholith, in which the SiO_2 content has a wide range (53 to 78 wt%; Fig. 7), could have induced the concentration of elements of economic importance. The Cullen Batholith also has a fairly wide and high-temperature contact aureole, implying that the initial emplacement temperatures were high, and that the granite introduced significant heat into the local environment.

Mineral deposit types appear to be associated either within or surrounding particular granite types according to their degree of fractionation (Figs. 5 and 8), particularly for the leucogranite suites. The Saunders suite is the least fractionated of the leucogranite suites and is unmineralised. In contrast, the relatively oxidised Burnside suite shows some signs of fractionation and has the greatest range of mineralisation types in the nearby contact aureoles; and the most fractionated and relatively reduced Tennysons suite has vein mineralisation associated with it — particularly Sn, W, and U.

Cu, Au, Pb, Ag, and Zn deposits are mostly located in contact aureoles. Some of the more distal of these deposits cannot be easily related to a particular granite pluton, especially as Au, Pb, and Zn can occur up to 3000 m from a pluton boundary. Precipitation of these metals appears to reflect interaction with a specific host rock. Au deposits are hosted by either reduced carbonaceous mudstone or pyritic chert-banded dolomitic rock in the contact aureole (e.g., Koolpin Formation, Mount Bonnie Formation), whereas Pb and Zn are mainly hosted by carbonate-rich rocks (e.g., parts of the Koolpin Formation). Small Cu deposits are associated with the zoned plutons, particularly those rich in hornblende. Though they are hosted by similar lithologies to the Au deposits, they are not spatially associated with Au deposits, and are confined to within 1500 m of granite boundaries.

Mineralogy is a controlling factor on a country rock's potential to host a particular kind of mineral deposit in the Cullen Mineral Field. This control can be demonstrated with reference to recent results from proton-induced X-ray emission (PIXE) analysis of fluid inclusions from other granite-related ore systems. Analyses of coexisting magmatic brine and vapour inclusions in the Mole Granite in New England (Heinrich et al. 1992: *Economic Geology*, 87, 1566–1583) and the Kidston Au-rich breccia pipe (Heinrich et al. 1993: *Geological Society of Australia, Abstracts*, 34, 28–29) suggest that sulphide-complexed Cu and (by inference) Au are preferentially transported in the magmatic vapour phase, whereas Cl-complexed Fe, Mn, Pb, and Zn are preferentially transported in the brine. The sulphur-enriched vapour phase, which can transport significant amounts of Au, will have a low viscosity, and hence has the capacity to move considerable distances from the pluton boundary. This would explain why the Au deposits associated with the Cullen mineralisation are up to 3 km from the nearest pluton boundary.

The implications of the PIXE analyses are that Pb and Zn will be preferentially hosted by carbonate-bearing lithologies, and that Au will be precipitated in reduced rocks, such as graphite-, sulphide-, and magnetite-bearing lithologies, which are common in the Koolpin and Mount Bonnie Formations. The Burrell Formation in the Mount Todd district is also graphite-rich in places (Kim Hein, PhD student, University of Tasmania, personal communication 1993), and should be more seriously considered as a prospective host for Au. To be effective, exploration for Au should focus on rocks with an abundance of minerals such as graphite, magnetite, or sulphides, rather than targetting specific stratigraphic units, particular lithologies, or rocks of a specific age.

More detailed information is available in the newly released AGSO *Bulletin* 229, 'The geology and mineral deposits of the Cullen Mineral Field' by P.G. Stuart-Smith, R.S. Needham, R.W. Page, & L.A.I. Wyborn.

For further information, contact Dr Lesley Wyborn or Dr Peter Stuart-Smith (Minerals & Land Use Program) at AGSO.

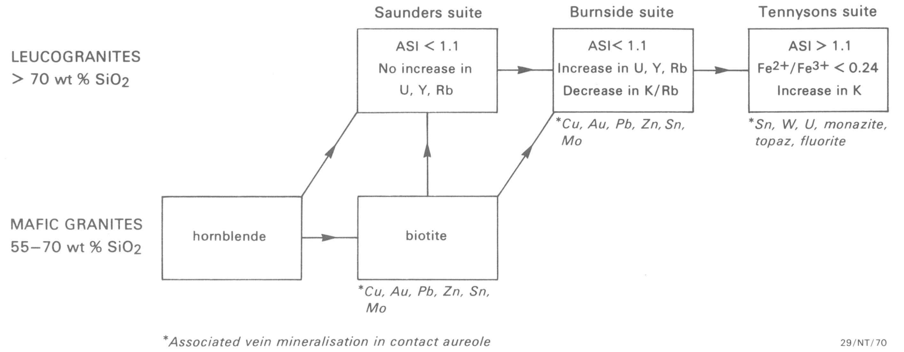


Fig. 8. Relationship between mineral deposit type and fractionation pathway.

Environmental monitoring strategies and non-renewable resources, offshore Sydney

In September–October 1992, AGSO conducted a joint survey, aboard RV *Rig Seismic*, of the continental shelf off Sydney and between Newcastle and Wollongong with the University of Sydney (Departments of Geology and Geophysics), the Ocean Sciences Institute (OSI), the Water Board (Sydney), and the Geological Survey of New South Wales (GSNSW). The survey integrated several disparate components, including elements of environmental monitoring and evaluations of non-renewable resources, that focus on ecological sustainability.

An assessment of the nutrient status of coastal-zone sediments offshore from Sydney was made with the Water Board. The data indicate that aerobic metabolism is prevalent in interfacial sediments, which are depleted of oxygen at depths of about 1 cm. These data will assist an evaluation of the capacity of the sediments to accommodate organic matter, and associated nutrients, from ocean-outfall discharges.

Many sediment samples, collected by the Water Board and University of Sydney from nearshore to the edge of the continental shelf, will be used to assess the possible long-term impact of anthropogenic materials transported from the coastal zone. They will be analysed for several heavy metals and organic toxicants. Baseline concentrations of these compounds will provide a database which can be used to assess long-term environmental change. As part of the sediment-geochemistry program, pore waters were carefully separated from the sediments to investigate diagenetic, natural processes controlling the distribution and concentration of metals in sediments.

The continuous-geochemical-tracer capability aboard *Rig Seismic* was used to trace the dispersion of hydrocarbon plumes from Sydney's ocean outfalls (at Bondi, Malabar, and North Head) into the coastal zone. Sewage discharged from the ocean outfalls is indicated by elevated methane concentrations (Fig. 9); other anthropogenic hydrocarbons which appear to be emanating mostly from Botany Bay are characterised by elevated C2+ hydrocarbon abundances. The depletion of oxygen (Fig. 9) from the vicinity of the ocean outfalls indicates that organic matter and nutrients are being recycled in the water column (as distinct from the sediments). These data will also contribute to an evaluation of the coastal zone's capacity to accommodate anthropogenic organic matter and nutrients.

A systematic and comprehensive geological program conducted by the University of Sydney, OSI, and GSNSW between Port Stephens and Wollongong has provided data that can be used for both environmental and non-renewable resource assessments. Sediment cores and high-resolution seismic data from the continental shelf have provided new insights to processes controlling the distribution of sediments on the shelf. The same cores are also being used to assess past climatic change — especially the extent of low sea levels during the last glacial — and heavy-mineral occurrences in continental-shelf sediments. The mineral resource potential is greatest on the inner shelf, where large discrete deposits of clean sand could provide a source of marine aggregate.

An extensive collection of rocks dredged from the continental slope has helped us reassess the stratigraphy and development of the offshore Sydney Basin. Triassic 'basement' rocks were dredged at more than one location. Upper Cretaceous rocks were dredged at a number of locations, and significantly show high TOC contents and evidence of active fluid-based diagenesis; these data have implications for the fluid history of the basin. The Upper Cretaceous rocks reflect shallow-marine sedimentation, and are variously quartz-rich to volcaniclastic. Thick Upper Cretaceous sequences are apparent on the continental slope. Dredged lower Cainozoic facies consist of greensand-carbonates; since the Eocene, they appear to have subsided from shallow-water depths to depths >3600 m. These data have important implications for Sydney Basin gas and coal exploration, and also for the prospectivity of the Lord Howe Rise.

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

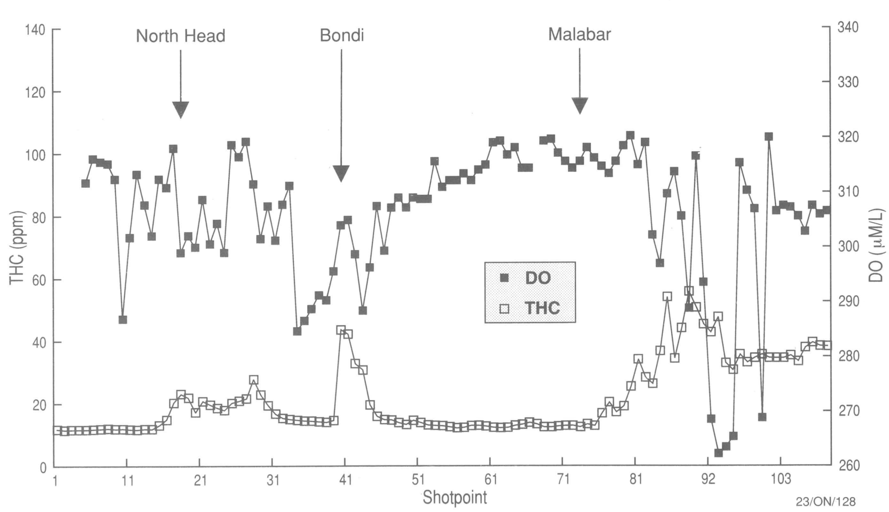


Fig. 9. Total hydrocarbons and dissolved oxygen at a water depth of 25 m along a 35-km traverse in the vicinity of the ocean outfalls, offshore Sydney.

Correlation of structurally disrupted layered ultramafic–mafic intrusions in the East Kimberley

Is Big Ben part of the Panton intrusion?

Recent field mapping by AGSO in collaboration with the Geological Survey of Western Australia has identified a previously undocumented Lower Proterozoic layered ultramafic–mafic intrusion that contains some of the thickest chromitite layers known in the East Kimberley. Similarity in geological setting and reconstructions of pre-faulting structures indicate that the Big Ben body might be a transposed tectonic slice of the Panton intrusion, which hosts one of the largest resources of platinum-group elements (PGEs) in Australia. The East Kimberley layered intrusions with the potential for hosting stratiform and remobilised chromium–PGEs–nickel–gold and nickel–copper–cobalt–PGEs deposits, are concentrated in two northeast-trending parallel corridors.

Big Ben layered ultramafic–mafic intrusion

The previously undocumented Big Ben layered ultramafic–mafic intrusion (8 in Fig. 10) crops out near the intersection of a series of north-northwest-trending faults with the Halls Creek Fault system 36 km northeast of Halls Creek. Sinistral displacements of about 15 km along the Panton Fault and nearby parallel faults farther west can account for the offset positions of the Big Ben, Armanda (14 in Fig. 10), and Panton River (15 in Fig. 10) intrusions relative to two northeast-trending parallel metallogenic corridors (described below). Although partly obscured by alluvium, the sinistral faults near the Big Ben intrusion probably extend northwards into the Springvale Fault system (Fig. 10).

The Big Ben body contains one of the thickest sequences of ultramafic cumulates and chromitite layers of the 32 layered intrusions mapped so far in the McIntosh, Turkey Creek, and Mount Remarkable 1:100 000 Sheet areas. It comprises a lower ultramafic zone, ~1500 m thick, of dunite, lherzolite, and tremolite–actinolite rock, and an overlying mafic zone, ~500 m-thick, of mottled anorthosite, gabbro, gabbronorite, and norite (Fig. 11). Steeply dipping chromitite layers occur in both the lower and upper parts of the ultramafic zone. Of greatest economic interest are the chromitites just below the ultramafic–mafic zones contact; they are up to 15 cm thick and crop out for several hundreds of metres along strike. Hornblende–biotite and aplitic granites intrude the ultramafic–mafic zones contact, and in places have disrupted the chromitites.

Stratigraphic and mineralisation features of the Big Ben intrusion are generally similar to the nearby mineralised Panton intrusion (1 in Fig. 10), which contains one of the largest resources of PGEs (2 Mt @ 6 g t^{-1} PGEs + Au and 0.28% Ni;

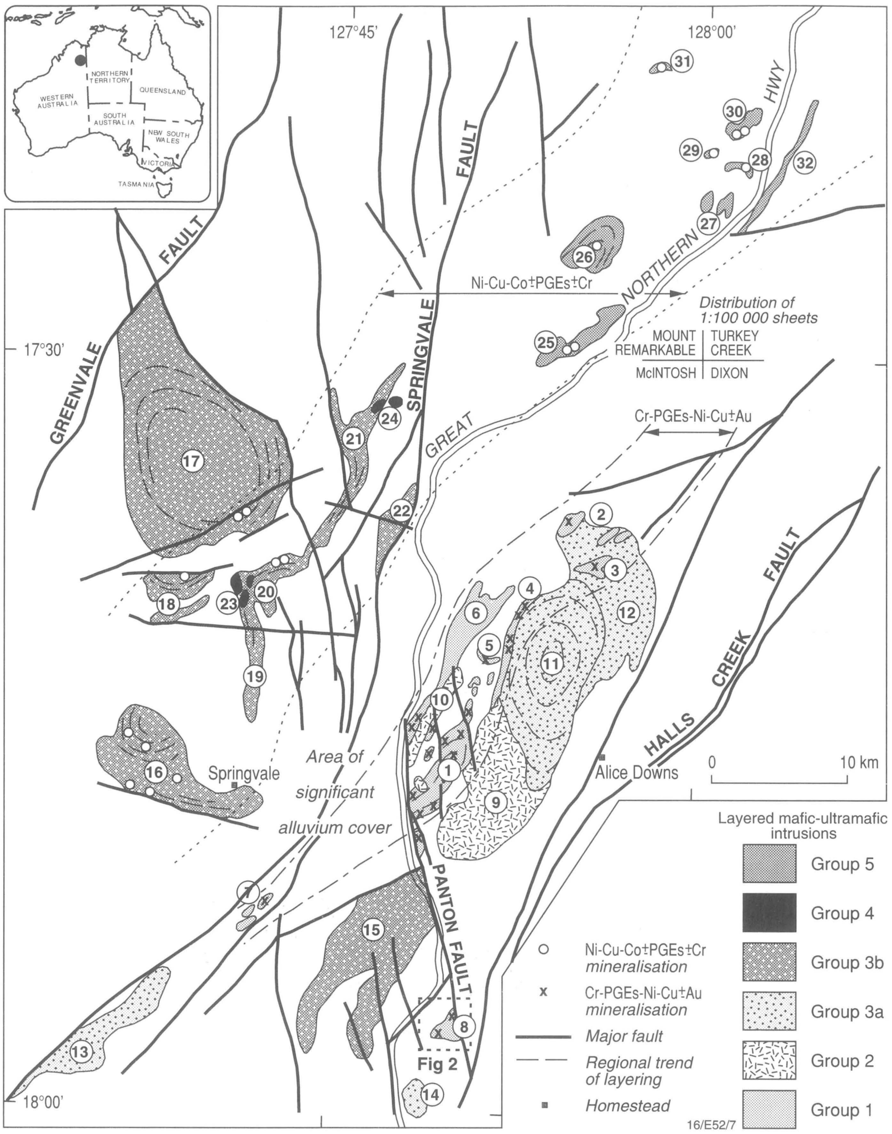


Fig. 10. Regional distribution of Lower Proterozoic layered mafic–ultramafic intrusions investigated in the East Kimberley. The two northeast-trending corridors containing mineralised intrusions are indicated by the dashed–dotted lines. Intrusions shown include: 1 = Panton, 2 = Melon Patch, 3 = South Melon Patch, 4 = West McIntosh, 5 = Mini, 6 = Highway, 7 = West Robin Soak, 8 = Big Ben, 9 = Wild Dog Creek, 10 = West Panton, 11 = McIntosh, 12 = Northeast McIntosh, 13 = Three Sisters, 14 = Armanda, 15 = Panton River, 16 = Springvale, 17 = Toby, 18 = Juries, 19 = Paperbark–Sandy Dam, 20 = Billymac Yard, 21 = Sandy Creek, 22 = Togo, 23 = Black Hills Yard, 24 = Egg, 25 = McKenzies Spring, 26 = Spring Creek, 27 = Tickalara Bore, 28 = Dave Hill, 29 = Three Nuns, 30 = Sally Malay, 31 = Keller Creek, 32 = Fletcher Creek.

Table 1. Classification of layered mafic–ultramafic intrusions in the East Kimberley.

	Type example	*Thickness (km)*	*Form*	*Major rock types*	*Mineralisation documented*
Group 1	Panton	0.2 to 2.0	Steeply dipping folded sheets, faulted blocks	Du, Ha, Cr, Tr–An, Amph, Gab, Gabn, N, AnG, An, Fg	Cr, PGEs, Ni, Cu, Au
Group 2	Wild Dog Creek	0.5 to 2.0	Gently dipping sheets	Mlgab, MtGab, BiotGab, Dior	None
Subgroup 3a	McIntosh	1.0 to 7.0	Dipping sheets, basins, funnels, faulted blocks	OGab, OGabn, Troc, MtGab, AnG, Lherz	Cu
Subgroup 3b	Toby	0.3 to 3.0	Dipping sheets, faulted blocks	BiotGab, OGab, Gab, Troc, AnG, An, Du	Ni, Cu, Cr, PGEs
Group 4	Black Hills Yard	0.2 to 1.0	Steeply dipping plugs	Troc, OGab, OGabn, Gab, BiotGab	None
Group 5	Sally Malay	0.2 to 3.0	Dipping sheets, basins	OGab, Troc, Gab, Gabn, N, AnG, An, Lherz, Du	Ni, Cu, Co, PGEs

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

Perring & Vogt 1991: 'Sixth International Platinum Symposium Field Excursion Guidebook 3', *Geological Society of Australia*, 97–106) associated with a layered intrusion in Australia. Two major differences between the two intrusions are the higher ratio of ultramafic/mafic cumulates and the presence of younger granites in the Big Ben body. However, these could be due to different erosional levels, resulting from dip-slip displacement along the Panton Fault, and to post-faulting granite emplacement. The Cr–PGEs–Ni–Cu ± Au potential of the Big Ben intrusion is enhanced by the apparent absence of exploration activities and its possible relationship to the Panton intrusion. Further geochemical–isotopic studies are required to establish if Big Ben was originally part of the southwestern extension of the Panton intrusion.

Regional distribution of layered intrusions in the East Kimberley

Hoatson & Tyler (1993: *AGSO Research Newsletter* 18, 8–9) introduced a preliminary classification (groups 1 to 3) for large layered intrusions in the McIntosh Sheet area. On the basis of different metamorphic–structural histories and mineralisation features, this scheme is now expanded to five groups (Table 1, Fig. 10), to include younger bodies in the Turkey Creek and Mount Remarkable Sheet areas. The scheme excludes older pre-Group 1 mafic intrusions which generally do not form large layered bodies — e.g., the Woodward Dolerite southeast of Halls Creek, and thin metamorphosed sills in the Tickalara Metamorphics (Dow & Gemuts 1969: *BMR Bulletin* 106).

Group 1 intrusions (including Big Ben) are the oldest layered intrusions recognised in the East Kimberley. They have been deformed by tight, upright, northeasterly trending folds, and have been metamorphosed under lower-amphibolite-facies conditions to form steeply dipping folded bodies up to 2 km thick. PGE-bearing chromitite layers are invariably associated with olivine cumulates just below the interface of the ultramafic and mafic zone, in the basal parts of the ultramafic zone, and more rarely in ultramafic lenses in the mafic zone. Group 2 intrusions form sheet-like mafic bodies that were emplaced after the main metamorphic–deformational event which affected group 1.

Group 3, the most common of the known East Kimberley layered bodies, comprises two subgroups of large basinal and funnel-shaped mafic bodies and smaller fault-bounded blocks; they intrude the Tickalara Metamorphics and group 2 intrusions east of the Springvale Fault (subgroup 3a) and the Bow Granite batholith west of the fault (subgroup 3b). The temporal relationships between these subgroups are unclear because stratigraphic marker units west of the Springvale Fault are lacking. Subgroup 3b intrusions have anomalous Ni–Cu–PGEs concentrations associated with disseminated chromite in plagioclase-rich cumulates (anorthosite and troctolite) in the lower and upper parts of these bodies.

Group 4 intrusions, troctolite plugs at Black Hills Yard and Sandy Creek, are discordant to biotite gabbros of group 3b; they probably have limited economic potential for base- and precious-metal mineralisation. Mafic–ultramafic intrusions of group 5 in the Turkey Creek and Mount Remarkable Sheet areas contain basal segregations of Ni–Cu sulphides. They generally intrude garnet–cordierite-bearing migmatitic gneisses and folded metagabbroic sills of granulite facies, and, in turn, are intruded by small irregular bodies of fine-grained norite. The sulphide-rich character of group 5 intrusions contrasts with the more chromite-rich nature of the older intrusions to the south.

The East Kimberley mineralised layered intrusions display regional spatial relationships (Fig. 10) that provide a powerful exploration tool. The group 1 intrusions with potential for stratiform chromite-associated PGEs–Ni–Cu ± Au deposits are restricted to a narrow northeast-trending corridor in the McIntosh Sheet area. Groups 3b and 5 intrusions with potential for remobilised Ni–Cu–Co ± PGE sulphide segregations near their basal contacts occur in a parallel and larger corridor 8 km farther northwest. The regional distribution of the mineralised intrusions also indicates that mafic–ultramafic magmatism in the Halls Creek Orogen generally occurred progressively later towards the northeast, and that PGE-sulphide associations appear to have become dominant with time relative to PGE-chromite associations. Hoatson & Tyler (1993) provide more detail on the emplacement mechanisms and economic potential of these intrusions.

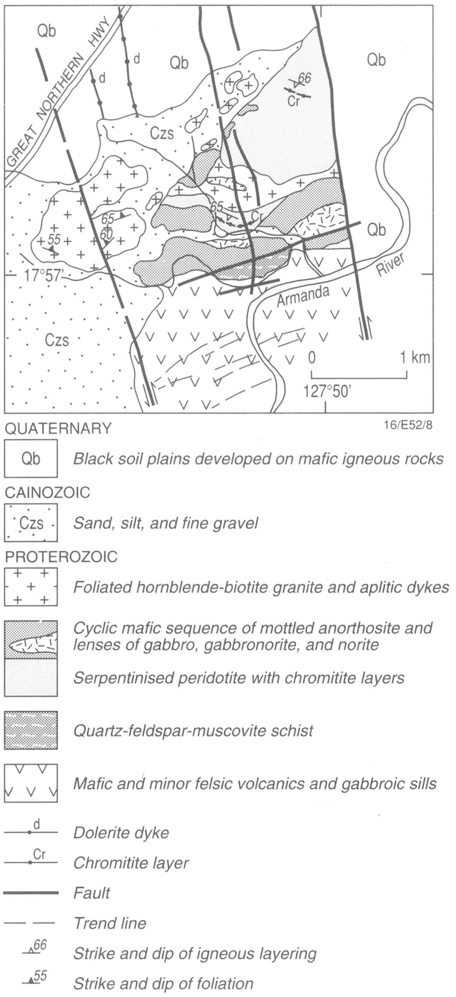


Fig. 11. Preliminary geology of the Big Ben ultramafic–mafic intrusion.

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

Mapping natural hazards

Geological hazards in the Australian region have caused billions of dollars worth of damage to property and agricultural lands, disruption of communities, and losses of human life measured in the tens of thousands. Yet how much information is available on these destructive events and how easily is it obtainable? Where and how often do these events take place? Can the magnitude, intensity, and frequency of the events be recorded in such a form that they can be used to mitigate the effects of such hazards in the future? These questions underpin an effort begun recently in AGSO to map and assess the nature of geological hazards in the southwest Pacific and southeast Asian region. This effort is being undertaken against the backdrop of the 'IDNDR'.

The United Nations has designated 1990–1999 as the International Decade for Natural Disaster Reduction (IDNDR). The objective of the Decade is to reduce, through intensive international action and especially in developing countries, the loss of life, property damage, and economic disruption caused by natural disasters. The goals are wide-ranging, but they include devising guidelines for applying scientific and technological knowledge to mitigate the effects of natural hazards. The Prime Minister announced on 21 April 1989 that Australia would participate in IDNDR activities, and announced the formation of an Australian Coordination Committee chaired by the Director–General of Emergency Management Australia (EMA, formerly the Australian Natural Disasters Organisation). This Committee consists of members from a wide range of governmental, academic, scientific and community organisations, and is responsible for coordinating IDNDR activities of both governmental and non-governmental organisations in Australia.

AGSO is participating in IDNDR activities through a natural-hazards mapping project. This includes the mapping of meteorological hazards as well as geological ones, and involves contributions from scientists from several other organisations — including the Australian Bureau of Meteorology, Macquarie University, and the University of New England. The natural-hazards mapping is coordinated through a Natural Hazards Map Working Group, consisting of 14 members, who meet annually at the Australian Emergency Management Institute, Mount Macedon (Vic.). Attendance at the meetings is supported through the generosity of EMA.

Four different maps are planned for production during the Decade. The first will be a 1:10-million map of natural hazards in the southeast Asian and southwest Pacific region, including Australia. The United States Geological Survey will publish it as part of the Southwest Quadrant series of geoscience maps produced by the Circum-Pacific Council for Energy and Mineral Resources through the Council's Circum-Pacific Map Project. The map will be compiled digitally in AGSO, using the partial support of a grant from the Australian Coordination Committee for IDNDR. An attempt is being made to depict the following three groups of hazard types on the map:

- group 1: earthquakes, volcanoes, tsunamis, cyclones, and landslides;
- group 2: severe storms, droughts, floods, and bushfires; and
- group 3: wave heights, pack ice and icebergs, and superstructure ice.

Group-1 hazards are the easiest to represent, as data are available throughout the region. Group-2 hazards can be represented on the map for Australia, but less well (if at all) for the remainder of the region because of difficulties in accessing any existing data. Group-3 hazards are less important, but are easily represented on the map because they occupy the Antarctic parts, and therefore will overlap little with hazards represented in the central and northern parts of the map.

Major challenges in the design of the map include representing many different hazard types on the same map, and representing those hazards (for example, landslides) that are best represented at a larger scale.

The second map under consideration is a 1:5-million natural-hazards map of Australia. Compilation of the two other planned maps will depend heavily on data availability. They are a 1:10-million natural-hazards-risk map of the Southwest

Quadrant; and a multihazard-potential map of the Southwest Quadrant, in which the difficult problem of ranking and combining different natural-hazard types would be tackled (the idea would be to represent the 'hazardousness' of different areas by a single parameter, or factor, and then to contour the entire region).

The availability of data on several important natural hazards is a serious problem for the Australian region. Digitally based data are available for hazards such as earthquakes and cyclones, but information on other hazard types is dispersed widely, non-digitally, and, for some, obscurely. These limitations affect the ability to assess the past impact of different hazard types in the region. There is a clear need to attempt to collect or network data digitally using a national geographic information system (GIS), including hazard data for the remainder of the southeast Asian and southwest Pacific region. AGSO and the Bureau of Meteorology recently made a commitment to explore jointly the possibility of establishing a national GIS network for natural hazards that could serve as a resource for emergency services, land-use planners, the insurance industry, and other groups concerned with the impact of natural hazards. A national natural-hazards GIS network would represent a major achievement of the Australian IDNDR effort.

For further information contact Dr Wally Johnson (Environmental Geoscience & Groundwater Program, AGSO).

Earth science and environmental diversity in the Jervis Bay area

An understanding of the Earth sciences is fundamental to an appreciation of the processes that form landscapes above and below sea level. Landscapes provide the framework for the several ecosystems in Jervis Bay and its catchment area of coastal southeast Australia. This area lies in the southern part of the Permo-Triassic Sydney Basin (Fig. 12). It is underlain by Lower Permian clastic rocks cut by Upper Permian minor dolerite intrusions, and unconformably overlain mainly by a surficial cover of Quaternary sand and clay (Fig. 13). Our geological understanding of this part of the coast is the key to providing an effective response to the environmental problems that affect it.

Landscapes

Erosional landscapes. Precipitous cliffs face the open sea along the east coast of Bherwerre and Beecroft Peninsulas and Bowen Island; Steamers Head has the highest sea cliffs (135 m ASL) along the New South Wales coast. Cliffs, caves, gorges, stacks, arches, and rocky headlands, commonly fringed by wave-cut platforms, are primarily controlled by prominent subhorizontal bedding and vertical joints in sandstone (Ps).

Most of the catchment is undulating and forested; some has been cleared for rural development. Clearing of native vegetation on gentle terrain with well structured soils is most marked on the Berry Siltstone (Psb), which contrasts with the adjacent valley cliffs (20–30 m high) formed in sandstone (Ps) in the upper reaches of Parma Creek.

Depositional landscapes. Wetlands and tidal creek areas (Currumbene, Moona Moona, and Callala Creeks, Carama Inlet, and small inlets on Bherwerre Peninsula) are characterised by a flat muddy landscape across which meander tidal channels. Mangrove stands, swamps, and salt marshes occur behind prograding sandbars. Bherwerre Peninsula has several sand-dune lakes and swamps — Lakes Windermere and McKenzie, Blacks Waterhole, and Ryans Swamp.

Unconsolidated sediments form beaches and foredunes around Jervis Bay and along Currarong and Bherwerre Barriers. Apart from the sediment source, the dunes rely on a vegetation cover for their stability; their fragility is easily disrupted by human activity or natural processes. In 1974, storms and high tides damaged the frontal dune at Callala beach, and 78 homes built on the dunes were threatened.

The submarine topography is smooth and gently sloping. Quartz sands in Jervis Bay and offshore have high permeability and generally poor exchange capacity, suggesting a depositional environment which promotes 'throughflow of dissolved pollutants, and easy contaminant disposal through the bay and into the open sea. However, pollutants adsorbed on particulate matter (e.g., phosphorous) could be stored in the sediments until released by changes in the water system.

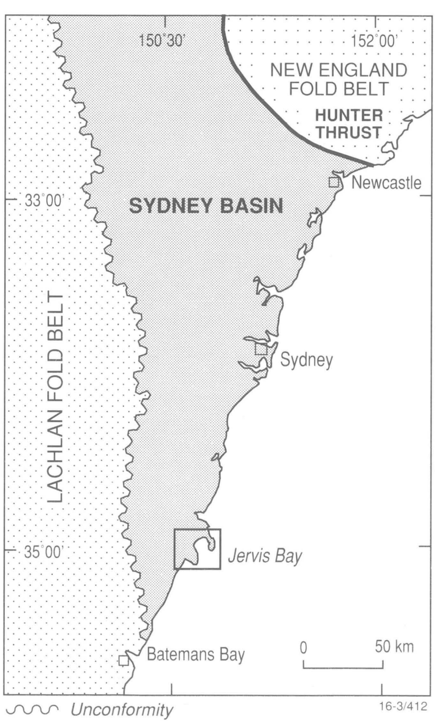
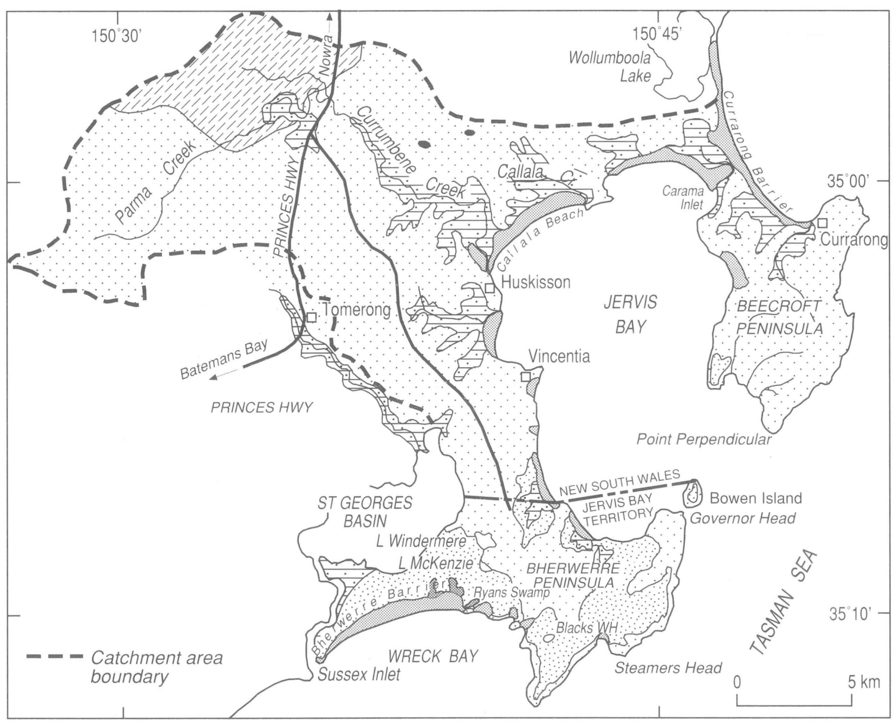


Fig. 12. Location of Jervis Bay.



	UNIT	LITHOLOGY	DEPOSITIONAL ENVIRONMENT	ECOSYSTEM
HOLOCENE	Qhbr	Sand	Dune barrier and beach	Dune landscape: intermittent drainage with perched sand dune lakes; high moisture storage encouraging deep rooting vegetation (forest); permeable sediments permitting low runoff and groundwater pollution. Unstable - easily disturbed by natural and human processes; e.g., storm damage / land-use change
	Qhs	Sand; organic silt / clay Qhs$_1$	Transgressive dunes and claypans	
	Qha	Clay, silt and sand	Alluvial and estuarine	Wetlands: flat muddy landscapes; tidal influences (salt marshes / mangroves); drainage meanders / cutoffs; fragile - acid sulphate soils
PERMIAN	Pd	Dolerite	Marine	Dissected landscapes (habitat corridors): low moisture storage (lithosols) generally supporting heath and open forest; impermeable sediments permitting high runoff and runoff pollution
	Psb	Siltstone; minor shale (Berry Siltstone)		
	Ps	Sandstone and siltstone		

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Fig. 13. Simplified geology, Jervis Bay area.

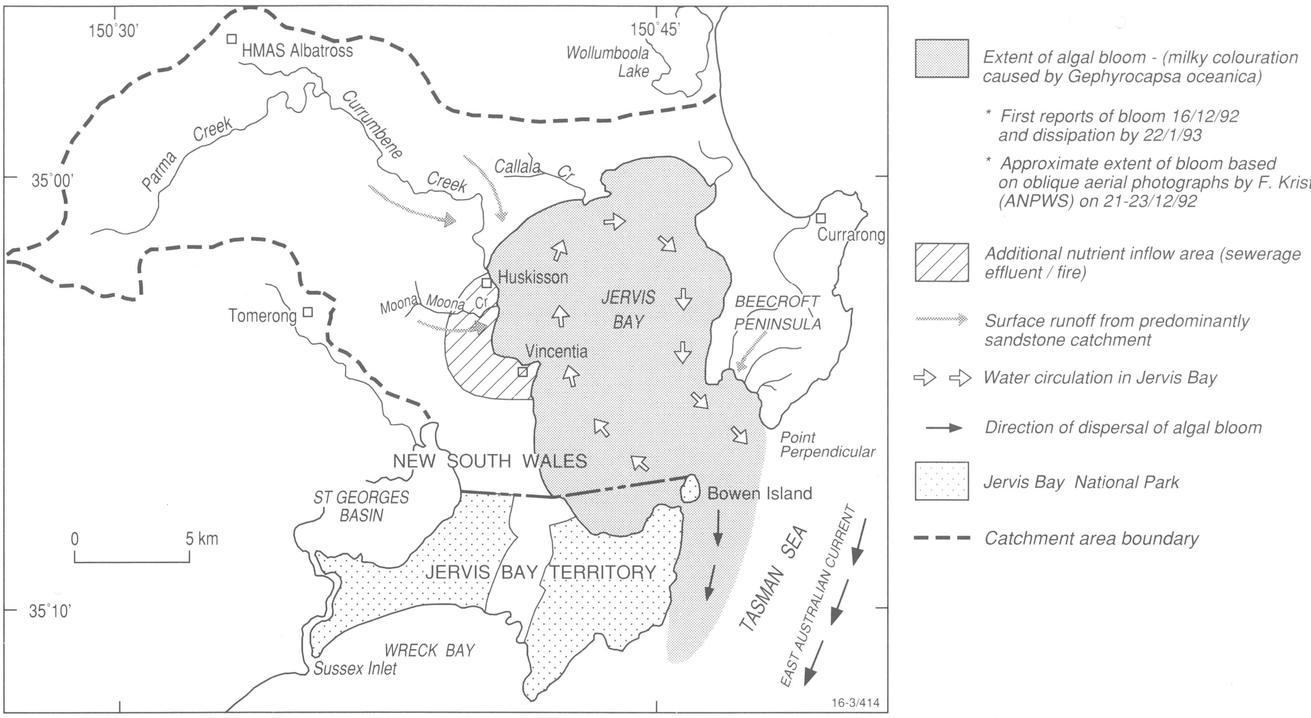


Fig. 14. Algal bloom at Jervis Bay, December 1992 to January 1993.

Hydrology

The Jervis Bay catchment area has high rainfall and vulnerable freshwater resources. Most of it is dominated by considerable but variable surface-runoff processes on lithified Permian sediments (Ps); groundwater is of minor importance. Drainage density and pattern vary considerably, but dense drainage networks generally support high runoff rates on Permian sandstone. Hence, *runoff pollution* is a potential hazard in catchments feeding Jervis Bay. One of the controls is impermeable sandstone exposed in bedrock streams, whose sensitive response to rainfall events results in the quick discharge of nutrients into the bay.

Areas with a deep sand cover have little or no integrated drainage, but contain a valuable groundwater resource. In this environment, *groundwater pollution* may be a problem, notably salt-water encroachment and disposal of septic effluent into the ground. Vulnerable areas are Quaternary dune and barrier sands on Bherwerre Peninsula and adjacent to Jervis Bay.

Ecosystems

Understanding the interrelationships of geology, soils, and hydrology in an area is essential for an appreciation of its ecosystems.

Vegetation and soil moisture. Deep-rooted forests tend to thrive on sand dunes, whose retention of soil moisture assists in recycling nutrients into the ground to promote growth. In contrast, shallow-rooting trees and heath tend to inhabit sandstone areas which have high runoff, low moisture storage (lithosols), and quick nutrient removal.

Acid sulphate soils. Clay-rich soils containing iron sulphide occur mostly in association with tidal wetlands. Disturbance of this sensitive environment by dredging for channel clearing or land reclamation can expose these soils to the air. Oxidation processes release, into watercourses and bays, toxic levels of sulphate and alumina, which might threaten vegetation and aquatic fauna.

Algal blooms. Study of an algal bloom that covered the whole of Jervis Bay in December 1992 (Fig. 14) showed that the dominant alga was probably seeded by the upwelling of the East Australian Current into Jervis Bay (Jacoby 1993: *CSIRO*, unpublished report). The bloom might have resulted from the chance concurrence of transient events: an upwelling of the current into the bay occurred at about the same time as a leakage of sewage at Plantation Point, a bushfire, and major runoff after heavy rainfall. The combination of these events and the geological and topographic characteristics of the system apparently favoured the occurrence and continuance of the bloom.

Palaeoecosystems. Simplified palaeogeographic maps compiled for the Jervis Bay area for the last 140 000 years are applicable to the reconstruction of palaeoecosystems. Thus, if the present-day distribution of a bird species is known — e.g., ground parrots or bristle birds — some speculation on its palaeodistribution can be attempted.

Conservation and management

Mean annual runoff from the Jervis Bay catchment is 300–350 mm from a mean annual rainfall of about 1100 mm. Little use is made of the surface water resources except for the streamflow that maintains Lake Windermere, the main water-supply source for the Jervis Bay Territory. Unconsolidated barrier and dune sands (Qhbr/Qhs) store a valuable but undeveloped groundwater resource. Treated sewage from the Jervis Bay catchment is disposed of mainly into the bay. Onland spreading of some sewage has been proposed, but the suitability of catchment soils for long-term effluent disposal needs to be evaluated.

The small ratio of terrestrial catchment (270 km^2) to bay (120 km^2) helps maintain clear water in Jervis Bay, whose water quality nevertheless is vulnerable to land-use change in the catchment. The catchment should be managed to minimise sediment and pollutant loads. The wetlands and swamps behind barrier sands — important for trapping nutrients — need better protection. Sewage effluent contributes a substantial nutrient load to Jervis Bay; the recent algal bloom might indicate long-term deterioration in the health of the macroecosystem (bay area and its surrounds), and is therefore a matter for public concern.

Groundwater-management issues include the need to protect sand-dune aquifers, particularly in Bherwerre Peninsula. Overpumping near the coast must be avoided to minimise salt-water intrusion into the barrier dune (Qhbr) aquifers. Septic tank systems, and the use of pesticides and herbicides, on or near the highly permeable barrier dunes will need careful monitoring.

Distinctive hydrological features need protection; lakes and wetlands are important scientific and ecological sites. Planning for and managing such features should consider the variety of lake types and their diverse ecosystems. Extensive tidal zones have a distinctive flora and fauna; they need special consideration during land development and in the design and construction of transport lines along the coast. Some of the tidal creeks, such as Carama Inlet, have a small terrestrial input, and will be susceptible to any change in topography or circulation in the bay.

The natural landscapes of Jervis Bay are under constant threat from encroaching environmental pressures created by the competing needs for development land, resource requirements, recreational space, and defence needs. Nevertheless, balanced management to achieve multiple objectives is being attempted by activities of the State and local departments of the New South Wales and Commonwealth Governments. A positive environmental decision was the establishment of a National Park in Jervis Bay Territory in April 1992.

For more information, contact Mr Robert Abell (Environmental Geoscience & Groundwater Program) at AGSO, or Dr Neil Jones (University of Canberra).

Hydrocarbon plumes on the continental shelf

The detection of light hydrocarbons in bottom-water of the continental shelf has been used as a petroleum exploration tool to assess the thermal generation of hydrocarbons in sedimentary basins offshore from Australia and the Philippines. Light hydrocarbons in mid-water plumes of the continental shelf, however, are unusual, and result from a non-continuous, or pulsed, input of

hydrocarbons from sediments to the overlying water. These hydrocarbons are trapped within a stratified water column, and may persist for about one year. Modelling of vertical profiles has provided new insights into the behaviour of light hydrocarbons in sea water, which is pertinent to offshore exploration.

AGSO is carrying out 'direct hydrocarbon detection' studies offshore to assist hydrocarbon exploration. As part of these studies, several vertical profiles of hydrocarbons in the water column have been measured in order to understand the processes controlling the dispersion and survival times — on the continental shelf — of hydrocarbons, which are indicators of subsurface hydrocarbon accumulations. As part of these studies around Australia and in the Philippines, AGSO has determined several vertical profiles of light hydrocarbons in sea water. Some of these profiles from the Philippines are unusual, showing light hydrocarbon anomalies in mid-water plumes (Fig. 15).

The vertical distribution of light hydrocarbons in sea water from around Australia and the Philippines generally can be explained as either a present-day flux of hydrocarbons from the sea-floor, resulting in hydrocarbon concentrations being highest in the bottom-layer and decreasing systematically upwards. The unusual distribution of light hydrocarbons in mid-water plumes is believed to reflect the remnants of a pulsed input of hydrocarbons from the sea-floor. The hydrocarbons are trapped in a mid-water plume as a result of the hydrodynamic conditions in the stratified zone of the water column. The modelling results suggest that surveys on the continental shelf should be carried out during summer months, when the water column is most stratified and any seepage from the sediments will remain trapped in a bottom layer near the sea-floor. During winter months, when seasonal stratification is eroded, particularly in southern Australia, hydrocarbon plumes are rapidly dispersed in the water column, and may be more difficult to detect.

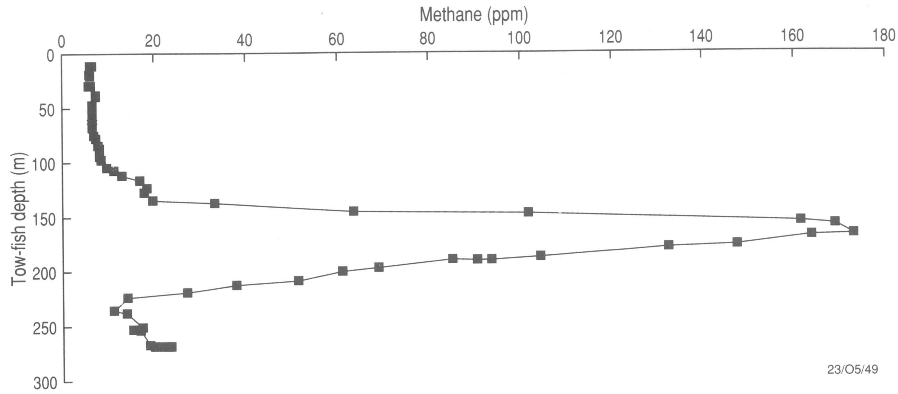


Fig. 15. Vertical distribution of methane for the Ragay Gulf, Philippines.

For further information, contact Drs David Heggie or Andrzey Radlinski (Marine Geoscience & Petroleum Geology Program) at AGSO.

Nd-isotopic 'fingerprinting' of Cu/Au mineralisation in the Lachlan Fold Belt

The Lachlan Fold Belt is currently the focus of a major exploration effort by mining companies searching for magmatically related copper and gold deposits. Exploration budgets in the tens of millions of dollars are being expended, and in the last few years Cu and Au resources approaching $10 billion in value have been delineated, with the promise of much more to come. The main geological environment for this effort is an association of mantle-derived Ordovician shoshonitic volcanic rocks with high copper and gold and low sulphur contents (Wyborn 1990: *BMR Research Newsletter*, 13, p. 8; 1992: *Tectonophysics*, 214, 177–192). Specifically, large subvolcanic intrusive complexes are the engines for such mineralising events, where fractional crystallisation below sulphur saturation leads to a build up of copper, gold, and dissolved fluids in the magma, to the point where fluid evolution occurs. These systems are analogous to those that produced the large deposits in Papua New Guinea and Irian Jaya.

The mantle source for the Ordovician magmatism contrasts with the crustal source for most other magmatism — mainly Silurian to Devonian — whose products occupy about half the better exposed eastern part of the Lachlan Fold Belt. Fractionation in the Ordovician magmas led to the generation of more felsic rocks which have been confused with the younger crustally derived magmatic rocks. Most of the younger magmatic rocks are poor sources of mineralisation, because fractional crystallisation did not operate during their generation.

The neodymium-isotopic method is an ideal technique to apply to the problem of differentiating magma types in the Lachlan Fold Belt, as it sensitively discriminates between different source rocks during melting. It is effectively an index of crustal residence time. Following convention, variation in $^{143}Nd/^{144}Nd$ are presented in terms of deviation from the average chondritic value (CH):

$$\varepsilon Nd_1 = \left[\frac{(^{143}Nd/^{144}Nd)_{sample} - (^{147}Sm/^{144}Nd)_{sample}\,(e^{\lambda T}-1)}{(^{143}Nd/^{144}Nd)_{CH} - (^{147}Sm/^{144}Nd)_{CH}\,(e^{\lambda T}-1)} - 1 \right] \times 10^4$$

A portion of ^{143}Nd of a sample is derived from α-decay of ^{147}Sm (with a decay constant, $\lambda = 6.5410^{-11} yr^{-1}$). Magmas derived from the long-term light-REE-depleted mantle (i.e., with $^{147}Sm/^{144}Nd$ greater than the chondrite value of 0.1967) show positive initial εNd values, whereas crustally derived granites (commonly with $^{147}Sm/^{144}Nd = 0.11 \pm 0.01$) from a source region with long-term (often >1000 Ma) light-REE enrichment have negative εNd values. In practice, the measured $^{147}Sm/^{144}Nd$ of mantle-derived samples can be considerably lower than the long-term $^{147}Sm/^{144}Nd$ of mantle sources, as both subsequent enrichment and partial melting processes can depress this ratio. Also, whole rocks and minerals (such as tourmaline) related to hydrothermal alteration can have $^{147}Sm/^{144}Nd$ different from the host granite.

Lachlan Fold Belt εNd values

S-type granites of the Lachlan Fold Belt typically have εNd values of –6 to –10 at 400 Ma (corresponding to –5.5 to –9.5 at 450 Ma), and I-type granites have overlapping to higher values (0 to –9; McCulloch & Chappell 1982: *Earth & Planetary Science Letters*, 58, 51–64; McCulloch & Woodhead 1993: *Geochimica et Cosmochimica Acta*, 57, 659–674). In contrast, Ordovician shoshonitic rocks at North Parkes have εNd of +5.8 to +7.6 (Whitford et al. 1993: 'Research report for 1991–92', *CSIRO, Centre for Isotopic Studies*, 81–84).

As part of its contribution to the National Geoscience Mapping Accord in New South Wales, AGSO has analysed Ordovician intrusive and extrusive shoshonites regionally from all four volcanic belts defined by Wyborn (1992) — including the important mineral areas of Gidginbung, Lake Cowal, Cadia, Copper Hill, and Forest Reefs (Fig. 16). With the exception of the sample from Gidginbung, all data fall in the same range (+5.7 to +8.0; Sun & Wyborn in preparation), and show that the Ordovician igneous rocks constitute an isotopically unique suite in the Lachlan Fold Belt. The samples include whole-rock volcanics and intrusives, and pyroxene and amphibole mineral separates from both volcanics and intrusives. The data support the evidence from AGSO geochemical data that intrusive rocks associated with the Ordovician volcanics are plutonic equivalents of the volcanics.

Nd-isotopic systematics of alteration assemblages

In addition to carrying out a regional Nd-isotopic survey of Ordovician igneous rocks, we collected data from the likely products of mineralising events associated with these rocks. In particular, we sampled tourmaline-bearing veins and breccias and tourmalinised rock spatially related to Ordovician intrusive complexes but hosted by

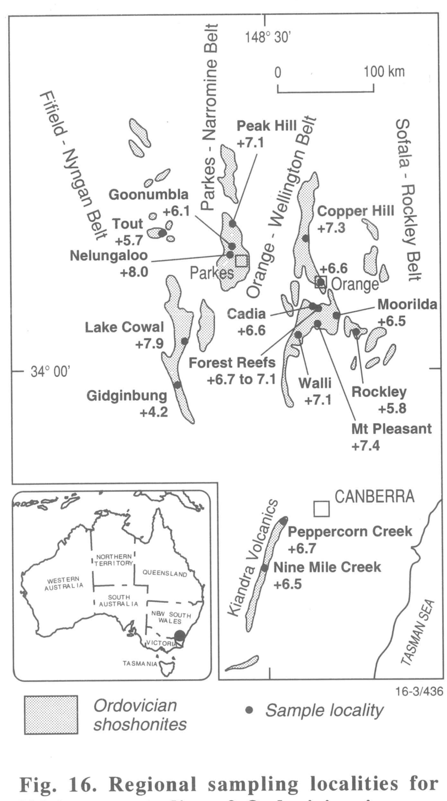


Fig. 16. Regional sampling localities for Nd-isotope studies of Ordovician igneous rocks, and εNd values.

Table 2. εNd results of alteration assemblages in the Lachlan Fold Belt.

Sample number	Locality	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Nd (measured)	Nd at 450 Ma
92844462	quartz–tourmaline vein in Forest Reefs Volcanics	5.08	1.05	0.1253	0.512686 ± 6	+0.70	+4.8
92844508	quartz–muscovite–tourmaline greisen in Forest Reefs Volcanics	72.9	12.5	0.1035	0.512690 ± 7	+0.77	+6.1
92844511	tourmalinised feldspathic ashstone near Cadia	3.41	0.912	0.1618	0.512779 ± 6	+2.51	+4.5
92844521	quartz–tourmaline breccia at Porters Mount, 18 km ESE of Lake Cowal	12.6	2.85	0.1370	0.512806 ± 6	+3.03	+6.5
92844514	quartz–tourmaline vein associated with I-type Carcoar Granite	1.44	0.325	0.1365	0.512387 ± 9	–5.04	–1.6
92843156	tourmaline pebble in Devonian sandstone, Ballarat, Victoria	7.51	1.72	0.1382	0.512081 ± 6	–11.00	–7.7

adjacent and overlying country rocks (Wyborn & others 1992: *AGSO Research Newsletter*, 17, 13–14); for comparison, we also sampled tourmaline-bearing rocks away from the Ordovician complexes. The Nd isotopes should provide definitive constraints on whether or not the one or more episodes of tourmaline alteration reflected in these samples are related to the Ordovician intrusives.

With εNd values only slightly lower than those of the primary shoshonites, the first four samples (Table 1) have a strong affinity with the Ordovician magmatic rocks. It is remarkable that such exceptional rock compositions retain essentially mantle-like εNd signatures, and the results testify to the ability of these systems to fractionate to an extreme degree, thus increasing their metallogenic significance. The εNd values of the last two samples (Table 1), which are unrelated to the Ordovician rocks, show values typical of a continental crustal source.

We can therefore confidently state that the altered rocks are indeed derived from the Ordovician shoshonitic rocks by post-magmatic processes, most likely magmatic fluid evolution. The ore potential of rocks at depth must be greatly enhanced by the presence of these altered rocks at the surface. The Cadia locality is a good case in point: the newly discovered Cadia Hill gold deposit is within a few hundred metres of the tourmalinised zone from which sample 92844511 in Table 1 was acquired, and is more proximal to the centre of magmatism.

Exploration drilling beneath zones of alteration could be greatly assisted by detailed geophysical (magnetic and detailed gravity) studies at the surface. The magnetic method would aim to delineate zones of demagnetisation resulting from alteration during fluid evolution. However, some large areas of Ordovician volcanics have been demagnetised by low-grade regional metamorphism, thus rendering the method less useful. The gravity method, perhaps more promising, would aim to delineate the most fractionated (lowest density) centre of the underlying intrusion, or cupola to a larger intrusion. Cu/Au mineral deposits would be concentrated in the top and immediately above that part of the intrusion, as it is from there that the greatest amount of fluid evolution would have taken place.

Conclusions

The Nd-isotopic method is reliable and cost-effective for differentiating Ordovician shoshonitic magmatism from other igneous rocks in the Lachlan Fold Belt. It is robust to post-magmatic processes. The Ordovician magmatism has a range of εNd values of +5.7 to +8. Quartz–tourmaline alteration zones in proximity to centres of Ordovician magmatism retain a mantle-like signature testifying to the magmatic source of the alteration. These zones upgrade the prospectivity for magmatic Cu/Au mineral deposits, as they are indicators of evolution of fluid from a fractionated Ordovician intrusive complex at depth. Detailed gravity should provide the best method of targeting the source intrusive body; Cu/Au deposits are likely to be located near the upper contact of the body.

Opportunities for collaborative Nd-isotopic investigations

AGSO is seeking expressions of interest from exploration personnel with samples to which the Nd-isotopic method could be applied under the auspices of the National Geoscience Mapping Accord.

For further information, contact Drs Doone Wyborn or Shen-Su Sun (Minerals & Land Use Program) at AGSO.

Pliocene to Holocene stratigraphic chart for Antarctica records a fluctuating ice sheet

A new compilation presents a detailed account of Cainozoic stratigraphic sequences in Antarctica and the Southern Ocean, and on sub-Antarctic islands south of the Antarctic Convergence. Providing a framework for investigating regional climatic, glaciological, and sedimentological events since the start of the Pliocene 5.3 Ma ago, it is an important contribution to the Natural Variability Subprogram of the Cooperative Research Centre for the Antarctic and Southern Ocean Environment (the Antarctic CRC). AGSO is a member of the CRC consortium.

This compilation is in preparation as an AGSO/CRC *Record*. It synthesises research on the sedimentary sequences at 83 sites, and comprises a stratigraphic chart and supporting text. Information on individual sites is available through *Autoref* library accession numbers referred to in the extensive bibliography.

The chart depicts the sequences for all sites. Columns feature lithological symbols developed from those depicted on previous AGSO palaeogeographic maps, and are set against a biostratigraphic framework assembled from high-latitude palaeontological data; the global-average deep-sea oxygen-isotope curve is also shown for reference.

The text outlines the methodology, and provides a detailed summary of glacial events reported in the literature. It also elaborates on the correlations depicted in the chart. A possible breakdown of the described sequences, into time-slices based on correlatable stratigraphic breaks and palaeoenvironmentally significant intervals, is shown in tabular form.

The report is designed to draw attention to the history of Antarctica's late Cainozoic and continuing glaciation, and will provide a basis for selecting time intervals for which palaeogeographic maps will eventually be compiled. It will eliminate the need for a great deal of literature searching, and facilitate rapid assessment of whether events at particular sites were of more than local significance. It should prove to be a valuable aid to research into the history of Antarctic glaciation and its role in the global-climate system. The chart and time-slice maps should help to show regional palaeoclimatic trends.

At this stage in the research, it appears that the East Antarctic ice cap (which covers a continental landmass and is thus described as a *terrestrial* ice sheet) started forming at about the end of the Eocene (36 Ma ago). The smaller West Antarctic ice sheet rests on a rugged bedrock surface that is mostly below sea level and is termed a *marine* ice sheet; it developed during the Late Miocene (less than 11 Ma ago). Hiatuses of Late Miocene to earliest Pliocene age (to about 5 Ma) across the Antarctic region relate to expansion of both ice sheets.

The Early Pliocene, from 5.3 to 3.4 Ma, was a time of relative warmth in Antarctica; as a consequence, sea level rose. Glacially excavated valleys on the Antarctic continent were invaded by the sea and became fjords, and temperate wet-based glacier systems which survived until the mid-Late Pliocene were formed.

Increased cold and aridity in the latest Pliocene and earliest Quaternary resulted in dry-based glacier systems, greater ice-sheet stability, and ice-shelf grounding. Inland or *alpine* glaciers (notably those in the dry valleys of Victoria Land) fluctuated out of phase with ice-shelf grounding because this restricted the availability of marine moisture and therefore reduced precipitation on the continent.

Ice retreat after the last glaciation occurred at different rates in different places, and was accompanied by isostatic rebound. The peak of post-glacial sea-level rise, about 6000 years ago, was followed by increased regional uplift, particularly in coastal areas, which induced a change from marine to lacustrine conditions at many localities. The ice core from Vostok station, in the interior of East Antarctica, indicates that the warmest period of the Holocene was about 9900 years ago, but the warmest conditions on the Antarctic Peninsula and sub-Antarctic islands occurred between about 8000 and 5000 years ago. A number of Holocene warm intervals induced local glacier advances.

For more information, contact Anne Walley, Elizabeth Truswell, or Bob Tingey (Environmental Geoscience & Groundwater Program, AGSO).

Albian and Maastrichtian nannofloral biogeographic provinces in Western Australia

Implications for palaeolatitudes and pole positions for Australia

A continuing study of Albian calcareous nannofloras from the Carnarvon Terrace, offshore Carnarvon Basin, northwest Australia (Shafik *in* Colwell et al. 1990: *BMR Record* 1990/85, 56–82), needed information on Albian palaeolatitudes to help explain the co-occurrence of cool- and warm-water forms: an association of *Seribiscutum primitivum, Sollasites falklandensis,* and *Biscutum dissimilis* (cool-water species), and *Microstaurus chiastius, Hayesites albiensis, H. irregularis,* and *Flabellites biforaminis* (warm-water species). A great range of palaeolatitudes for the Carnarvon Terrace during the Albian, from 28°S to 60°S, has been indicated in papers referring to hot-spot or palaeomagnetic data. Nannofloral assemblages shed some light on the probable range of palaeolatitudes.

According to Barron & Harrison (1980: *Mechanisms of continental drift and plate tectonics*; Academic Press, London, 89–109) hot-spot data suggest a palaeolatitude for the Carnarvon Terrace of about 60°S during the Albian, but the Albian magnetic pole of Idnurm (1985: *Geophysical Journal of the Royal Astronomical Society*, 83, 399–418) indicates a palaeolatitude of about 51°S. Palaeomagnetic data and plate reconstructions in Veevers (1984: *Phanerozoic Earth history of Australia*; Clarendon Press, Oxford) suggest a palaeolatitude of about 45°S, whereas Besse & Courtillot (1988: *Journal of Geophysical Research*, 93, 11791–11808), using plate reconstruction models and palaeomagnetic data, predicted a palaeolatitude of about 41°S. Palaeomagnetic results from a study of Lower Cretaceous cores from the Argo Abyssal Plain (Kodama & Ogg 1992: *Proceedings of the Ocean Drilling Program, Scientific Results,* 123, 549–554) indirectly suggested a much lower palaeolatitude — about 28°S.

Calcareous nannofossils with restricted geographic distribution include many stenothermal forms, which are broadly useful as palaeolatitudinal indicators. This is best exemplified by those species with bipolar distribution, which are absent from low latitudes (e.g., the Barremian–Santonian *Seribiscutum primitivum* and the late Maastrichtian *Nephrolithus frequens*). These are particularly important during those Cretaceous intervals in which the latitudinal climatic differentiation was sharp.

Analysis of calcareous nannofloras from the Australian region, and particularly for the Carnarvon Basin, suggests that the palaeobiogeographic settings for the middle Albian and late Maastrichtian were similar, unlike during most of the intervening intervals. For the Albian and Maastrichtian, three distinct biogeographic provinces — each coinciding with a palaeolatitudinal belt — can be recognised. The middle, or Extratropical Nannoprovince, where cool- and warm-water species coexisted, included the Carnarvon Basin during both intervals, suggesting that this basin lay in the same palaeolatitudinal range — i.e., within the forties and fifties — during the Albian and Maastrichtian. However, a subtle difference in the ratio of cool- to warm-water species between the Albian and Maastrichtian assemblages suggests that the northern Carnarvon Basin (Giralia Anticline–Carnarvon Terrace region) was within the northern half of the Extratropical Nannoprovince during the Albian, and within the southern half of the same province during the Maastrichtian.

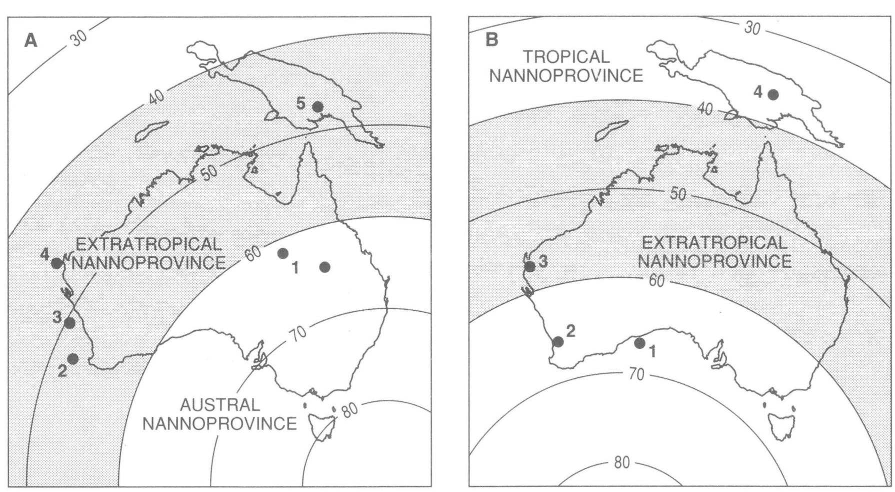
The high-palaeolatitude belt, the Austral Nannoprovince, where the nannofloras comprised abundant cool- but no warm-water species, included the central Eromanga Basin (NE Australia) during the Albian and the Perth Basin (WA) during the late Maastrichtian; it is believed to have covered palaeolatitudes in the sixties. The low-palaeolatitude belt, the Tropical Nannoprovince, which contained abundant warm- but no cool-water nannofloras, included the Papuan Basin (PNG) during the Maastrichtian; it is presumed to have been wide then, covering palaeolatitudes in the thirties.

Albian nannofloras in which the cool-water *Seribiscutum primitivum* is more common than the warmer-water *Microstaurus chiastius* and *Axopodorhabdus albianus* have been recorded from the Naturaliste Plateau (off southwest Australia; Thierstein 1974: *Initial Reports of the Deep Sea Drilling Project*, 26, 619–667). These evidently came from the southern part of the Extratropical Nannoprovince. Coeval assemblages from the central Eromanga Basin contain abundant *Seribiscutum primitivum* and lack warm-water species (Shafik 1985: *BMR Journal of Australian Geology & Geophysics*, 9, 171–181) — characteristic of the Austral Nannoprovince. The nannofloras from both localities indicate that the central Eromanga Basin was at higher palaeolatitudes than the Naturaliste Plateau during the Albian (Fig. 17A). At the same time, the Carnarvon Basin and Papuan Basin, which contain a similar mix of cool- and warm-water Albian nannofossils in equal abundances, were at similar, lower palaeolatitudes in the Extratropical Province (Shafik *in* Colwell et al. 1990; de Leon 1988: *Robertson Research, Report* 1676). This Albian Extratropical Province can also be identified in the Perth Abyssal Plain by the mix of *Seribiscutum primitivum, Hayesites albiensis,* and *Flabellites biforaminis* among the nannofloras recorded by Proto Decima (1974: *Initial Reports of the Deep Sea Drilling Project*, 27, 589–621). The Albian scenario of nannofloral provinces supports the position that Embleton (*in* Veevers 1984) suggested for the south pole of 105 Ma ago — i.e., off present-day southeast Australia at latitude 53.0°S, longitude 158.0°E.

During the Turonian–Campanian, latitudinal differentiation along the western margin of Australia probably was not as distinct as during the Maastrichtian. The Santonian nannofloras in the Perth and Carnarvon Basins are strikingly similar, indicating equable climate and similar water masses (Shafik 1990a: *BMR Report* 295). Early Campanian nannofloras in the Perth Basin include elements suggesting the onset of a climatic deterioration (Shafik 1990a). During the late Campanian–late Maastrichtian, differentiation of the water masses of the Perth and Carnarvon Basins became increasingly marked.

During the late Maastrichtian, the Austral Nannoprovince covered the Perth Basin and western Great Australian Bight (and New Zealand), as indicated by the dominance of cool-water species (such as *Cribrosphaerella daniae, Nephrolithus corystus*, and *N. frequens*) and the absence of warm-water species (such as *Micula murus*; Shafik 1990a; Shafik 1990b: *BMR Journal of Australian Geology & Geophysics,* 11, 437–497). At the same time the Papuan Basin and the Carnarvon Basin were quite different biogeographically, unlike the Albian (cf. Fig. 17A, B). Late Maastrichtian nannofloras from the Papuan Basin include abundant warm-water species (such as *Micula murus*) but no cool-water species, suggesting that it was within the Tropical Nannoprovince (Shafik 1990a). Those from the Carnarvon Basin contain a mix of frequent cool-water species (such as *Nephrolithus frequens*) and rare warm-water species (such as *Micula murus*), a characteristic of the southern half of the Extratropical Nannoprovince (Shafik 1990a). The nannofloras support the position that Embleton (*in* Veevers 1984) suggested for the Maastrichtian south pole of 65 Ma ago — i.e., off present-day southern Australia at latitude 56.0°S, longitude 120.0°E.

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



A:
1 BMR Boulia 3, Tambo 38 - Eromanga Basin
2 DSDP site 258 - Naturaliste Plateau
3 DSDP site 259 - Perth Abyssal Plain
4 Carnarvon Terrace - Carnarvon Basin
5 Hedinia 1x

B:
1 Between the Eyre & Ceduna Terraces - GAB
2 Several localities - Perth Basin
3 Several localities (including the Giralia Anticline) - Carnarvon Basin
4 Mendi area - Papuan Basin (PNG)

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Fig. 17. Palaeolatitudes and nannofloral provinces for the Australian region during the Albian (A) and Maastrichtian (B) based on studies of calcareous nannofloras. The concept that province limits coincide with palaeolatitudes needs testing with more data points.

High-nitrate groundwater in the Australian arid zone

Origin of the nitrate, and possible denitrification technology

A group of researchers from AGSO, the Australian National University, CSIRO, and the Centre for Appropriate Technology has undertaken field trials leading to the development of a solution for one of arid Australia's most persistent water quality problems: high-nitrate levels in groundwater (Fig. 18). In addition to its potential contribution to improved water quality in existing settlements, the work has significant implications for the development of Aboriginal outstation communities. The origin of the nitrate, previously a mystery, now has been elucidated.

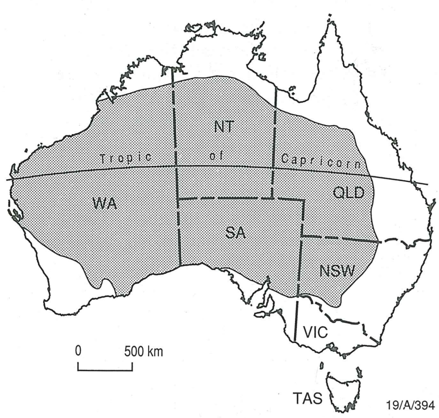

Fig. 18. Approximate extent of the Australian arid zone. Within this vast region most shallow aquifers have high-nitrate concentrations.

In the Northern Territory, recent developments in the granting of title to areas of land on stock routes and reserves, and the excisions program on pastoral leases, will require a major water supply program. This will include the drilling of water-bores in many places which are not favourable for groundwater development. In particular, high-nitrate concentrations, which are a health hazard, are likely to be a major constraint on this program.

Many central Australian groundwater supplies contain high concentrations of nitrate — commonly exceeding the accepted safe maximum limit (45 mg L^{-1}) for human consumption determined by the World Health Organisation (WHO). Many of the communities at risk are Aboriginal settlements, some of which live on water supplies with nitrate levels as high as 200 mg L^{-1}. In the past, many bore-waters have been rejected for domestic use for this reason, and the holes have been back-filled.

Origin of nitrate

The origin of high-nitrate groundwaters in the arid zone has been investigated by the team at two sparsely populated Northern Territory locations — Ti-Tree and Yulara — at which anthropogenic sources of the nitrate can be discounted. Water-bore data from these areas indicate a correlation of high-nitrate groundwater with shallow unconfined aquifers. The aquifer hydrochemistry indicates that the groundwater was emplaced by episodic Holocene recharge events in an otherwise arid-climate regime. The groundwater recharge events occur about every 20 years, and flush nitrate through the unsaturated zone which apparently lacks denitrification activity. The unsaturated zone is typically 10–20 m thick.

Soil profiles were augered at a number of sites reflecting different ecological zones. They showed that the nitrate originates by near-surface biological fixation. The contributing organisms include cyanobacteria in soil crusts, and bacteria in termite mounds. The highest soil-nitrate concentrations were found in the outer skin of termite mounds (Fig. 19). Bacteria associated with the termites appear to fix nitrogen, which eventually appears in inorganic form — principally as ammonia. Nitrate is produced by bacterial oxidation of the ammonia, and is leached to the outside of the termite mound by capillary action. Diffuse recharge from extreme rainfall events then flushes this nitrate to the water-table. Knowledge of the origin of the nitrate will assist the future strategic siting of bore sites.

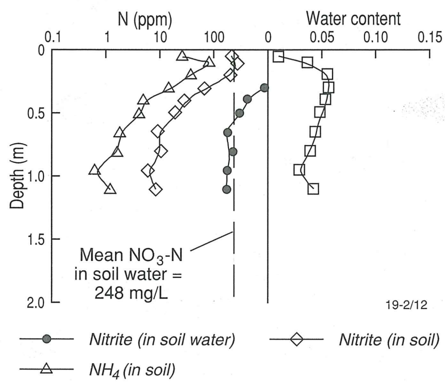

Fig. 19. Nitrate and ammonia concentrations in a soil profile through a termite mound.

Biological denitrification of groundwater

Several mechanisms can be applied to remove nitrate from drinking water — e.g., reverse osmosis, electrodialysis, ion-exchange, and solar distillation. However, all them require a ready supply of power and/or skilled maintenance personnel, neither of which is generally available in small, remote central Australian communities. Biological denitrification is an alternative process, and probably the most appropriate to suit the needs of these communities. It has been successfully developed in many parts of England and Europe, where nitrate — generated from fertiliser — is a serious contaminant of the drinking-water supply.

By combining the ability of denitrifying bacteria to reduce nitrate to nitrogen gas under anaerobic conditions, with some simple plumbing, a low-maintenance 'bioreactor' system can be employed to remove nitrate from these excessively nitrate-rich groundwaters. A bioreactor tested in Alice Springs involves the immobilisation of denitrifying bacteria on an inert support. These bacteria are housed in a reaction chamber, and nitrate-rich water passed through the reactor is denitrified to yield a suitable drinking-water supply. The current system uses the denitrifying bacterium *Hyphomicrobium*. The bacteria are immobilised on a polyurethane support, and maintained on a low concentration of methanol, their carbon-energy source.

Two alternative plumbing systems have been investigated: the 'flow-through' system and 'batch' system. Laboratory tests indicate that the flow-through system totally reduces nitrate, which is given off as gas, and results in nitrate-free water. Difficulties encountered with the design of the methanol (flow-through) dosing system led to a decision to develop a batch-plumbing system. Promising results have been obtained from field trials in which the batch system operated successfully, unattended, for four weeks. This resulted in the daily production of 50 L low-nitrate water (less than 10 mg L^{-1}) from bore-water exceeding 150 mg L^{-1}. The system totally reduces nitrate in groundwater to produce virtually nitrate-free water under field conditions (Fig. 20).

Potential

The communities to be served and their remote nature mean that a number of criteria need to be satisfied in the development of a drinking-water denitrification unit. Some of these criteria include:

- small-volume treatment (20–30 L per person per day);
- low maintenance;
- minimal specialised tools and maintenance equipment;
- maintenance skills easily and quickly learnt;
- reliability;
- ease of transportation;
- ease of installation;
- ready availability of materials; and
- low cost (capital and operational).

With the research phase completed, the next stage is to develop an operational prototype to be installed at a suitable site. Some engineering problems remain to be solved. If the prototype is successful, the bioreactor will find widespread application in small communities in central Australia. There is also the possibility of developing markets overseas where nitrate pollution of groundwater supplies is a serious and growing concern for millions of people.

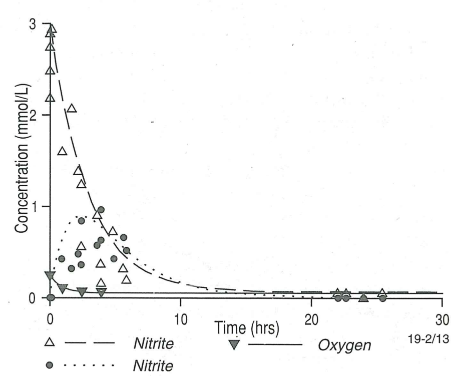

Fig. 20. Results of field trials on a nitrate-rich groundwater, showing nitrate, nitrite, and oxygen levels as a function of time.

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