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Mineral resources of the Australian Antarctic Territory

P.G. Quilty

Comments

R.J. Tingey

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Mineral resources of the Australian Antarctic Territory

Patrick Quilty

Introduction

No subject has heightened interest in Antarctica quite so much in recent times as the question of the continent's potential mineral resource value. Leading magazines such as *Time* and *The Washington Post* referred in early 1983 to immense reserves of iron, coal, nickel, chromium, uranium, gold and the largest oilfields in the world. The sources of these extravagant claims are unknown but they may emanate from a misunderstanding of statements contained in such major compilations as that produced by the Central Intelligence Agency (1978). The first hints that Antarctica could contain valuable mineral deposits came from coal discoveries near the south pole by both Shackleton and Scott expeditions early in this century. Despite the claims referred to above, our knowledge of Antarctic mineral resources has not advanced far although evolution of geological theory and knowledge has provided new bases for attempting some evaluation.

There have been many attempts in recent years to summarise the mineral potential of Antarctica, often prepared in association with comments relating to technological developments required for development or concern for environmental protection in the event of development. Most such compilations concentrate on either minerals or hydrocarbons and generally relate to all of Antarctica. The most comprehensive reviews are those by Holdgate and Tinker (1979), Behrendt (1983), Rowley, Williams and Pride (1983), Ford (1983), Bergsager (1983), Mitchell (1983), Tessensohn (1983) and Gjelsvik (1983). This list is not exhaustive but the comprehensiveness of review and recent publication dates are an indication of the upsurge in interest in the mineral resources of the continent. These papers should be compared with that of Runnells (1970) which was one of the earliest on the topic.

Australians have not often commented on the resource potential of Antarctica but Chalmers (1957), Cameron (1981), Lovering and Prescott (1979) and Tingey (in press) have all made significant contributions to the topic.

Exploration for minerals in Antarctica

In the early days of the existence of the Antarctic treaty, the concerned nations recognised that resource questions would pose severe threats to the treaty itself and thus took positive steps to ensure that the two major resource types — living and mineral — would be the subject of international conventions developed under the umbrella of the treaty.

To date, only the living resources have been the subject of successful convention formulation — the Convention on the Conservation of Antarctic Marine Living Resources. The minerals question took second place in the queue for several reasons:

- living resource exploitation was imminent;
- the mineral resource question raises such difficult matters as sovereignty, some financial benefit to sovereign nations and so on.

It was recognised that the treaty nations must move quickly to the timely adoption of a mineral resources regime and thus discussions were initiated at a meeting in Wellington, New Zealand in June 1982. Five meetings (two formal, three informal) have been held since.

During the interval before a minerals resource regime is brought into effect, the Antarctic treaty nations have agreed to a 'moratorium' — or more properly, a policy of voluntary restraint — on mineral exploitation, although vigorous geological research is being conducted by some Antarctic nations.

A key issue to emerge is that of the difference between scientific investigation and the early phases of mineral exploration. This is a confused area, and the one which involves opinions which reflect national practice. In domestic legislation for example, the United

States allows off-structure deep drilling (with appropriate environmental safeguards) in the prospecting phase of activity, even before leases have been let. This is very different from Australian practice. What is appropriate for home nation practice may not be appropriate for Antarctica.

My response to companies expressing an interest in Antarctic activities is that environmentally 'benign' activities (sample taking, airgun seismic surveys) are allowed so long as done for scientific purposes, the chief criterion being that any results generated should be published as soon as possible and made available to the scientific (and wider) community. No results from such activities can be seen as proprietary information. Only activities conducted in a spirit of scientific enquiry are permitted.

Limits of exploitation

Antarctica is a harsh and isolated environment, in virtually pristine condition. Both factors will impose severe restraints, economic and environmental, on any projected resource development activity on that continent. This review does not address the issues limiting development in Antarctica. The limits are political, technological and economic. I believe that if the political and economic constraints can be overcome, technology will develop quickly if needed.

Hydrocarbon potential of the Australian Antarctic Territory

Organic matter in sediments

Oil and natural gas are now believed to be produced from the breakdown, under diagenetic heat and pressure, of organic matter originally included in a sediment. Approximately 1-2 percent of all sediments consist of organic material, and oil and natural gas are the remains of some 1/16000 of this. Most such matter is oxidised at the site of deposition or is eroded later, either before or after hydrocarbons have been generated, and thus is not part of the story. An average shale contains about 1 percent organic material but some, such as those under the North Sea, contain up to 14 percent and constitute excellent source rocks. For a convenient summary of the origin of petroleum, see Barker (1979). Experience has shown that there is a gross relationship between environment of deposition and the chemistry of the organic matter incorporated. This manifests itself eventually as a relationship between hydrocarbon type and environment of deposition of parent sediments. Most hydrocarbons are produced from the breakdown of plant material and the common portrayal of dinosaurs as an oil source is misleading. The main differentiation we need to consider here is that between aqueous and land plants.

Plants living in an aqueous environment have no need of a waxy coating (or cuticle) to protect them from the dessicating effects of air. In addition they can attain enormous size without major supporting structures; this can be seen to be true in the Sargasso Sea and in kelp. In contrast, land plants, to attain any size must have supporting structures — woody tissues — and they have to have a waxy coating on leaves. These differences have a profound effect on the chemistry of the organic matter which accumulates in marine and non-marine environments.

Experience has shown that oil is the dominant product from the maturation of accumulated organic matter from organisms which lived in water, and that gas is the dominant product of the maturation of land plant organic matter. This has degenerated into the generalisation (incorrect in detail) that marine sediments produce oil and non marine sediments produce gas. There are many exceptions, including the Gippsland oil-fields which yield dominantly oil from non-marine source rocks. Other hydrocarbon fields, however, such as the oil at Barrow Island and gas on the Northwest Shelf of Australia, are consistent with the generalisation.

Organic material in marine water consists of dissolved, particulate and colloidal material, and accumulates in the sediments together with organic material generated by organisms living in the sediment. Colloidal material flocculates before settling out; that in solution is partly adsorbed onto settling clays, and particulate matter falls under the influence of gravity. As all this matter sinks, it is subject to attack, particularly by marine bacteria which remove any readily metabolised material.

Most organic matter in marine sediments is generated in the marine environment but some is carried in by rivers and the wind. The amount in the sediment is a function of the productivity of the water, and thus can be expected to be higher in such areas of upwelling as off the west coast of South America (where organic contents greater than 3 percent are not uncommon) and in the circum-Antarctic. The great productivity caused by abundant nutrients also causes depletion of oxygen and leads to long term accumulation of organic matter. For preservation of the organic matter, it is necessary to have a reducing environment, which implies still conditions. Hence high energy environments which accumulate sandy sediments are unlikely sites for source rock accumulation. Shale and siltstone are more likely source rocks and experience has shown this to be so.

Maturation of organic matter

'Maturation' is used in the sense of a sediment being mature when it is at the temperature/pressure conditions where hydrocarbons are being generated. Thus there are premature and post-mature sediments, the former which have not yet reached peak generation conditions, and the latter where the rocks have been raised to temperatures at which all their potential hydrocarbons have been generated and perhaps destroyed. The function of maturation is to produce liquid and gaseous hydrocarbons from forms which may be solid or highly viscous liquids if present at the earth's surface. The ultimate fate of any normal hydrocarbon is to change eventually to methane (CH_4) and carbon (C), the latter in the form of graphite. The breakdown will occur in reducing conditions to produce an even partition of carbon between the two end products. Fortunately for our lifestyle, much of the breakdown only proceeds part of the way to produce liquid hydrocarbons.

Original composition depends on whether the parent organic matter was derived from an aqueous (algal-bacterial) or terrestrial (land plant) source. That of presumed algal-bacterial origin is amorphous and seems to generate normal crude oils. An interesting apparently anomalous aspect of this maturation is that what was an initially hydrogen-rich source (11.5 percent in Fig. 22) produces a relatively hydrogen-poor product, oil.

In contrast, terrestrial land plants are relatively poor in hydrogen (5.3 percent in the example) but produce a hydrogen-rich product — methane gas. This anomaly is explained by the fact that terrestrial plants have a high content of cellulose and lignin, of which only lignin survives surface activity and is incorporated into sediment. Here, under rising temperature, methane and ethane cleave off from the

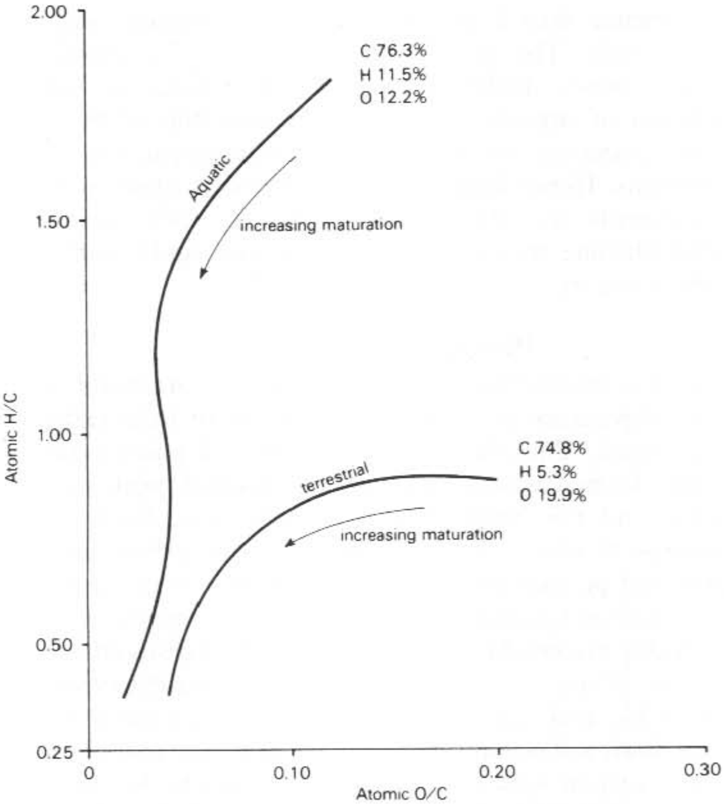

Figure 22. Pathways of evolution of different types of organic matter during hydrocarbon maturation.

more complex structures which are then concentrated in the remainder. Under 'normal' conditions with a geothermal gradient of 1°C per 30m depth, the hydrocarbon generation 'window' is between 3 and 5.5km deep and this is the sediment thickness range required for hydrocarbon generation at the site of generation although it should be noted that hydrocarbons generated at this depth can migrate into shallower sediments.

Other factors

Time has a role in influencing the type of hydrocarbons produced, although its role is minor compared with temperature. It is now believed that the older the source rock, the lower the temperature at which maturation occurs, because the reactions proceed at about twice the rate if the temperature is raised 10°C. Thus a sediment 170 million years old (Jurassic) that may have achieved a temperature of about 60-70°C to reach the same maturation as a 5 million year old sediment which needs to be heated at 120°C. Pressure seems to have no significant effect on generation, unless it favours the formation of oil as a smaller volume product.

There is an empirical link between sediment age and hydrocarbon occurrence although it should not be used to downgrade an area as large as a continent which has not been explored. Around the Australian Antarctic Territory margin, the expected accumulation sediment age would seem to be highly favourable for hydrocarbons. Most hydrocarbons (more than 70 percent) have been recovered from rocks younger than 200 million years (post Triassic), although there are many noteworthy accumulations in the exceptions.

Migration

Hydrocarbons remaining at the site of generation would be preserved as very minor components of an impermeable rock and, as such, virtually beyond recovery with existing technology. Oil exploration to date has depended on the migration from site of generation to a more permeable reservoir where the content also is higher. The mechanisms of migration are very poorly known.

Some geological considerations

Until 125 million years ago, Antarctica was part (some say the keystone) of the supercontinent of Gondwanaland which disintegrated through a well known series of steps (Veevers et al., 1980) each of which influenced the type of rocks formed, their thickness and environment of deposition (and hence potential hydrocarbon type).

The reconstruction of Gondwanaland used here is that now generally accepted by most geologists (Powell et al., 1980). The tie between India and Antarctica is very strong, partly geometrical, partly geological (Fedorov et al., 1982). The Australia-Antarctica position is controlled by features which cross the boundary from western Tasmania to northern Victoria Land (Laird et al., 1977) and by structures which cross the boundary in the vicinity of Adelaide. There is also emerging the possibility that the trough of the Vanderford Glacier (Allen and Whitworth, 1970) near the Australian Antarctic station — Casey — is an Antarctic continuation of the Perth Basin of Western Australia.

Fig. 23 shows the most commonly accepted reconstruction of Gondwanaland approximately 100 million years ago (after Powell et al., 1980; Quilty, 1982). A large question mark in the reconstruction concerns what lay between Western Australia and India in what is sometimes termed sinus australis? Two theories are debated. The apparently simpler says that nothing was there except ocean. Another says that India was much larger, the Greater India of Johnson et al. (1976), and that the extra mass is now under Tibet or contorted in the Himalayan Collision Zone. The latter is commonly favoured because sediments which accumulated in a non-marine environment

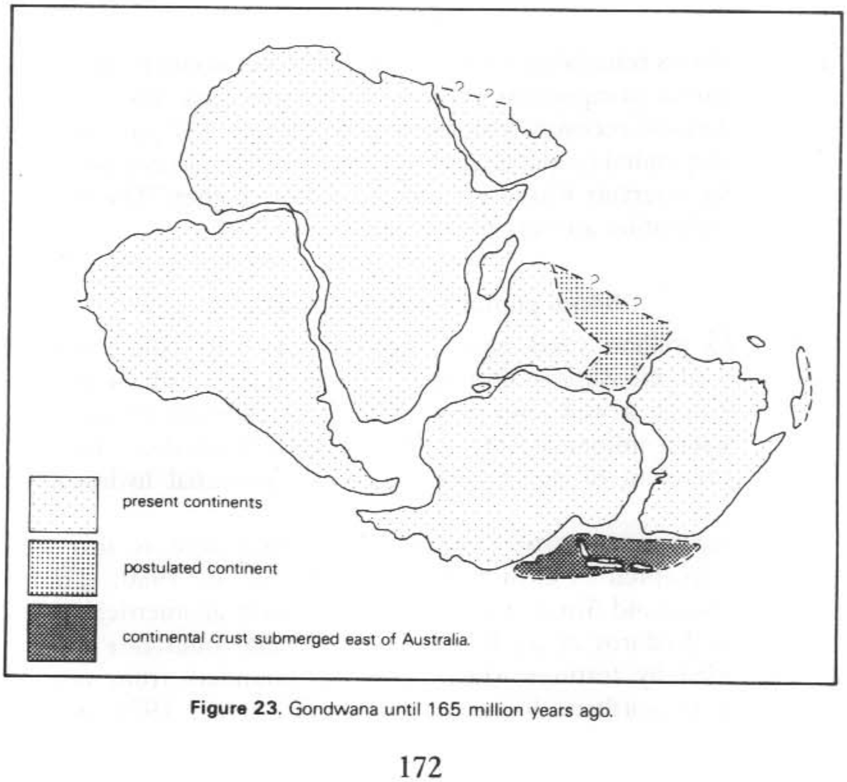

Figure 23. Gondwana until 165 million years ago.

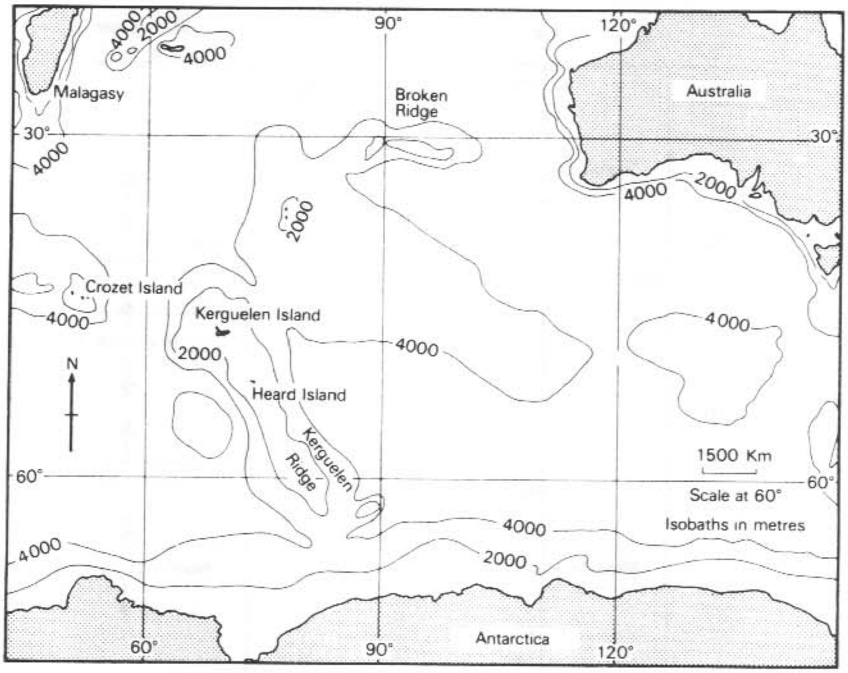

Figure 24. Kerguelen and Broken Ridges: their relationship to each other and sea floor spreading features.

are normal along the Western Australian margin until the Indian Ocean proper development about 125 million years ago and because some of the sediment offshore from Western Australia has structures which can be interpreted as suggesting a continental source to the west.

Another problem area concerns Kerguelen Ridge and Broken Ridge (Fig. 24), a pair of major submarine topographic features which clearly are divided remnants of a larger mass split by sea floor spreading (Quilty, 1973). It is not clear whether these are continental or oceanic in character and thus whether or not they are part of the Gondwanaland jigsaw.

A time scale

Gondwanaland disintegrated by a series of well known steps (detailed below) over 125-127 million years, relatively recently when considered in the context of the age of the earth estimated to be some 4600

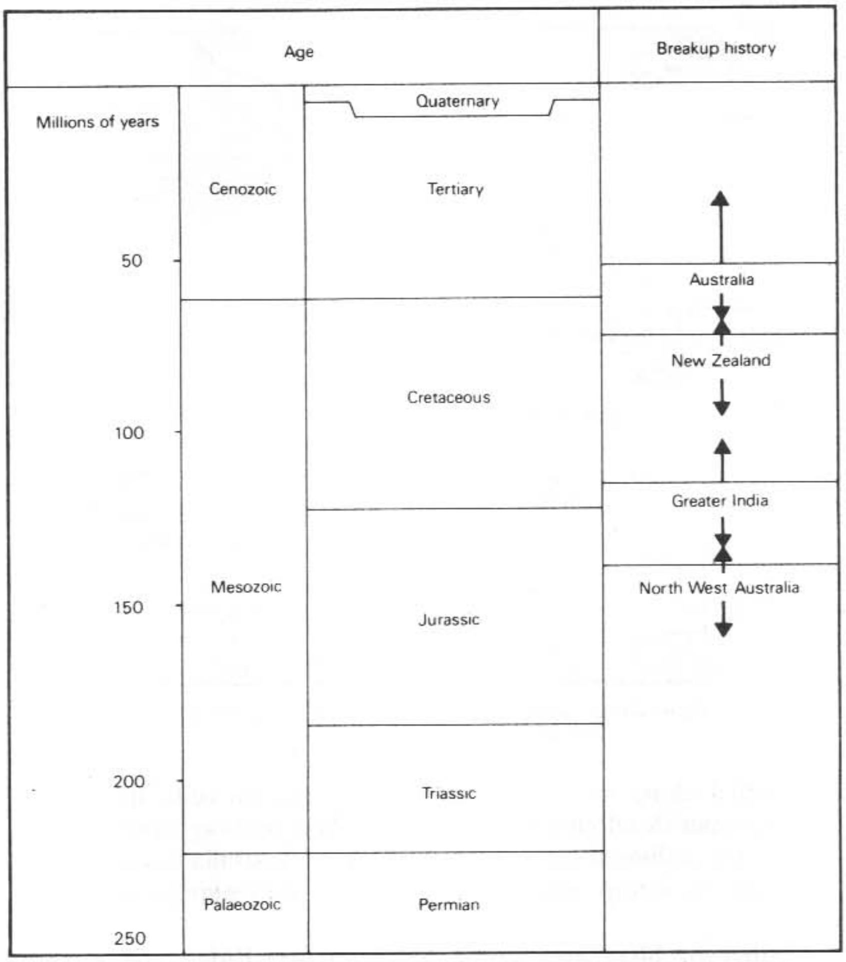

Figure 25. A geological time scale.

million years. The complete story involves more than just that part of geological time involving the breakup steps. Fig. 25 aids in this presentation.

Glaciation

Antarctica presently is overlain by a thick ice sheet but over the time span we are considering this probably is abnormal. Geological studies suggest that the present phase of glaciation began some 35 million

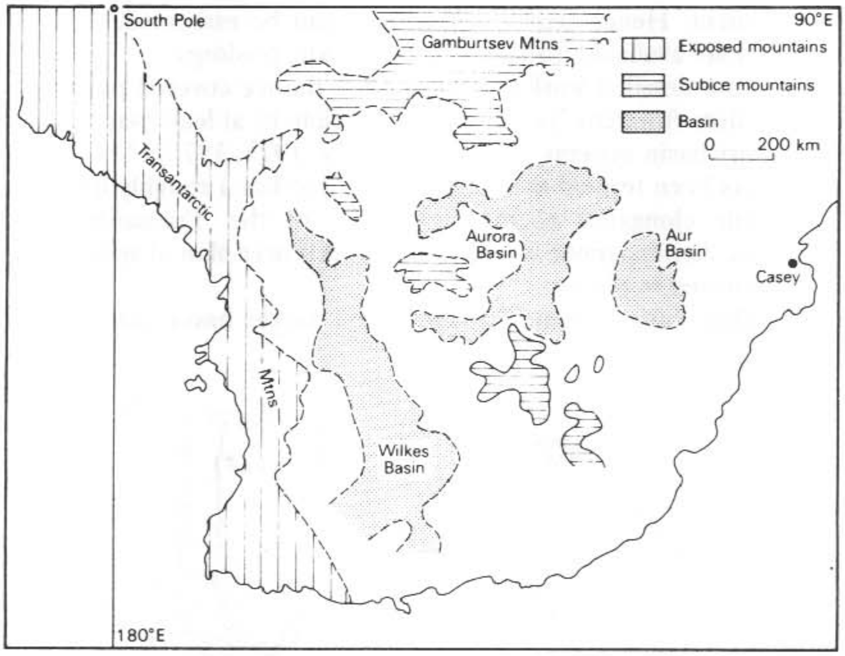

Figure 26. The subice geology of the eastern Australian Antarctic Territory.

years ago and underwent progressive intensification particularly at about 12 and 5 million years ago (Shackleton and Kennett, 1975). Evidence is slowly emerging for sporadic glaciation between 65 and 35 million years ago (Webb, pers. comm.). There was an earlier phase of glaciation, probably not of constant intensity, over the interval 300-230 million years. Between these two intervals there is no evidence that Gondwanaland underwent any glaciation at all.

Onshore potential

Combined US-UK studies in the Australian Antarctic Territory have been carried out over large areas using radio echo sounding techniques (Drewry 1975, 1976; Steed and Drewry, 1982), which give data particularly on ice thickness and stratigraphy and bottom topography. In addition, spectral analysis of subice (or rock) reflections, has been used to differentiate sedimentary basins from the more rugged basement. On occasions the aircraft has carried a magnetometer which gives valuable evidence on the distance between 'plane and basement. Hence sediment thickness can be estimated. Additional data are available from land-based gravity readings.

This quite detailed work has shown that the ice covered parts of the Australian Antarctic Territory are underlain by at least two major sedimentary basin systems (Fig. 26) (Drewry, 1975, 1976). The best defined has been termed the Wilkes Basin and has a roughly linear, north-south elongated character, parallel to the Transantarctic Mountains. Aeromagnetic work has shown that over 6km of sediment can be expected in places.

The other basin system (rather than a single basin) has been

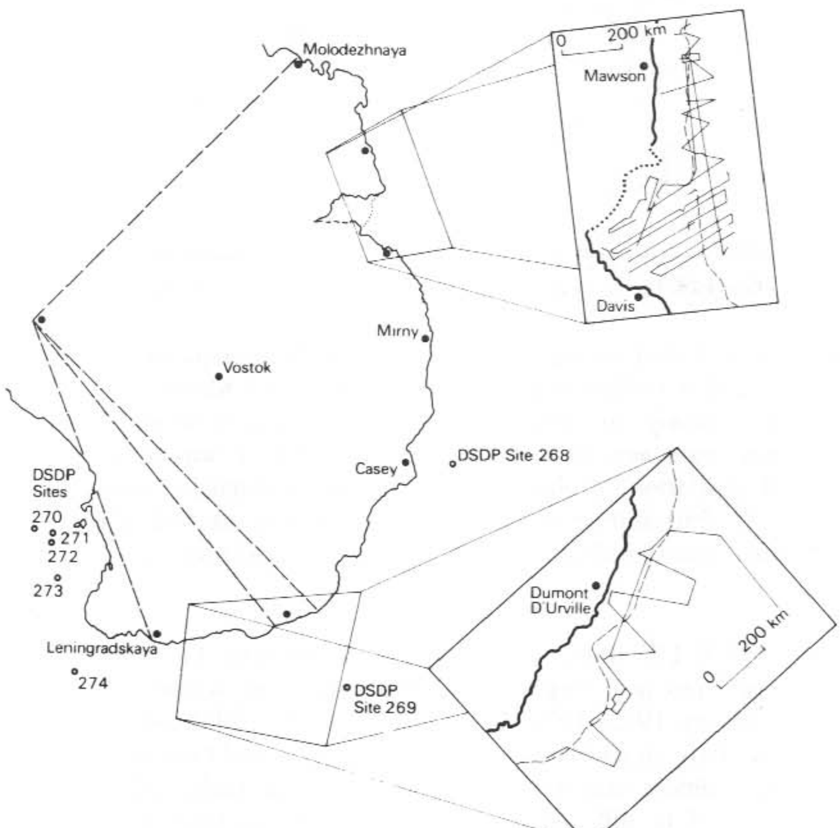

Figure 27. Seismic surveys so far undertaken offshore Australian Antarctic Territory.

identified as the Aurora Basin and occurs west of the Wilkes Basin separated from it by a linear series of 'mountains'. Its most interesting character is its meandrine, lobate form which suggests an origin different from that of the Wilkes Basin. Aeromagnetic results have indicated over 3.5km of sediment. The details of the geology of these basins are unknown as no rocks have been recovered from them. However, comparison with Australia in a reconstituted Gondwanaland (see later) may give some clues.

When Australia and Antarctica were united, the Wilkes Basin trend was directly towards western Victoria or eastern South Australia suggesting a comparison with the geology there. This would appear to decrease its hydrocarbon potential. Another view, put forward by British commentators is that the Wilkes Basin is floored with Beacon Group sediments, such as in the Transantarctic Mountains, all (or mostly) non-marine, allowing a possibility of a gas source. The former hypothesis would suggest that the 'mountains' between the Wilkes and Aurora Basins are comparable with the rocks of the Flinders Ranges of South Australia and the Gawler Block to the west.

The Aurora Basin's meandrine habit, and its situation in the reconstruction would all suggest a comparison with a series of Jurassic-Cretaceous intracratonic basins on Australia, such as the Eucla, Great Australian and Canning. Some of these are now the subject of successful hydrocarbon exploration and if the comparison is valid, the Aurora Basin must have some potential.

Some clues to the geology of these basins can be obtained from a study of sediments offshore. Glaciers scraping over the basins pick up rocks that occur there, carry them out to sea, and deposit them. Dredging and coring these sediments allows examination of their microfossils, which gives clues to both age and environment of deposition of the rocks in the basins. Studies carried out by personnel of the Bureau of Mineral Resources (Kemp, 1972; Truswell, 1982), of the few samples so far available suggests that a series of rocks of different ages within the interval Permian-Tertiary may exist under the Antarctic ice. These studies are almost in their infancy.

Offshore potential

Although little direct evidence (geophysical or geological) exists to provide a firm knowledge of the geology of much of the offshore Australian Antarctic Territory margin, the geometrical relationship

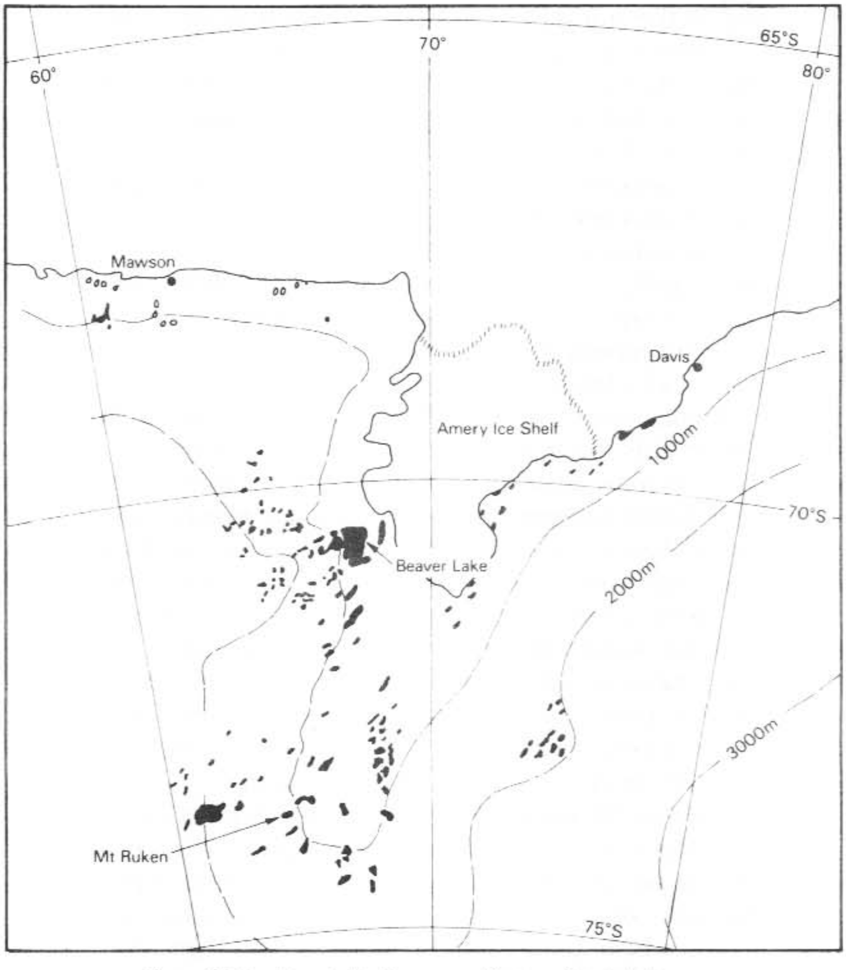

Figure 28. Locations in the Mawson — Davis — Beaver Lake — Prince Charles Mountains region.

of Antarctica with other Gondwanaland continents is well documented, and the interpretation of Antarctic geology can be more firmly based here than in other parts of the offshore continental margin of Antarctica. Thus tentative conclusions based on indirect knowledge concerning what is likely to be there are better based than for most other areas of Antarctica. Moreover recent moves by several countries to implement extensive offshore seismic programs will lead to a substantial increase in direct knowledge.

Most of the evidence on the offshore geology around the Australian Antarctic Territory is in the vicinity of Prydz Bay (Fig. 27) and comes from Soviet magnetic/gravity studies and a sole Australian seismic program (Stagg, in press). These programs provide information on the Amery and Enderby Basins (Fig. 34) which probably are not as distinct from each other as implied in Bergsager's figure.

Gravity/magnetic data indicate a potential sediment thickness as great as 10-12km and the seismic information penetrated depths as great as 3.5-5km. Taken together these data suggest that this is an area which, if economic and logistic circumstances were favourable, would be worthy of further exploration. The other area where seismic data will be valuable is that traversed by a seismic program on board *Explora*, in a survey undertaken for the French government, mainly offshore from Terre Adélie (Fig. 27), but extending on the eastern part of the program over a considerable area off the eastern sector of the Australian Antarctic Territory (Wannesson, reported in Behrendt, 1983). Direct sampling of apparently *in situ* sediment comes from the work of Domack *et al.* (1980) who collected a single core of cretaceous sediment from off the eastern sector of the Australian Antarctic Territory.

No drilling has been conducted in search of hydrocarbons around Antarctica, but the Deep Sea Drilling Project conducted Leg 28 in Antarctic waters and reported the results in Hayes et al. (1975). Sites 268 and 269 are off the coast of the Australian Antarctic Territory, in deep water and sites 270-274 are in the Ross Sea. Sediments encountered in the Ross Sea yielded various amounts of ethane, suggesting more maturation of contained organic matter and constituting the only direct evidence for the existence of Antarctic hydrocarbons. The significance of this ethane cannot be properly evaluated at this time.

The breakup of Gondwanaland

The breakup of this part of Gondwanaland occurred in the following phases, (Veevers *et al.*, 1980 and many other authors), all of which have great hydrocarbon significance:

Prebreakup — rifting phase

Phase 1	— 125 million years — India commences drift away from the rest of Gondwanaland
Phase 2	— 80-55 million years — New Zealand drifts away
Phase 3	— 86 million years — Australia begins to drift north from Antarctica

Prebreakup — rifting phase While the southern continents were joined to form Gondwanaland, the individual continental masses probably acted as somewhat independent blocks with much activity along the sutures. Although the exact length of time is unknown, there is a long period prior to breakup, perhaps hundreds of millions of years, during which the continents exhibit tensional features at their margins. Tension leads to rifting, and the East African Rift System is a modern example. Slight extension occurs between continents, the crust of the earth thins, allowing deeper heat sources closer to the surface. As a result the continent-continent boundary generally seems to arch upwards to form simple highlands which eventually split to form depressed, downdropped troughs (*graben*) into which sediment is carried by rivers. The sediment so formed is non-marine and often is rich in land-derived organic matter, eventually a source for natural gas.

Evidence of tensional features is widespread along the Australian Antarctic Territory margin. The Permian non-marine Beacon Group sediments of the Beaver Lake area (Fedorov et al., 1982), in the Lambert Rift Zone (Fig. 28) of the Australian Antarctic Territory near the Australian stations of Mawson and Davis fit this scenario well. The Tasmanian and Ferrar Dolerites (Jurassic — 165 million years) seem also to have been intruded as molten rock as part of the tensional regime.

In the Eyre Basin south of the Western Australian — South Australian border, in the Basin of the Great Australian Bight (Fig. 29), sediments over 5km thick seem to be dominantly of Jurassic age, non-marine and overlain by thinner younger marine sediments. These were tested by Esso-BHP Jerboa-1 (Bein and Taylor, 1981),

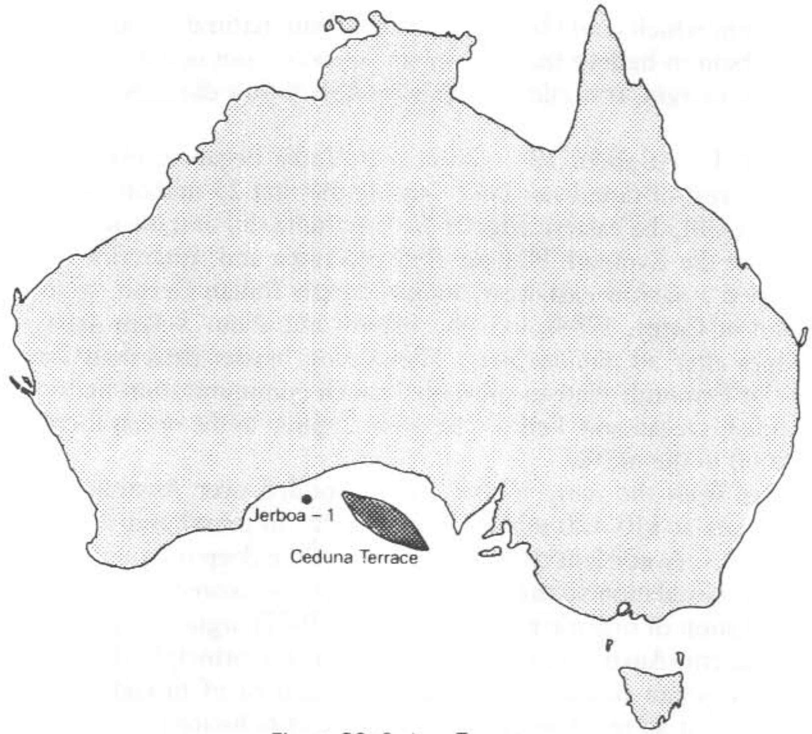

Figure 29. Ceduna Terrace.

which was unsuccessful but contained some evidence that oil had existed there in the past. Interpretation of seismic data suggests that Permian rocks also exist here. The Jurassic sediments are clearly filling tensional graben, but the character of the Permian and its relationship to specific tectonic regimes is not known. It may be filling an earlier rift feature.

Along the east coast of India there is a series of small sedimentary basins — Cauvery, Palar, Godavari — Krishna and Mahanadi — which have many features (Permian — Jurassic — Early Cretaceous non-marine followed by mid Cretaceous and younger marine rocks) in common with those along Australia's south and west coast (Sastri *et al.*, 1974). They are all basins which open seawards and most contain sections thick enough and of the right rock type to produce hydrocarbons. These basins probably have counterparts along the Enderby Land margin of east Antarctica.

All these prebreakup features include a significant non-marine component which could be expected to contain natural gas and there is no reason to believe that equivalent basins do not occur along the Antarctic margin. It would be highly unlikely if they did not.

Phase 1 At about 125 million years India began to drift north from the rest of Gondwanaland. During the first 25 million years of drift (Fig. 30), the eastern edge of Greater India slid past the southern margin of the Exmouth Plateau. Between India and Antarctica there developed a narrow east-west elongated early Indian Ocean (sphenochasm of Carey, 1958), initially shallow, but about 3-4km deep at its edges after 20 million years. The shallow barrier (less than 2km) over the Exmouth Plateau prevented much communication between the Indian Ocean and Tethys (the name applied to the ocean there at this time) to the north.

Water from the early Indian Ocean flooded over Australia as a shallow sea at 110-120 million years (Quilty, in press) and seems to have been very nutrient rich. The bottom of the deep ocean probably had poor circulation so that reducing conditions existed, ideal for the accumulation of organic matter. Andrews (1977) argues this case for the Antarctic-Australia area particularly but the principles hold also for other ocean basins. (There is also a school of thought which proposes that all mid Cretaceous seas were in reducing conditions at their base, but this has yet to be proven.)

During this period, marine conditions became the norm along the Western Australian margin and that part of the Antarctic margin between Gunnerus Bank and the vicinity of Davis (and probably east approximately to Casey), after a long period of dominantly non-marine sedimentation. There had been short marine phases before this time along the Western Australian margin, and may have been along the Antarctic margin. The offshore Perth area underwent violent activity immediately before and at breakup and great sediment thickness accumulated (Johnstone et al., 1973). These sediments produced the excellent oil shows encountered in Gage Roads 1 and 2 in rocks formed in this interval.

Russian work (Fedorov *et al.*, 1982) suggests that great sediment thicknesses (as great as 12km) exist in the offshore area of Prydz Bay (Prydz Bay or Enderby Basin, although the two terms may not be absolutely synonymous) and that these sediments are of about this age. Also relevant here is a comparison of the Lambert Rift Zone (of

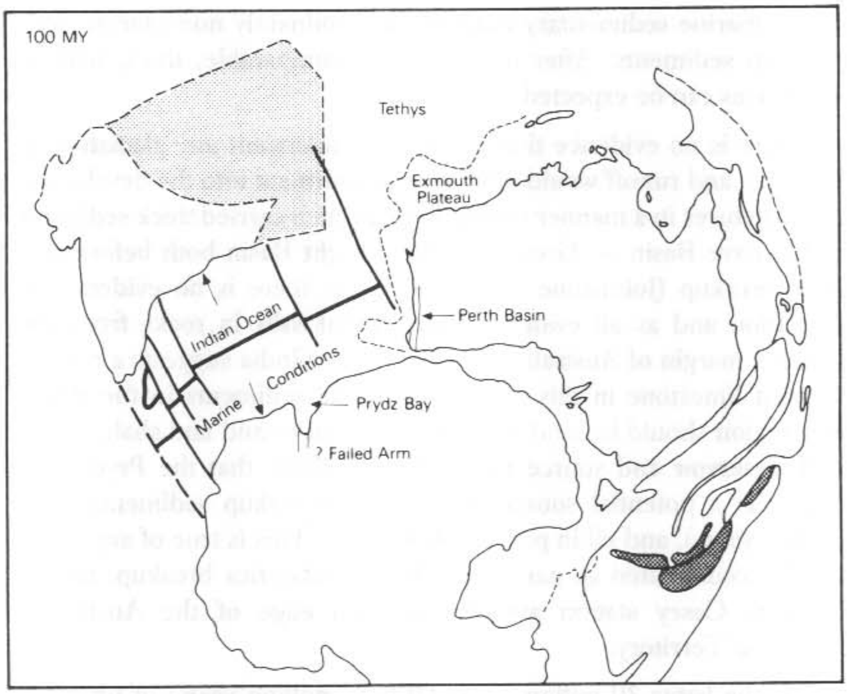

Figure 30. Gondwana 100 million years ago.

which Prydz Bay is part) with the southern Perth Basin, Gippsland Basin and a structure generally termed an aulacogen or 'failed arm'.

Commonly immediately prior to breakup, rift structures meet in a 'Y' junction but at breakup only two arms are the loci of separation with sea floor generated therein. The third 'fails', the rift phase here dies, and the end result is a graben structure entering a continental mass. Such structures commonly contain considerable sediment and have hydrocarbon (particularly gas) potential. The Lambert Rift Zone may well be one of these. The Gippsland Basin is small but contains oil; the southern Perth Basin has produced considerable gas flows in several wells from sediments only a little older than or coeval with the Permian sediments at Beaver Lake.

The history of the Antarctic margin in the vicinity of Prydz Bay would then seem to be fairly similar to that along the western margin of Australia, particularly the Perth Basin, and may even include some minor marine sedimentary units in the dominantly non-marine pre-breakup sediments. After breakup, very comparable, thick, marine sequences can be expected.

There is no evidence that Antarctica underwent any glaciation at the time, and runoff would tend to carry sediment into the developing rift structures in a manner similar to that which carried thick sediment to the Eyre Basin — Great Australian Bight Basin both before and after breakup (Johnstone et al., 1973). As there is no evidence of glaciation and as all evidence from microfossils in rocks from the western margin of Australia and east coast of India suggests a regime without limestone in this time interval, the sediments in the Prydz Bay region should be land derived, particularly sand and shale giving both reservoir and source rocks. It is probable that the Prydz Bay region is a potential source of gas in prebreakup sediments (125 million years), and oil in post breakup rocks. This is true of any rocks which accumulated as part of the India-Antarctica breakup, that is between Casey station and the western edge of the Australian Antarctic Territory.

For the latter 20 million years (100-80 million years) of phase 1, Greater India had cleared the southern edge up the Exmouth Plateau, the Indian Ocean became a 'mature' ocean with open connection to the ocean to the northeast and probably assumed a more oxidised water environment not so favourable to the accumulation of organic matter, although smaller pockets of reducing environment would still exist. The spreading orientation between India and Australia changed by some 15° (Veevers *et al.*, 1980), but this affects the hydrocarbon story very little.

Australia seems to have assumed a more arid aspect (Quilty, in press), so that sediment supply to the ocean dropped dramatically, the ocean warmed and the sediment produced had a much higher carbonate content, probably part of a worldwide change at this time. Recent evidence (Cande and Mutter, 1982) indicates that Antarctica and Australia began moving apart very slowly about 86 million years ago, allowing a seaway to develop between the continents for the first time in the interval under discussion.

Phase 2 80-55 million years (Fig. 31). During this phase, New Zealand moved away from the still almost joined Australia-Antarctica block by the opening of the Tasman Sea (Hayes and Ringis, 1973) which only occurred during this interval. The Gippsland Basin seems to have developed as a form of 'failed arm' as part of this development. Slow movement between Australia and Antarctica continued and weak marine conditions entered between the continents. Sediment thickness of this age seems minor. There is evidence, in the form of rare microfossil occurrences (Webb and Neall, 1971), that warm ocean water filled the Ross Sea Antarctica, suggesting that no major glaciation was active on Antarctica. Australia continued to be domi-

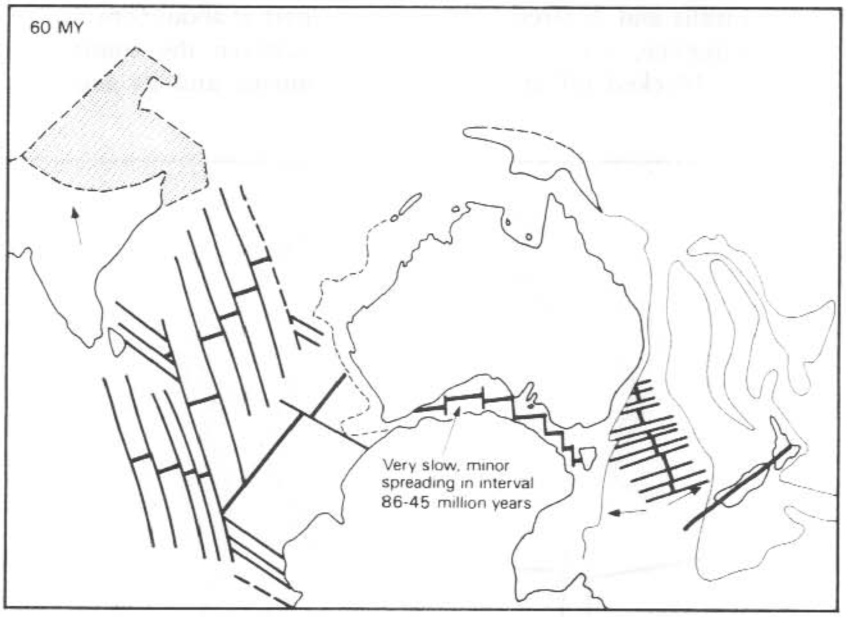

Figure 31. Gondwana 60 million years ago.

nated by aridity and carbonate marine sediments were the norm.

Oceanic circulation in both Indian and Pacific Oceans consisted very dominantly of anticlockwise patterns of water moving between polar and tropical regions so that there was no real opportunity for surface water masses to remain cold (Gordon, 1973). In consequence there probably was much less differentiation of climatic zones at this time than is now the case.

Phase 3 55 million years to the present (Fig. 32). At about 60 million years ago the sea floor spreading between Australia and New Zealand ceased and instead faster separation began between Australia and Antarctica, commencing at 53-55 million years. It is still active, with Australia and Antarctica now moving apart at about 6cm a year. In consequence, a major ocean entered between the continents, essentially blocked off at the east by Tasmania and its southern

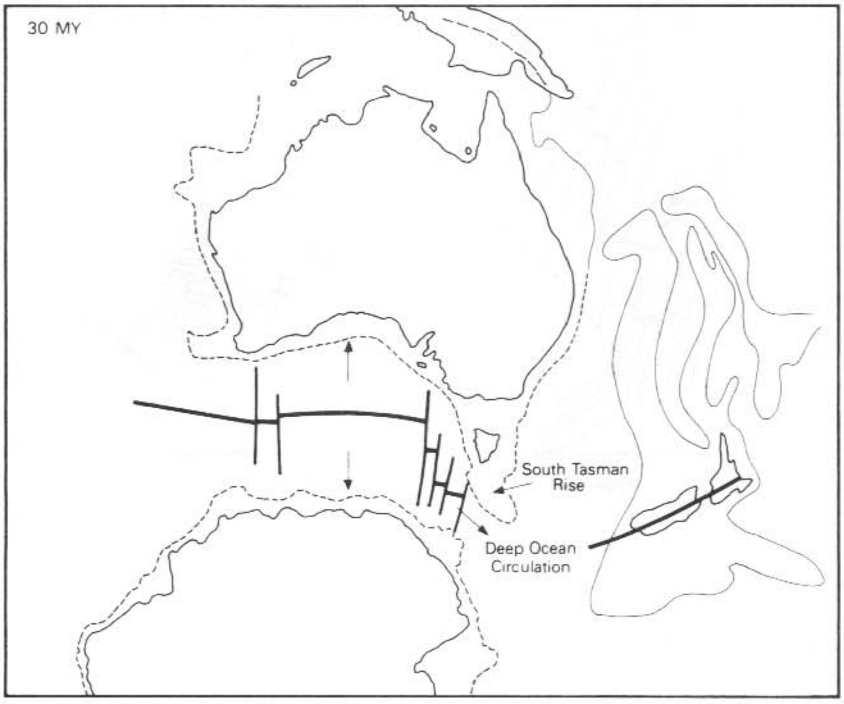

Figure 32. Gondwana 30 million years ago.

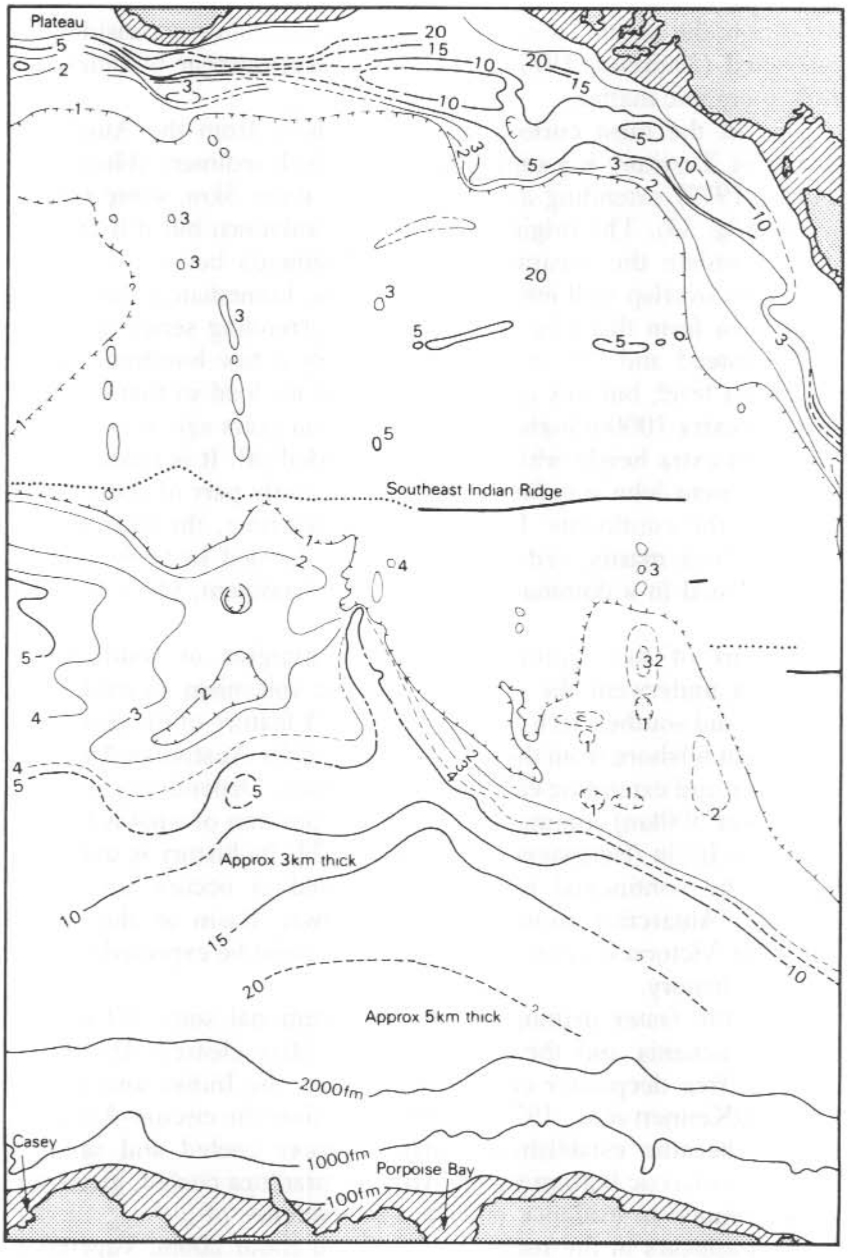

Figure 33. Possible area of thick sediment east of and offshore from Casey.

extension, the South Tasman Rise. Thus circulation was considerably restricted (Andrews, 1977) allowing the development of sediments rich in organic matter.

One of the most curious features offshore from the Australian Antarctic Territory is a supposed lobe of thick sediment (Houtz and Markl, 1972) extending at a thickness of about 5km, some 600km north (Fig. 33). The origin of this lobe is unknown but if it exists it must postdate the separation of the continents because it would otherwise overlap well into South Australia. Immediately onshore in Antarctica from this lobe is a north-south trending series of 'highlands' (Steed and Drewry, 1982) now only a few hundred metres above sea level, but this is depressed by an ice load so that it was at least an extra 1000m higher about 50 million years ago as well as an unknown extra height which has been eroded off. It is possible that this sediment lobe was formed during the early part of the drifting between the continents. If it formed at this time, the lobe should contain thick marine sediments (although formed in fairly shallow seas) formed in a dominantly reducing environment, ideal as an oil source.

As part of the drifting process, the margins of southeastern Australia underwent the extensive basaltic volcanism so evident in Victoria and southeastern South Australia. A feature of the continental margin offshore from the eastern sector of the Australian Antarctic Territory and extending eastwards off the Ross Dependency is a very wide (over 300km) continental shelf in the position of what is termed the Scott Basin (Bergsager, 1983) in Fig. 34. Its history is unknown but in the continental reconstruction used, it occurs across the Australia-Antarctica suture from the Otway Basin at the South Australia-Victoria border. On that basis, it could be expected to have a similar history.

After the faster drifting had been operational some 20 million years, Tasmania and the South Tasman Rise cleared Antarctica, allowing free deepwater circulation between the Indian and Pacific Oceans (Kennett *et al.*, 1972). At the same time the circum-Antarctic current became established. Antarctic water cooled and sank to develop Antarctic bottom water (ABW). Antarctica cooled, glaciation became much in evidence and the first evidence of iceberg-carried detritus appears in the rocks. Sea level fell about 200m. Vegetation on Antarctica was reduced to a few alpine species, and Australia became isolated. From this time, glaciation increased until virtually all vegetation was wiped from Antarctica about 12 million years ago. All that now remains are a few mosses and lichens.

A major consequence of the development of the circum-Antarctic current was the development of a supply of nutrient-rich water which could lead to reducing bottom conditions and abundant marine organic matter for maturation into hydrocarbons. Upwelling of this water causes very high organic productivity at the Antarctic margin. If the lobe of sediment off the BANZARE Coast is of this later age, it can be exected also to be of high hydrocarbon potential. All sediment would be land derived, giving good source and reservoir sediments, but the role of glaciation in sediment production is not yet even partly evaluated.

The high nutrient water, upwelling and high productivity, are probably unique to the Antarctic margin and helped develop a regime whose role in hydrocarbon development has not been fully consid-

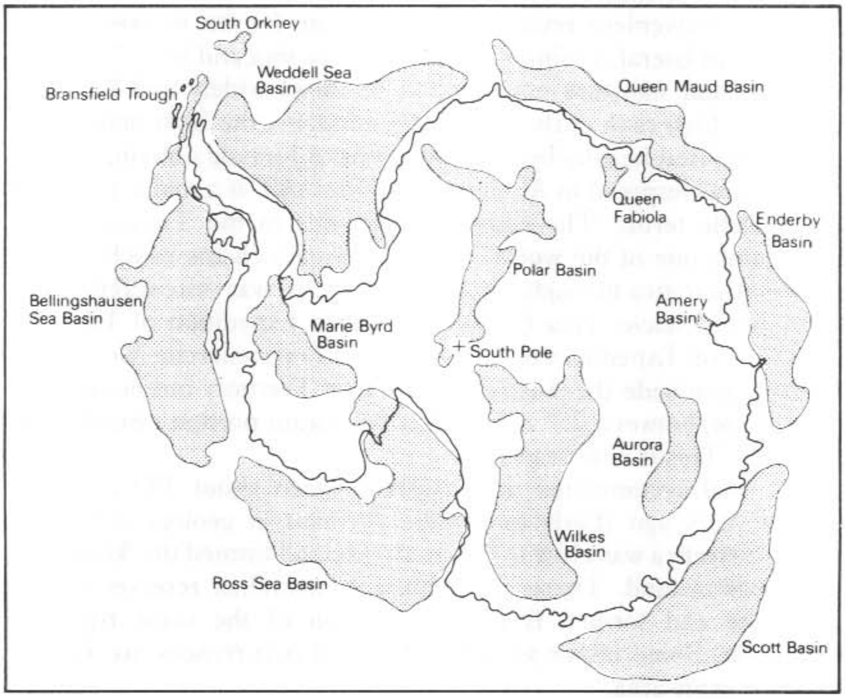

Figure 34. Sedimentary basins of Antarctica.

ered. The Bass Basin evolved rapidly at this time (Robinson, 1974) in consequence of the movement between Australia and Antarctica and a small lateral movement of Tasmania with respect to Australia.

Coal

Coal is formed over geological time, when rich concentrations of plant matter accumulate in swamps, attain considerable thickness, are overlain by other rocks and buried. Over time, and with some temperature increase as a result of burial, water is expelled and the carbon content of the residue increases. If moisture and mineral matter are of low content, if the resultant coal beds are thick enough, and shallow enough in the earth's crust and a market established, exploitation can occur.

No comprehensive account of reserves or quality exists for Antarctic coal and in most summaries of mineral resources, coal is ignored or passed over in a few paragraphs. Lovering and Prescott (1979) provide a convenient review. What coals are known to exist suffer from lack of lateral continuity and usually are thin and lenticular with high ash and moisture content. Grade varies widely and includes nominally high rank coals, including anthracite, the high rank being due to localised heating by later intrusions of Jurassic dolerite.

Coal is widespread in Antarctica and the AAT is a major province in Antarctic terms. The main occurrence is in the Transantarctic Mountains, one of the world's major mountain chains which almost crosses Antarctica through the south pole. Coal was discovered in the Beardmore Glacier area by the Shackleton Expedition of 1907-09 and the Scott Expedition of 1910-12. The Transantarctic Mountains are largely outside the Australian Antarctic Territory but because of their shape, between 75° and 80°S, a significant portion extends into the AAT. This is coal bearing.

The coal accumulated dominantly between about 290 and 245 million years ago (Early to Middle Permian in geological terms), when Antarctica was close to the south pole and formed the 'keystone' of Gondwanaland. There are important Australian reserves of the same age and formed from accumulation of the same types of vegetation. Some minor younger (Triassic) occurrences are known from the same area.

The second area of occurrence of coal in the Australian Antarctic

Territory is at Beaver Lake in the Prince Charles Mountains (Figs. 28, 38). Here the coal is of Middle Permian age forming seams up to 3.5m thick. This area has not been subject to post-deposition heating so the grade is generally lower than that of the Transantarctic Mountains deposits, although the same problems of ash and moisture content prevail. This reserve seems to be of a potentially useful steaming coal.

Any attempt to summarise the reserves or grade of coal would be only an academic exercise as the world's supply of more readily accessible coal is so great (Tables 2, 3) that there can be no foreseeable use of Antarctic coal except for small scale local purposes.

Antarctic minerals

All elements which human beings exploit occur naturally in the earth's crust, usually in low abundance. The abundance is low enough that normally such an occurrence is not exploitable economically. For the element to be economically exploitable, natural processes must have concentrated it in some way. The ratio of concentration in an ore over the natural background level is termed a 'concentration factor'. Many examples are given in Table 4, although it must be emphasised that the factors are about present average values and will change with demand and technology. Local needs may require lower concentration factors. To a large extent, the study of ore distribution is a study of the ways in which natural processes have concentrated naturally occurring elements into unusually high abundance.

The occurrence of minerals Elements for human needs are extracted from ores, formed by a series of natural processes. Concen-

Table 2 Global fossil fuel energy reserves

Fuel	Energy equivalent (Kilojoules)
Oil	3.9×10^{18}
Natural gas	2.65×10^{18}
Coal	1.8×10^{20}*
Tar sand	5.5×10^{18}
Shale oil	1.8×10^{20}†

* only 3% recoverable at present
† at time of 1979 oil crisis, it was estimated that 2% of this amount was close to economically recoverable.

tration of the resource can take place in two very different general ways. Primary ores can be seen as solid rock containing concentrations of elements. Such ores include coal and iron ores, sulphide ores and the like. Extraction of the resource involves first an assessment that the grade is high enough for commercially or strategically worthwhile mining; and second, mining of whole rock and final concentration by man of the required mineral resource.

In many instances, minerals are so widely scattered in rock that the

Table 3 Coal Reserves: World, US and Australia

	Reserves*	Energy Equivalent ≠
World	10.58×10^{12}	1.8×10^{20}
Australia	$.32 \times 10^{12}$	$.54 \times 10^{19}$
United States	2.57×10^{12}	4.3×10^{19}

Energy conversion at 1 tonne = 1.7×10^7 kilojoules

* Units — tonnes
≠ kilojoules

(Figures are estimates of total coal in the ground and are about 11-12 times greater than total measured reserves which are in turn about 3 times greater than economically recoverable reserves.)

Table 4 Relationship between natural crustal abundance, ore grade and concentration factor for some important elements

Element	Abundance (%)	Ore Grade (%)	Concentration Factor
Aluminium	8.0	25-30	3-4
Iron	5.8	30-60	5-10
Titanium	.86	1.7	2
Manganese	.1	45	450
Carbon	.02	30-90	1500-4500
Chromium	.0096	21.9	2000-2500
Zinc	.0082	2.5	300
Nickel	.0072	1	150
Copper	.0058	.6	80-100
Lead	.001	2	2000
Uranium	.00016	.1	1200
Tin	.00015	.2-.4	2000
Silver	.000008	.03	4000
Gold	.0000002	.0001	4000

resource would not, under normal conditions, be worth extracting. This is true of many occurrences of minerals such as gold, tin and heavy minerals. However, nature often weathers or erodes rocks chemically or physically and concentrates some elements at the earth's surface into economically extractable deposits. Excellent examples are afforded by heavy mineral beach sands where ilmenite, zircon, rutile and so on have been eroded from parent rocks and sorted by coastal currents by a process that removes the lighter grains, leaving a residue of the 'heavies'. This is secondary concentration or formation of secondary ores. The distinction between primary and secondary ores is important in the Antarctic context.

Secondary ores include the following main types of mineral occurrence

(a) Placer deposits, where such minerals as gold, diamond, cassiterite (tin oxide) which are chemically resistant, heavy and hard, or malleable and heavy, are concentrated in irregularities in stream beds as the lighter fraction is winnowed out.

(b) Heavy mineral beach sands, where heavy, resistant grains are concentrated by oceanic current activity.

(c) Supergene enrichment, where the weathered profile over a primary sulphide ore at depth contains a concentration of such minerals as copper oxide or gold. The result is often extremely high grade and can pay for initial mine development until the deeper primary ore can be mined. These ores are important in another way; they are relatively easily detectable and act as readily identifiable indicators of primary ore at depth.

(d) Residual concentrations in which a parent rock, not economically valuable, is leached of its non-valuable component, leaving a surface veneer a few metres thick of economically valuable concentrate. The most important here are bauxite (the main ore of aluminium) and lateritic iron and nickel ores.

From the samples quoted above, it is clear that secondary concentrations are very valuable sources of world mineral supplies. Our understanding of the generation of secondary concentrations is based, however, almost entirely on studies in the temperate and tropical regions of the world. Secondary concentrations of the type found elsewhere in the world will almost certainly be non-existent in Antarctica because several million years' erosional activity by a blanket of moving ice will have removed them and carried them into the sea.

It is possible that secondary concentrations formed by processes peculiar to the polar marine environment will be identified. Such possibilities include:

- formation of minerals on the seafloor (such as manganese nodules) by a process entitled diagenesis,
- concentration by physical sorting action of oceanic currents in the glacial environment.

An example of the latter possibility could be in Prydz Bay where an Australian geoscience cruise in 1982 (Stagg, in press) showed that a trough exists around much of southeastern, southern and southwestern Prydz Bay where the sedimentary fill of the bay joins the basement rock of the type exposed around the margins of the bay. It is possible that this trough is swept clean by current activity and that heavy materials are being concentrated. This hypothesis needs to be checked by a sampling program. The sediment of Prydz Bay contains abundant garnet (of no commercial value where it is) but other commercial minerals may also occur.

Primary ores In contrast to most of the world, Antarctic mineral prospecting exploration would be hindered by the absence of soil and by the fact that only some two percent of the continent is exposed. The rest is covered by ice, averaging about 2.5km thick with a maximum of 4.8km. The shape of the ice sheet ensures that even near the continent edge, ice thickness is great enough to prevent any economic mineral resource activity unless activity takes place for unforeseen reasons. The good exposure and the absence of soil on the exposed areas mean that the only ores which could be identified and extracted will be primary ores.

Exploration Two approaches to exploration can be envisaged in an initial attempt to establish the prospectivity of the Australian Antarctic Territory. The first is comparison with the prospectivity of continental margins once adjacent when all were part of Gondwanaland, using the same principles as used earlier in discussing hydrocarbons. The second is actual field search for minerals by geologists in Antarctica.

From the first approach, it is necessary to compare the prospectivity of the Australian Antarctic Territory coast between longitudes 110°E (approximately Casey station) and 160°E (the AAT eastern boundary), with southern Australia. Likewise the area from 45°E (western boundary of the AAT) to approximately 80°E (approximately the position of present northeastern India in the Gondwanaland reconstruction given earlier) should be compared with the east coast of India. The area between 80 and 110E appears to have had continental crust offshore from it, but the continent has not so far been identified. Assessment of prospectivity in this region is not possible on the basis of present knowledge of continental reconstruction.

Comparisons with southern Australia

Tasmania-North Victoria Land The mineral resources of western Tasmania are concentrated in what is termed the Dundas Trough, and include a great variety of mineral types of diverse ages although most occur in host rocks of very similar age (Cambrian — 500-600m.y.) (Solomon, 1981). An apparently similar structure — the Bowers Trough or graben — exists in North Victoria Land slightly east of the AAT boundary in the Ross Dependency (Laird et al., 1977). Modern detailed reconstructions of this part of Gondwanaland often show the Dundas and Bowers Troughs as continuous across the old intercontinental suture (Fig. 35). If the continuity is real, and if the geology is similar, it could be expected that the Bowers Trough could have mineral significance (economic constraints aside). Study of the Bowers Trough is the subject of some activity (Burrett and Findlay, in press), but knowledge is still very meagre.

Southwestern Australia — Wilkes Land coast. It is often said that the potential prospectivity of Antarctica is heightened because of its former proximity to mineral rich areas such as the old shield area of southern Western Australia. This is not necessarily so. The main mineral wealth of southwestern Australia occurs in the Yilgarn Block (Fig. 36), but interposed between the Yilgarn Block and the south coast is the relatively mineral poor Albany-Fraser Province (Fig. 36). If the adjacent part of Antarctica is likened to southwestern Australia, it may be the Albany-Fraser Province which is more appropriate.

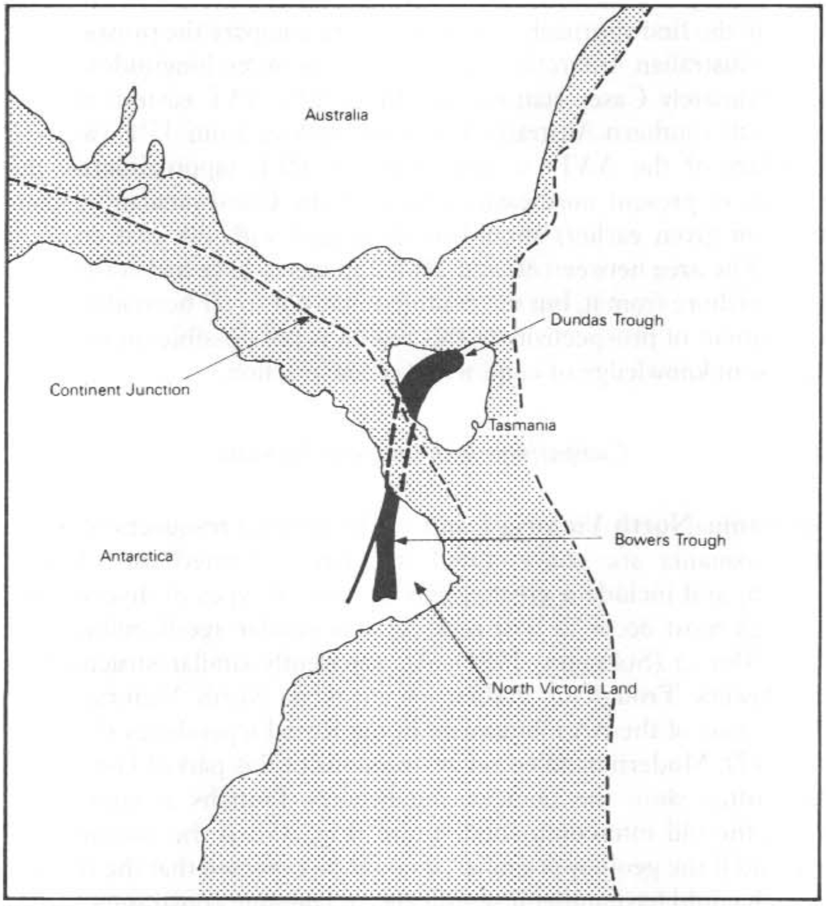

Figure 35. Structures linking Australia and Antarctica in Southeastern Australia.

This then may lower the mineral potential of the once adjacent coastal area of the Australian Antarctic Territory.

Comparison with India — Sri Lanka

Work in recent years has shown strong structural similarity (Fig. 37) across the India-Antarctica suture and has reinforced the dominantly geometrical seafloor-based reconstruction (e.g. Fedorov et al., 1982). However, apart from some relevance to iron ore (see later), the main significance of the similarity is in terms of hydrocarbon and coal potential.

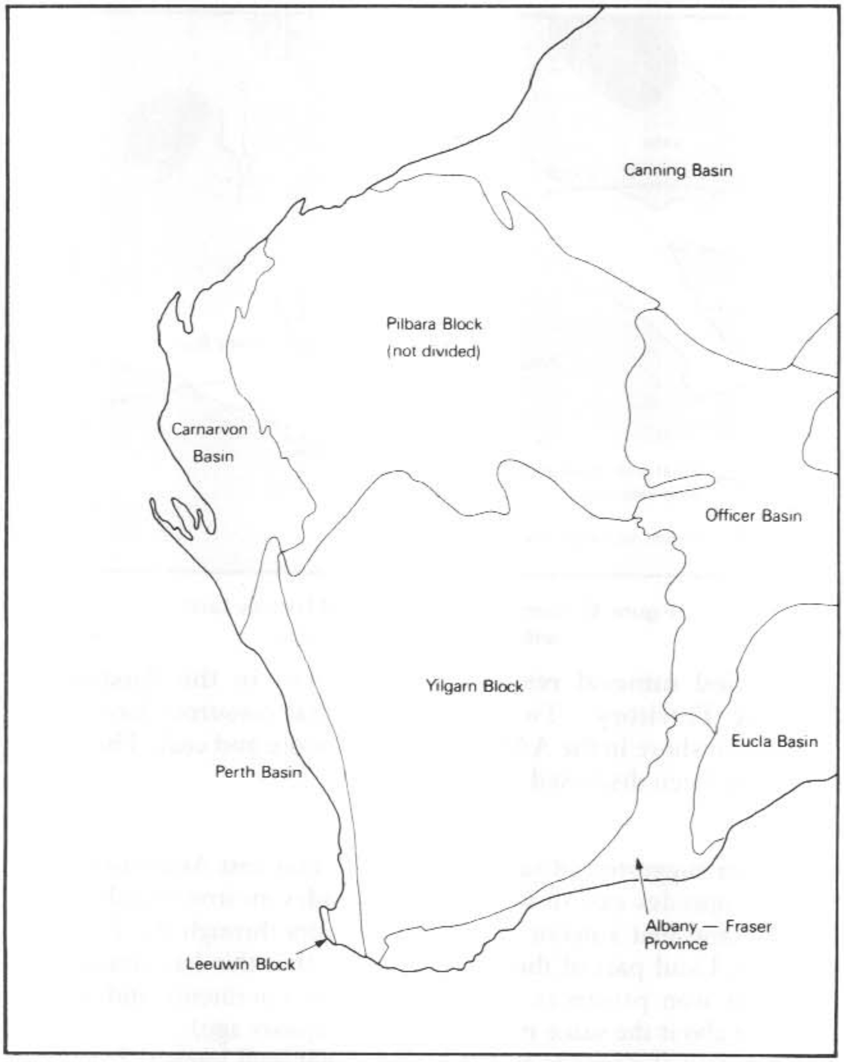

Figure 36. Tectonic elements western Australia.

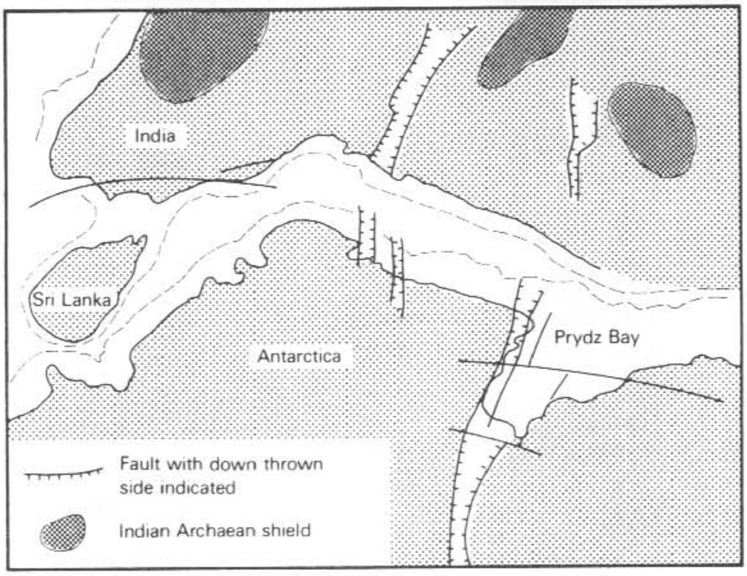

Figure 37. Comparison of geology of Enderby Land with that of India — Sri Lanka.

Identified mineral resource occurrences in the Australian Antarctic Territory Two potential mineral resources have been identified onshore in the AAT. They are iron ore and coal. The latter has already been discussed.

Iron ore

It has been suggested (Rowley *et al*., 1983) that east Antarctica (that part in longitudes east of Greenwich) includes an iron metallogenic province, and that a major subprovince occurs through the Enderby — Wilkes Land part of the AAT. Further, that this has similarities with other iron provinces that exist in most continents and which formed at about the same time (2-1.8 billion years ago).

The principal deposits are known (but not well known) from the southern Prince Charles Mountains (Tingey, 1982a, b), (see Fig. 38 for localities mentioned). Certainly the largest known outcrop is at Mt Ruker and is the source of most 'popular' reports of Antarctic iron ore. This is a banded iron formation (BIF) containing 25-46 percent iron and this is lowgrade with 0.17 percent phosporus pentoxide (P_2O_5) which is a severe hindrance to steelmaking. Running west from Mt Ruker are two aeromagnetically detected magnetic

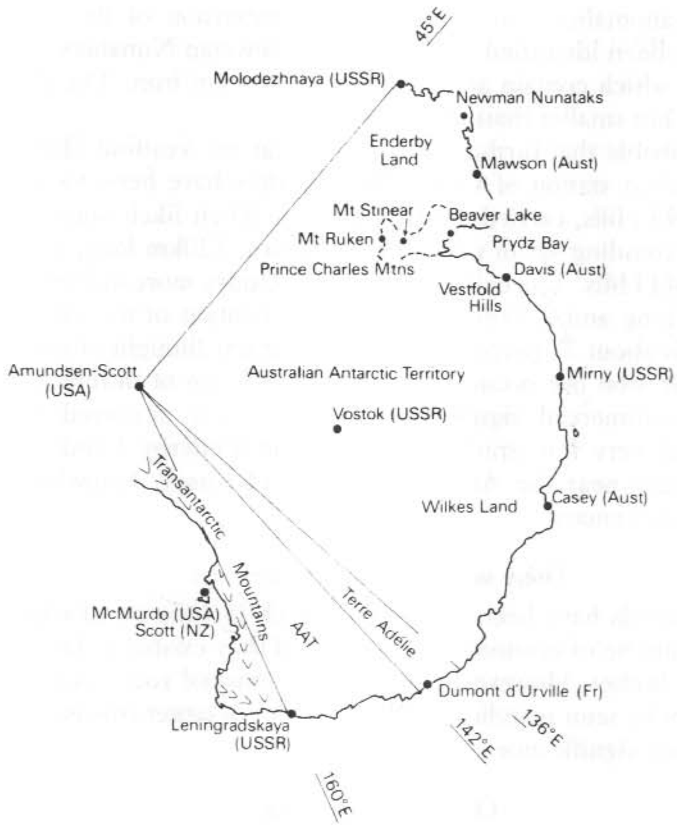

Figure 38. Locality map, Antarctica.

anomalies, 5-10km wide, 120-180km long which indicate that the ore outcropping at Mt Ruker is part of a more extensive iron ore subprovince (Hofmann, 1982).

The amount of iron ore has not been estimated, but what has so far been examined is far too low a grade to be considered commercial in other continents (Tingey, in press), except for specific local conditions. If BIFs elsewhere are any guide, it is likely that enriched 'pods' of ore could be expected, but it is likely also that they exist under considerable ice thickness and could not be considered as exploration targets in the foreseeable future. Mt Stinear, also in the Prince Charles Mountains, has yielded low grade BIFs, and aeromagnetic anomalies also indicate subice extension of the deposit. BIFs have been identified further west at Newman Nunataks, also in the AAT, which contain an average of 34 percent iron. The deposit is akin to, but smaller than, that at Mt Ruker.

It is probable that further BIFs occur near the Vestfold Hills near the Australian station of Davis. BIF-boulders have been located in the Vestfold Hills, carried there by glaciers. Their likely source is an east-west trending set of magnetic anomalies, 120km long, south of the Vestfold Hills. The belt of anomalies includes more discrete units 10-40km long and 2-4km wide. The iron content of the ore in the boulders is about 21 percent, far too low for any thought of exploitation. Other iron ore occurrences in the AAT are of different types with no commercial significance. They include scattered fissure filling, and very low grade occurrences in Enderby Land and in Wilkes Land near the Australian station of Casey. Knowledge of them is rudimentary.

Other metallic mineral occurrences

Many minerals have been discovered which include metal elements which would be of economic significance if they existed as large high grade ore bodies. However, they are quite normal rock occurrences and cannot be seen as indicating the presence of larger concentrations of economic significance.

Offshore potential

There has been much speculation and some experimentation on the use of manganese nodules from the seafloor as a source of various metals (Glasby, 1977). No economic exploitation has occurred. The deep seafloor between Australia and Antarctica and to the east and west of the Kerguelen Plateau (Fig. 39) contains an extensive occurrence of manganese nodules. Generally manganese nodules occur far from land, on the deep seafloor but not on higher ridges and plateaus (except active spreading ridges). They also seem to be absent from continental slopes. They seem to occur in well oxidised areas where sediment accumulation is very slow.

Manganese nodules have been seen as potential sources of copper, nickel, manganese and cobalt. Very little information is available on the potential economic value of the nodules off the AAT, but in the Pacific Ocean it has been found that the potential value is highest at

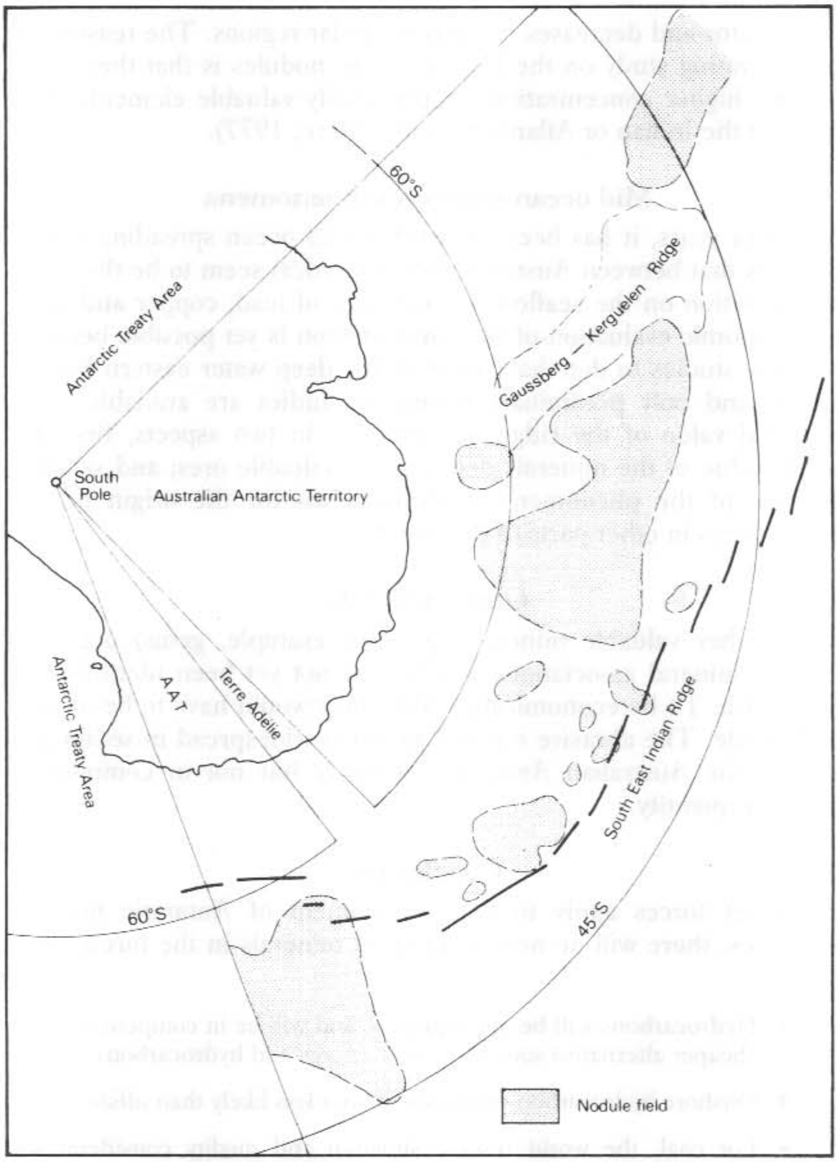

Figure 39. Manganese nodule fields off the Australian Antarctic Territory, south of the South East Indian Ridge. (after Frakes)

the equator and decreases towards the polar regions. The reason for concentrating study on the Pacific Ocean nodules is that they seem to have higher concentrations of potentially valuable elements than those of the Indian or Atlantic Oceans (Mero, 1977).

Mid ocean ridge crest phenomena

In recent years, it has been found that mid ocean spreading ridges (such as that between Australia and Antarctica) seem to be the locus of deposition on the seafloor of sulphides of lead, copper and zinc. No economic evaluation of this phenomenon is yet possible because the only studies to date have been in the deep water eastern Pacific Ocean and only preliminary results of studies are available. The potential value of the ridge question lies in two aspects, first the actual value of the minerals deposited as valuable ores; and second, the use of the phenomena as explanations for the origin of ore occurrences in other parts of the world.

Other minerals

Many other valuable mineral types (for example, gems) occur in specific mineral associations which have not yet been identified in Antarctica. To be economically viable, they would have to be of very high grade. The abrasive mineral garnet is widespread in sediments around the Australian Antarctic Territory but not in commercial grade or quantity.

Conclusion

If market forces apply to the development of Antarctic mineral resources, there will be no extraction of minerals in the foreseeable future.

- Hydrocarbons will be too expensive and will be in competition with cheaper alternative sources of both energy and hydrocarbons.
- Onshore hydrocarbon extraction is even less likely than offshore.
- For coal, the world reserve situation and quality considerations ensure that Antarctic resources will not be competitive.
- The area available for exploitation of primary metallic ores is very small, the largest area of the continent being covered with a very thick ice cover.

- Secondary ores have been removed but the possibility of concentrations being formed by processes peculiar to the glacial environment cannot be ruled out.

Market forces may not be the only considerations in development as there are many, particularly northern hemisphere nations, that are highly industrialised and lack sufficient indigenous supplies, especially of oil. Lack of a home supply of strategic metals could also lead to Antarctic development.

Having said this, I believe technology already exists for drilling on the deeper continental shelf of Prydz Bay and if supplies were found, they could be produced from safe subsea completion systems. The occurrence of coal, iron ore, significant sediment thickness and high concentrations of krill in the vicinity of Prydz Bay, make this a particularly attractive part of Antarctica for sovereignty purposes in strictly resource terms.

The potential of Antarctica to produce mineral resources is not great at present but pressure will grow in the future. The time is now ripe to commence monitoring the environment in Antarctica in great detail as this is the only essentially pristine continent: not only is this true of the continent, but it is also true of its surrounding ocean.

Endnote

1. This article does not discuss the subject of ice as a resource. From many technical points of view, it is of course, a mineral but in Antarctic research terms it is excluded because it is a renewable resource whereas those considered here are not.

Comments

R.J. Tingey

This commentary is intended as a broad review that builds upon the factual basis presented in Dr Quilty's contribution and draws attention to additional factors that impinge upon any consideration of Antarctica's mineral resource potential. It is written from the perspective of a research geologist active in Antarctic science.[1]

The title of Quilty's review might inadvertently convey the impression that knowledge of Antarctic mineral and petroleum resources is much more comprehensive than is in fact the case; a more suitable title might be 'The mineral resource potential ... etc.' The current situation is that direct knowledge of Antarctic mineral resources is minimal and that very few earth science research programs directly address the resource question. Most earth science programs in Antarctica are research oriented and aimed at scientific problems: an incidental spin-off is information that is applicable to the broad assessment of resource potential.

In his introduction Quilty alludes to 'extravagant claims' in articles jin the popular press, and it is true that some statements have taken an unrealistic view of the likelihood of Antarctic mineral exploitation. However I draw attention to items, including front page articles, in the *AAPG Explorer* (December 1982, December 1983, January 1984), house newspaper of the American Association of Petroleum Geologists. It appears that individuals in the industry are turning their attention to Antarctica. It may be that this interest is of an 'armchair' type, or perhaps confined to preventing others stealing a march, but it is also worth noting that Antarctica was 'on the map' in a presentation about world petroleum resources at the March 1984 BMR Petroleum and Minerals Review Conference in Canberra. There is no doubt that the petroleum and minerals industries are keeping a watch on Antarctic affairs (see Reynolds comments) and research results. It is not possible to gauge if, how, or when this will be translated into resource exploration activity.

Factors influencing possible minerals exploration in Antarctica

Quilty's comments on exploration for minerals in Antarctica mainly outline political and legislative factors; he does not discuss issues limiting development in Antarctica. He does not say that offshore petroleum development is the most likely type of activity in the Antarctic area but this is the premise (which is widely accepted) from which he works. He argues that if 'political and economic constraints can be overcome, technology will develop if needed'. To some extent this begs the question of offshore exploration which is quite feasible, although admittedly difficult, with present technology. Antarctic political factors may be a constraint on development in the sense that industry would prefer to know for certain that it will be able to develop the commodity for which it undertakes exploration. However political factors elsewhere, the Middle East for example, might, one day, serve to encourage nations, and industry, to look for alternative, and preferably assured, sources of supply. The first preference would be 'closer to home' sources but there would be obvious merit in keeping a close watch on remote sources like Antarctica.

In certain circumstances therefore political, and perhaps strategic, supply factors may serve to encourage the exploration for, and possible exploitation of, Antarctic minerals and petroleum deposits. However if, as seems likely, economic considerations are paramount, circumstances that would render Antarctic deposits attractive would have the same effect on many other deposits, including discovered deposits, that are more favourably situated, but not at present exploitable.

Quilty mentions that environmental considerations will be a severe restraint on resource development and this will be true in the sense that any additional expense will be a restraint. Nonetheless the petroleum industry is concerned to maximise the returns from its ventures and would take considerable care not to spill its expensively-won commodity. In addition, no industry would want to risk the bad press that would inevitably flow from an oil spill or other environmental drama.

Antarctica's petroleum potential

Offshore

Quilty's section on the hydrocarbon potential of the Australian Antarctic Territory starts with a dissertation on the generation of petroleum from organic matter in sedimentary rocks. Petroleum is now thought to be generated from plant material and the general scenario outlined is reasonable, though subject to many exceptions: Gippsland basin oils, for example, are derived from terrestrial plant material. Later there is mention of the oil generation 'window', an elastic but useful concept. Such understandings have developed empirically in the last twenty years from industry data and would be applied in assessment of the petroleum prospectivity of the Antarctic offshore area.

Quilty later discusses geological considerations that bear on the assessment of the petroleum and minerals potential of the AAT. Such considerations include 'Gondwanaland' and notions of continental drift, while there are details in Quilty's account that would be disputed by geologists, the main idea, so far as offshore petroleum is concerned, is that Antarctica's continental shelves were created when various other land masses 'drifted' away at various times (Quilty, Fig. 25). Various parts of the Antarctic shelf have thus existed for different times and experienced different geological evolutions, although a glacial regime has been common to all areas for about the past 20-30 million years. An example of what can be deduced from these continental separation ideas is the observation that marine conditions may have existed off the western part of the AAT since about 100 million years ago but only since about 50 million years in the sector 'opposite' Australia (Quilty, Figs. 30-32).

These considerations allow analogies to be drawn between parts of the AAT shelf and formerly adjacent shelves now joined to other land masses. The analogies are limited in scope and are based on limited geological data, especially from Antarctica, and an evolving theoretical framework. This framework also points to a different possible analogy, between the Prydz Bay/Amery Ice Shelf area of the AAT and the Niger Delta region in West Africa, on the basis that both locations are where an old continental assemblage started to break apart but failed to do so completely. The Niger Delta is an example where there are considerable petroleum resources, but it cannot be said that all such 'failed rifts' are prolific petroleum producers. Nevertheless it is quite possible that the Prydz Bay area may contain a substantial accumulation of deltaic sedimentary rocks. Some deltas like the Niger and Mississippi have proved to have abundant petroleum resources, but others such as the Ganges delta appear to be much less promising.

The geological analogue approach is only applicable to rocks that formed before Antarctica acquired its present glacial regime. The exact time when the present glaciation started in Antarctica is a topic for debate, but there seems to be consensus that glaciation had started by about 20 or 30 million years ago and grew to its present scale about 5 million years ago. Since glaciation started, the Antarctic continental shelf has been receiving glacial marine sediments, although the rate of accumulation is now much less than it was prior to 5 million years ago. Sediments are deposited in the sea: when they become dewatered, compacted and hardened they are converted to rock. The petroleum prospectivity of glacial marine rocks is not clear, and literature on the subject appears to be very limited, although one report suggests that petroleum is extracted from allegedly glacial marine rocks in Oman. The problem is compounded by the fact that current biological and sedimentological conditions around Antarctica's continent margins may not have existed throughout Antarctica's current glaciation epoch. For example although it is well known that Antarctic marginal seas now have very high rates of biological productivity (see Chittleborough in Chapter 5) it does not follow that older glacial marine rocks around the margins necessarily have a high content of biological debris, and thus a high petroleum prospectivity. This prospectivity can only be realistically assessed by drilling: the estimation of undiscovered oil and gas resources before any drilling is done 'continues to be a very inexact process' (Kerr, 1979, p.1069).

The glacial sediments off Antarctica were, however, drilled in phases of the Deep Sea Drilling Project (DSDP) in the early 1970s. The objectives of the drilling program were scientific and primarily aimed at elucidating Antarctica's glacial history but, as is well known, hydrocarbon gases were encountered in drill holes in the Ross Sea Shelf. The significance of this experience in the assessment of Antarctic petroleum prospectivity is not clear, and at the time the DSDP scientists said it was premature to attach any economic significance to the Ross Sea hydrocarbons. Nonetheless the hydrocarbons have made a considerable political impact, as is underscored by Chittleborough.

Onshore

Quilty follows his examination of the offshore petroleum potential of the AAT with a discussion of the onshore sedimentary basins that are thought to exist beneath the AAT glacial cover. These basins could be analogous to, say, the Eromanga Basin that underlies large areas of Queensland and South Australia. The Eromanga Basin is the site of a substantial petroleum exploration effort at present. In Antarctica, the Wilkes and Aurora subglacial basins are very poorly known from direct evidence, but indirect geophysical and geological techniques have been used in assessing their nature and extent. Antarctic subglacial geology is of necessity a very speculative business and only fragmentary information is available. No matter what picture of geological prospectivity emerges it is very difficult to envisage that there will be serious attempts at resource exploitation in these areas in the foreseeable future, bearing in mind the bulk and mobility of the ice cover, and the many other practical impediments to Antarctic development.

Non petroleum mineral resource potential

Offshore

The prospects for mineral developments off the AAT coasts are bleak. Quilty mentions 'manganese' nodules and mid ocean ridge sulphide deposits. The commercial attraction of manganese nodules lies in their nickel and cobalt content, rather than manganese, and, as Quilty points out, nodules near the equator have higher contents of the valuable metals than nodules nearer the poles. Quite apart from difficulties posed by the outcomes of the United Nations Conference on the Law of the Sea, practical difficulties continue to confront deep sea nodule mining ventures even in the warm latitudes. The chances of such mining in high latitudes where the nodules are much less commercially attractive, and the practical difficulties are enhanced, appear very remote.

The mid ocean ridge sulphide deposits mentioned by Quilty have also been studied only in warm tropical areas. There appears to be very little likelihood that these deposits will be explored in the Antarctic region in the foreseeable future.

Onshore

Quilty gives accounts of coal and iron ore, the two resource commodities that are known to occur in substantial quantities in the AAT. A comprehensive account of Antarctic coals has been compiled by the Australian geologists McElroy and Rose, and is to be published (J. Splettstoesser, ed. in press). There is little reason to think that the exploitation of Antarctic coals will occur for many years yet, if at all, and it is worth noting that most coal types known from Antarctica are likely to prove unsuitable for conversion to petroleum. This is because most of them have been heated when hot molten rock masses were emplaced nearby. This has given the coals a high 'rank', but resulted in the removal of volatile components needed in the petroleum conversion process.

Although bodies of iron rich mineralization are well known from the AAT the possibility that these rocks could be seriously considered for exploitation is almost negligible. The main body at Mount Ruker in the Prince Charles Mountains is not large, its grade (about 35% Fe) is at best, modest, and the exposure is on the inland side of a major 50 km wide glacier 600 km inland from an ice bound coast that is accessible to shipping for only about six weeks every year. There are many thousands of millions of tonnes of higher grade ore waiting to be mined in much more favourable circumstances such as the Yilgarn Block in Western Australia.

However, although these deposits have little prospect of being exploited economically, they serve to demonstrate that Antarctica is likely to contain resource mineral accumulations of a size and grade that would in other situations be sufficient to warrant exploitation. This can be inferred from the size of the Antarctic land mass and the inferences can be refined by taking account of geological information. Indeed mineral species that are economically exploited elsewhere have been and will continue to be, encountered as Antarctic research proceeds, but these occurrences are orders of magnitude smaller than any that would constitute economically exploitable targets.

What then, are the prospects of finding such targets? My view is that they are remote 1. because so little rock is exposed (see Budd, Chapter 6); 2. because the exposed rocks have been scraped clean by glacial ice of special indicator rocks, such as gossans that might in other terrains be important in prospecting for buried deposits; and 3. because water-dependant geological processes on which to a substantial degree 'conventional' surface geological exploration for minerals is based are not operative. It follows that such ore bodies as are exposed will in general need to be found by direct sampling or by encounter in the field, as indeed many notable ore bodies such as Sudbury in Canada, and Broken Hill in Australia, have been. However rock exposures in Antarctica are minimal, and access to them is generally difficult. Ore bodies beneath the main glacial cover are for practical purposes inaccessible, but if mineral exploration of such areas were to occur it would involve wide ranging geophysical surveys and expensive follow-up drilling. Blind ore bodies have been found elsewhere by the application of geological deductions and indirect techniques as, for example, Roxby Downs, but it is extremely difficult to envisage economic circumstances that would induce a search for subglacial mineral deposits in Antarctica.

Earth science research and mineral exploration

It has been said that mineral exploration starts when an exploration scientist opens a textbook. On this basis any earth science research activity, indeed any geographical exploration, yields information of value to explorationists. It is probably advisable, however, to distinguish between the assessment of prospectivity and practical exploration in the field. The assessment of prospectivity has geological and economic aspects. In the main it is economic, and to a certain extent, political circumstances that govern whether or not mineral exploration will proceed. The direction of the practical exploration will depend upon an assessment of geological prospectivity, and in the first instance this depends on the results of geological (including geophysical) research.

Quilty's sub-section entitled 'exploration' is largely about the assessment of geological prospectivity, or what information can be deduced from geological knowledge regarding the type of mineral deposits that might occur in a particular area. He discusses the geological comparison approach, an approach which, as noted previously, has limited scope, particularly in Antarctica where it relies on such a restricted base of 'hard' information. The Antarctic ice cap plays a dual geological and economic role; on the one hand it restricts the amount of available geological data because it covers so much of the bedrock, and on the other it presents formidable logistic and practical problems for exploration and exploitation.

Apart from these problems, political and diplomatic considerations arise from the Antarctic treaty system. These are discussed elsewhere in this volume and further comment is limited here to a brief discussion of earth science research. The sensitivity of this topic arises from the continuing Antarctic treaty discussions on an Antarctic minerals regime and the existence of a moratorium on 'all exploration and exploitation of Antarctic mineral resources'. The relevant treaty recommendation (IX-1(8)) says that (the Governments of the Antarctic Treaty nations) will thus endeavour to ensure that, pending the timely adoption of agreed solutions pertaining to exploration and exploitation of mineral resources, no activity shall be conducted to explore or exploit such resources'. The 'moratorium' recommendation carries clear implications for earth science research programs in Antarctica, the full nature of which depend upon what distinction might be drawn between research and mineral exploration.

These implications became apparent in early 1983 when a number of nations, including Australia, were accused by environmental groups of being in breach of the moratorium. Australia's allegedly offending activity was a reconnaissence marine seismic survey of the Prydz Bay area. This survey was approved by the Antarctic Research Policy Advisory Committee (ARPAC), and seen by ARPAC to be consistent with its recommendation that Australia 'have a high quality research program in Antarctica directed towards: the living and mineral resources of the Antarctic and the environmental effects of their exploitation'. A preliminary account of the work was published in 1982 and further accounts are in press. The seismic line spacing, and sophistication of the equipment were not typical of a commercial exploration venture, nor was the prompt publication of results. The survey was scientific in concept and designed to study the composition, structure, and evolution of the Antarctic continental margin. Nonetheless, it yielded information that is useful in the broad assessment of the petroleum prospectivity of the Prydz Bay region. The survey could thus be regarded as part of the total resource assessment process, but not as exploration. However the ARPAC recommendation quoted above could be seen as sanctioning mineral resource exploration activities: the critical distinguishing feature was, and is, the publication of results.

The recent Antarctic activities of, for example, the Japanese National Oil Company and the French Institute of Petroleum, have drawn similar accusations of resource exploration links. Again the critical difference is publication, the Japanese having published accounts of their work (which is at about the same level of sophistication as the Australian survey), whereas no published account of the rather more sophisticated French survey in the Ross Sea and Adélie Land area in 1982 is known to this commentator. The Norwegian and West German marine geophysical studies in the Antarctic area are published; and accounts of the United States surveys off Victoria Land in early 1984 are now available. Soviet scientists have published a brief account of their geophysical surveys in the Weddell Sea area. It is thus apparently the French program that is exceptional in not being published.

The ARPAC recommendation quoted above concerning research 'directed towards the living and mineral resources of the Antarctic' might be seen to be somewhat inconsistent with the Antarctic treaty 'moratorium' on mineral resource exploration and exploitation (Treaty Recommendation 1X-1). It could further be construed that there is also inconsistency between research programs cast in a general resource framework (refer Australia. Antarctic Research Policy Advisory Committee, 1982: 10), and the need for Australia not to appear in breach of treaty agreements. The reality of course is that Antarctic earth science programs are very much oriented towards scientific problems even though they produce resource related 'spin off'. It is the ARPAC categorisation of programs that appears inconsistent, not the programs themselves. And a similar situation seems to exist in the Soviet Union and perhaps Japan. For example, Tass accounts of Soviet field geological research in Antarctica commonly refer to mineral resource issues, the recent activity in the Beaver Lake area of the Prince Charles Mountains being described in terms of an analogy with 'the famous diamond bearing Kimberlite pipes in South Africa'.[2] Presumably there are advantages in expressing research programs and objectives in terms of tangible outcomes rather than less tangible ones like scientific knowledge. However in the field there is little evidence that Soviet scientists, or those of any other nation, are exploring for mineral deposits in the Antarctic. Nevertheless, it is important that the minerals regime negotiations devise a method of distinguishing between earth science research and resource exploration activities. It is clear that the publication of results will be an important factor but making data available, and 'internationalizing' research projects, are two other possible courses of action that will open up the research effort and distinguish it from the essentially private nature of mineral exploration.

Summary

Quilty's assessment of the mineral resource potential of the Australian Antarctic Territory agrees with others that the prospects for onshore mineral resource development in the territory are minimal. It is clear that exploration would be extremely expensive and difficult because so little rock is exposed and many normal geological exploration methods would not be applicable.

Offshore petroleum resource development would be difficult perhaps even hazardous, but current methods of assessment and exploration technology could be used although it would be beset by difficulties. Quilty demonstrates that offshore resource developments are much less far away than others, and the AAPG Explorer articles show that oil industry personalities are taking an interest. The petroleum exploration industry has a history of overcoming difficult challenges in frontier regions, and political factors (not necessarily local ones) have been important in this. It is not inconceivable that the Antarctic continental shelves could become a worthwhile exploration target in the not too distant future, although it is impossible to make firm predictions. However, the scale and speed of petroleum resource development have been impressive, to say the least, over the past 25 years or so.

That the continental shelves are the parts of Antarctica most likely to be targetted for resource development raises the question of offshore territorial boundaries (see Prescott, Chapter 3). The most 'promising' area of the AAT shelf, Prydz Bay, is not affected, but the large lobe of deep water sediment to which Quilty draws our attention raises an interesting boundary question. However, its petroleum prospects cannot be rated highly.

The mineral resource perspective, outlined by Quilty's and this commentary, raises policy questions both at the international Antarctic treaty level, and nationally. The international policy aspects are taken up elsewhere in this volume, and although it is clear that Antarctic resource development, including petroleum development, is not likely to occur for a number of years yet, important principles need to be safeguarded in the minerals regime negotiations (Reynolds elaborates on some of these). The negotiations also need to, (and are proceeding to) devise some method of distinguishing between research activities and mineral exploration activities, and it may be that this will lead to a further internationalisation of Antarctic science in an effort to keep research 'open'.

At the national level there needs to be an answer to Dr Davis' question 'what is Australia trying to achieve in Antarctica'. This involves consideration of the whole spectrum of activities including the maintenance of stations, rebuilding, transport systems, policy, and science. As regards science, ARPAC's problem is to translate its perceptions of Australia's Antarctic interests into practical research guidelines and programs. Unfortunately ARPAC's effectiveness has been greatly hampered by logistics problems experienced by the Antarctic Division, and it has only been possible to implement parts of the ARPAC recommended program. This has resulted in supposedly resource related programs not being balanced by the 'scientific' and environmental programs also endorsed by ARPAC.

The supposedly 'resource related' programs seem to rest uneasily alongside the treaty 'moratorium' on Antarctic mineral exploration and exploitation activities. The desire to exploit Antarctic resources may appear to be a logical corollary of Antarctic sovereignty, and may justify Antarctic expenditure in the eyes of the man in the street, but it does not mesh easily with the current 'environmentally concerned' flavour of Antarctic treaty discussions. In this respect at least there seems to be a tension between sovereignty and Antarctic treaty interests.

As regards earth science programs, their categorisation in terms of mineral resources is somewhat misleading. The reality is that the programs address scientific problems and are largely motivated by the desire to 'see what's there'. They yield information that is relevant to the broad assessment of minerals and petroleum but this is by no means the primary purpose. Australia, through ANARE, operated some highly effective field programs in the Prince Charles Mountains and Enderby Land areas in the late 1960s and 1970s. Similar activities are needed to extend basic geological coverage, and that of other field sciences as well, to the AAT's eastern sector and the Bunger Hills-Denman Glacier area, and to follow up geological questions in the previously visited areas. The other main arm of the earth science program is marine based, and the main plan is for geological and geophysical studies that would yield valuable information on the structure, composition and evolution of the AAT continental margin, and help in the study of Antarctica's climatic and glacial history.

Benefit, in Antarctic terms, would flow to Australia from vigorous, wide ranging, field and marine scientific research programs in the AAT area. They would be consistent with sovereignty in that wide areas of the AAT would be examined, and consistent with the word and spirit of the treaty in being research, the Antarctic 'currency'. Antarctic earth science research is scientific research with a resources spin off, not resources exploration with a scientific veneer: it should be described as such. And a great deal remains to be done.

Endnotes

1. The views presented are those of the author and do not represent those of either the Bureau of Mineral Resources, Geology and Geophysics or the Department of Resources and Energy. Published with the permission of the Director, Bureau of Mineral Resources, Geology and Geophysics, Department of Resources and Energy, Canberra.
2. This refers to rocks in the Beaver Lake area that belong to the same broad family as the kimberlites; very few kimberlites contain diamonds.