

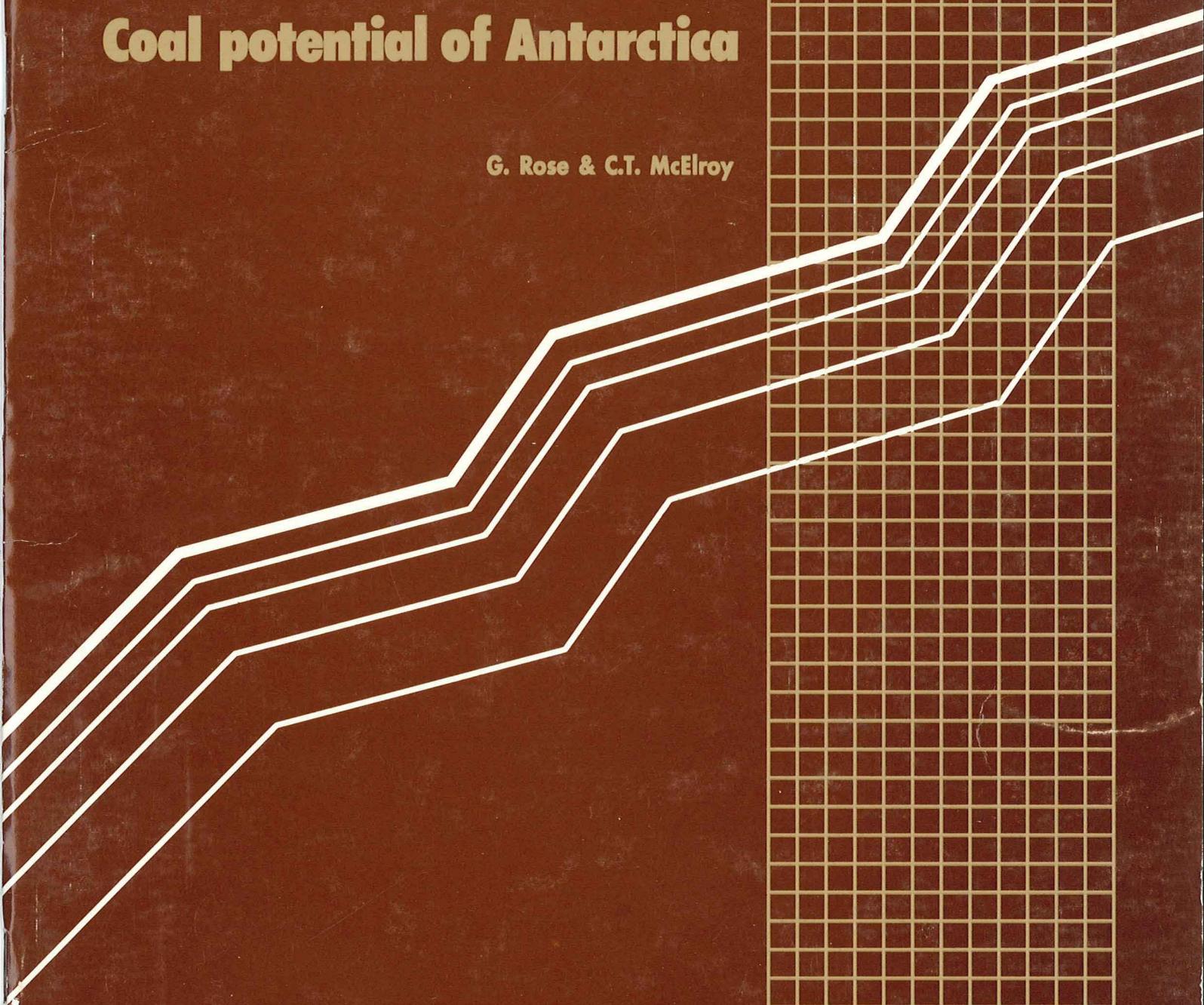


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Resource Report

Coal potential of Antarctica

G. Rose & C.T. McElroy



DEPARTMENT OF RESOURCES & ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RESOURCE REPORT 2

Coal potential of Antarctica

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FOREWORD

The Resource Report Series has been established by the Bureau of Mineral Resources to publish summary reports and compilations of information about mineral resources in Australia and its Territories. It is proposed that the reports will provide useful overviews or summaries of information including a very complete bibliography so that those who are interested in the mineral resources of Australia and its Territories will look to these reports as a prime source or starting point for their research.

It has been decided that we will publish Resource Reports by authors outside of BMR where the subject and the treatment are consistent with our overall objectives for the series. This particular report falls into that category and we hope that we will receive other documents from authors who are looking for a suitable outlet for information of this type.

The authors of this report are members of the New South Wales Antarctic Coal Measures Study Group and have considerable experience in the assessment of coal deposits. The report provides a useful summary of the geology and characteristics of the known coal measures and comments on possible exploration methods and the potential for utilisation and development of coal in Antarctica. The views expressed are solely those of the authors and do not necessarily represent the views of the Bureau of Mineral Resources.

A handwritten signature in black ink, reading "L.C. Ranford." The signature is written in a cursive style with a large initial "L" and a period at the end.

(L.C. Ranford)
*First Assistant Director,
Resource Assessment Division*

ABSTRACT

Most of the reported principal coal deposits in Antarctica lie generally within the Transantarctic Mountains: the majority are of Permian age and are present in the Victoria Group of the Beacon Supergroup. Several other deposits have been recorded in East Antarctica and in the Antarctic Peninsula, including minor occurrences of Mesozoic and Tertiary coal and carbonaceous shale.

Further studies are required to correlate the Antarctic coal measures with those of Gondwana sequences of other continents — at present, a broad age correspondence within at least the limits of geologic periods is reasonable.

As little systematic sampling using standard procedures has been carried out, it is impossible to make a reliable interpretation of data from the approximately 200 coal specimens analysed. Furthermore, the data refer to widely scattered localities, and do not provide a statistically reliable basis for assessing overall coal quality. However, the coals are dominantly bituminous or semi-anthracitic, the latter coal rank being developed in the proximity of igneous intrusion.

By normal coalfield geology standards, no progress has yet been made in assessing Antarctica's coal seams in terms of distribution, thickness and continuity, and subsequently towards the calculation, or even broadest estimation, of resources. Only rarely is information available on the extent of any particular coal seam beyond the observation made at a spot locality.

The possibility of economic coal exploitation, using known technology, seems extremely doubtful owing to: (1) the current insufficient knowledge of the deposits; (2) the difficulties and great expense involved in upgrading this information using known exploration techniques; (3) the environmental protection which would be required — particularly in regard to thermal effects, visual aspects, dust suppression, and waste disposal from possible beneficiation processes; (4) the practical difficulties of mining; (5) sociological factors; (6) the balance between energy used (i.e. fuel needed to establish and maintain a mine and deliver the coal to the market place) and energy gained (from mined products supplied to industry) as a result of coal exploitation; and (7) the economics of Antarctic coal in a competitive world market (beyond local use).

INTRODUCTION

This report attempts to bring together available information on the coal deposits of Antarctica and discuss factors that would be involved if these deposits were to be explored and mined.

The first indication of the possible existence of coal-bearing rocks in Antarctica was on the first Scott Expedition (1901-1904), when H.L. Ferrar, the expedition geologist, recorded the presence of carbonaceous material in a sedimentary sequence in Victoria Land (Ferrar, 1907).

Coal was first discovered by F. Wild during the British Antarctic ("Nimrod") Expedition of 1907-09 (David & Priestley, 1914). In the ensuing fifty years, only five more coal localities were recorded (Schopf & Long, 1966; Spletstoeser, 1980). Since the International Geophysical Year of 1957-58 many new data on the basic stratigraphy of Antarctic coal measures have been made available.

In assessing the previous work undertaken on the Antarctic continent which has a bearing on coal resources, the impressive geological and related studies in both the field and laboratory are noteworthy, in particular when one considers the limited duration of field seasons, the harsh climate, problems of accessibility and the blanketing by ice, snow and rock debris.

However, these studies of Antarctic coal measures have, to date, yielded information of little value in *properly* assessing the potential of the coal as an energy or other resource. Although a number of coal analyses are available in publications, these provide as little information on the coal resources as the chemical data of a single granite "spot" sample would on the chemical composition of a major batholith! Thus, the opinion that the Antarctic coal resources are substantial and may form a buffer against possible future world energy problems, must be viewed with scepticism. Geological knowledge of these coal resources is at best rudimentary. When all factors involved in upgrading this data are taken into account, it is evident that it will be a long time before the Antarctic coal resources can be *meaningfully* assessed.

Among the approximately 100 papers reviewed, there are only about ten containing useful analytical data on coal, of which seven are supported by petrographic information. Unfortunately, few of the analyses could be used in a *modern* coal exploration program. Only a few coal samples have been *properly* taken (i.e., to obtain a

representative channel sample) or located correctly in the coal seam during detailed stratigraphic studies. It is mostly unclear whether an attempt has been made to stratigraphically relate coal outcrops and their associated samples. Many published maps are designed for large-scale regional geological evaluation. Few maps are of sufficient detail to show coal measures as stratigraphic units, let alone individual seams, lateral continuity or areal distribution — not even of individual formations within such measures.

Many coal specimens used for laboratory studies are merely from a single spot locality (i.e., they are not channel samples) and, consequently, cannot be related to potential intra-seam variations. The accuracy claimed for the published data is in question. It is unfortunate that the logistical problems of working in the Antarctic, as related to proper sampling, stratigraphic measuring, and subsequent laboratory analyses, have only rarely resulted in reliable information.

It is obvious that a standardised methodological approach in the studies of Antarctic coal is needed, so that it becomes possible to integrate any data made available in the future. Only then can a reasonable assessment of the coal resources be made.

The New South Wales Antarctic Coal Measures Study Group was formed in 1980 with a view, among others, to put some of the agreed-upon principles in the investigation of coal deposits into practice. Earlier work, which members of this group undertook with the United States National Science Foundation, provided a basis for further study. More recently, the group has been working closely with the Antarctic Division of the New Zealand Department of Scientific and Industrial Research, operating in liaison with the Australian Antarctic Division. Detailed 1:50 000-scale mapping of the Quartermain Mountains and the Mt Fleming–Asgard Range–Olympus Range–Shapeless Mountain area has been completed. This has included the detailed measurement of sections (including coal seams) and sampling of such seams for chemical and petrographic analyses (Whitby et al., 1983; Bryan, 1983; McElroy & Rose, 1987). Further work was completed in 1985 in the Mt Bastion/Mt Robison area by Rose and Bradley of the NSW Antarctic Coal Measures Group (Rose, 1985).

STRATIGRAPHY AND COAL CHARACTERISTICS

General character of Antarctic coal measures

There is nothing unusual about the lithologic, stratigraphic or structural attributes of these coal measures when compared with various other coal deposits throughout the world. The mere existence of coal measures (by definition the lithologic record of abundant vegetation) in present-day ice-covered Antarctica (i.e., with outcrops of less than 1%) may on first consideration be surprising, implying that in the geological past a more temperate, even tropical, climate must have existed. This, together with much other evidence, has been interpreted as evidence that Antarctica was formerly part of the supercontinent Gondwanaland, joined to the other southern continents and to India. This is further discussed in the section on correlation.

The coal measures consist of sandstone and minor conglomerate, siltstone and grey shale, with both carbon-

aceous shale and coal seams as a relatively minor association. Many of the coal measures are intruded by Jurassic dolerites, mostly in the form of sills, discordant in places. Dykes are also common. The effect of intrusions on the coal seams is varied, but the low content of volatile matter in many of the analysed coals is attributable to the proximity of intrusions, as discussed in the section on **Coal characteristics**. Tectonic structures (due to moderate deformation) are rarely simple, but substantial displacements are commonly associated with several types of igneous intrusions.

Several geographically separated, distinct sequences of coal measures occur, and in the following description have been grouped according to their respective ages.

The accompanying map (Fig.1) shows that most of the coal-bearing units lie in the Transantarctic Mountains; others are present in the Ellsworth Mountains, Theron



■ Manned station
 ■ Beacon supergroup
 After "Geological Map of Antarctica" C. Craddock 1972

- 1 Areas where coal measure sediments have been identified (partly diagrammatic)
- TERTIARY COAL MEASURES (Table II)
 21 Cross Valley Formation
- JURASSIC COAL MEASURES (Table II)
 20 Ferrar Basalt (Interbeds of coal)
- ? JURASSIC/TRIASSIC COAL MEASURES (Table II)
 19 Unnamed - Smith Island
- TRIASSIC COAL MEASURES (Table II)
 18 "Timber Peak Beds"
 17 Allan Nunatak Formation
 16 Dominion Coal Measures, Falla Formation, Fremouw Formation
 15 Lashly Formation
- PERMIAN COAL MEASURES (Table I)
 14 Polarstar Formation
 13 Pecora Formation
 12 Theron Formation
 11 Bainedart Coal Measures
 10 Mithound Coal Measures
 9 Weller Coal Measures
 8 Takrouna Formation
 7 Unnamed - Horn Bluff
 6 Mt Glossopteris Formation
 5 Queen Maud Formation, Weaver Formation
 4 Buckley Formation
 3 Unnamed - Vestfjella (Kraul Mtns)
 2 Unnamed - Heimefrontfjella
 1 Amelang Formation

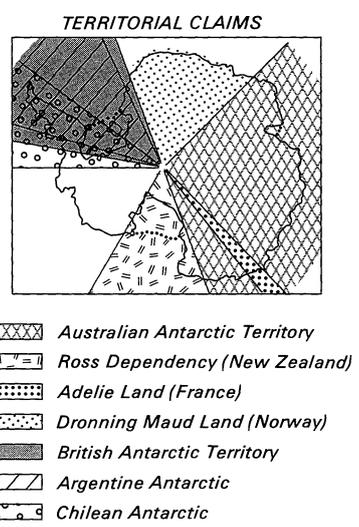


Fig. 1. Map showing location of coal measures in Antarctica. The Territorial Claims have been redrawn from the ANTARCTICA map (polar stereographic projection, 1:20 000 000, 3rd. edition, 1979), Division of National Mapping, Canberra. "The indication of boundaries on this map and the description of the areas within them are intended to agree with the national legislation of the countries concerned but are not to be treated as evidence of the official views of the Government of Australia with respect to the national legislation of other countries".

Mountains, Western Dronning Maud Land, Prince Charles Mountains, Horn Bluff, and Smith and Seymour Islands.

The major known coal seams lie in the Beacon Supergroup, the distribution of which is shown (after Craddock, 1972) on the map by the stippled area. Some minor seams occur on or adjoining the Antarctic Peninsula (including Map Ref. Nos. 19 and 21) and thin interbeds within a sequence of extrusive and intrusive rocks (i.e., flows, sills, dykes, plug-like bodies, and indeterminate irregular-shaped discordant bodies) of the Ferrar Group (Map Ref. 20).

The oldest sequence is almost entirely of Permian age (although it may extend to the top of the Carboniferous at one locality) (see Permian Coal Measures, and Table 1). The second major group is predominantly Triassic and/or Jurassic in age (see sections on the Triassic, Triassic/Jurassic, and Jurassic, and Table 11). In addition, a less important (i.e., not a proper "coal measure" *per se*) Cretaceous sequence of carbonaceous shales and siltstone occurs on the Antarctic Peninsula. Tertiary lignite has been recorded on Seymour Island.

The Permian coal measures are characterised by an assemblage of fossil leaves and other plant remains, the most typical being the simple *Glossopteris* leaf, and the Triassic by the fronded leaf of *Dicroidium*. Edna Plumstead and the late James Schopf have made noteworthy contributions to the knowledge of the fossil floras and the Permian/Triassic geology of Antarctica, as demonstrated by many references to their published and unpublished information. Spores and pollens also characterise these sequences (Kyle, 1976, 1977; Kemp et al., 1977; Kyle & Schopf, 1982).

Antarctica's most striking vertebrate fossils have been collected from the Triassic coal measures of the Fremouw

Formation (Elliot et al., 1970) at Coalsack Bluff in the Transantarctic Mountains.

The distribution of each of the coal measure sequences is described below, although in many cases only the more significant stratigraphic features are outlined. In most cases, there is little information. Details of coal seams and some examples of analytical data are given occasionally. For convenience, the sequences are described in numerical order, as shown on the Map Reference; the order of the numbering system has no significance within the age-based groups.

Permian coal measures

The geographic distribution of the Permian Coal Measures in Antarctica is similar to that of the Beacon Supergroup, as discussed in the Introduction. The individual sequences of the Permian Coal Measures differ considerably in thickness, lateral continuity, and internal make-up of the contained coal seams. Generalisations are, therefore, meaningless. (Quality variations in the coal are discussed below.)

As indicated in Table 1 and on the map (Fig. 1), there are fourteen coal measure sequences, including three unnamed ones, all considered to be Permian in age. These fourteen sequences are within the Beacon Supergroup, although evidence of continuity at time of deposition is lacking.

Amelang Formation and unnamed related units of West Dronning Maud Land (Map Ref. 1, 2 and 3)

In the extreme southwestern part of Kirwanveggen, Western Dronning Maud Land, the (?) Early Palaeozoic Urfjell Group is overlain unconformably by the Amelang Formation (Map Ref. 1) comprising 100 m of near-horizontal

TABLE 1. PERMIAN COAL MEASURES

LOCALITY	West Dronning Maud Land			Beardmore Glacier	Shackleton Glacier Area	Mt Fridtjof Nansen	Scott Glacier	Horlick Mountains (incl. Ohio Range)
	Kirwanveggen	Heimefrontfjella	Vestfjella (Kraul Mts)					
MAP REF	1	2	3	4		5		6
FORMATION	Amelang Formation	Unnamed — upper Beacon (? Upper Carboniferous)	Unnamed — upper Beacon	Buckley Formation			Queen Maud Formation Weaver Formation	Mt Gloss-opteris Formation
REFERENCES	Aucamp et al. 1972	Jukes 1972	Hjella A, & Winsnes, T. 1972	Grindley 1963 Grindley, McGregor & Walcott 1964 Barrett 1969	Barrett 1965 Laprade 1972	Barrett 1965	Doumani & Minshew 1965 Minshew 1967	Long 1964 Long 1965
LOCALITY	Horn Bluff	Rennick Glacier	Mulock Glacier to Mackay Glacier	Darwin Mountains	Lambert Glacier (Beaver Lake)	Theron Mountains	Pensacola Mountains	Ellsworth Mountains
MAP REF.	7	8	9	10	11	12	13	14
FORMATION	Unnamed	Takrouna Formation	Weller Coal Measures	Misthound Coal Measures	Bainmedart Coal Measures	Theron Formation	Pecora Formation	Polarstar Formation
REFERENCES	Mawson 1940	Dow & Neall 1974 Walker 1983	Allen 1962 Barrett et al 1972 Barrett & Kohn 1975 Kyle 1976 McKelvey et al. 1977 Matz et al. 1972 Mirsky et al. 1965 Mulligan et al. 1963a, 1963b Pyne 1979 Whitby et al. 1983 Pinet 1969	Haskell et al. 1965 Barrett et al. 1972	Crohn 1959 Mond 1972	Stephenson 1966	Schmidt & Ford 1969 Elliot 1975	Craddock et al. 1964 Craddock et al. 1965

Note: A very useful general reference is Elliot (1975)

strata that are correlated with the upper Beacon Super-group (Aucamp et al., 1972).

A 20 cm-thick carbonaceous shale occurs about 10-15 m above the unconformity. The sequence closely resembles that of the Permian sedimentary strata overlying basement at Heimefrontfjella (Jukes, 1972), about 120 km to the southwest (Map Ref. 2). The Heimefrontfjella sequence contains many thin coal seams between 2 and 10 cm thick. There is a general increase in coal seam thickness towards the top of the sequence, where one seam is 50 cm thick.

Other nearby outcrops of Permian sediments are at Fossilryggen, Vestfjella (i.e., Kraul Mountains) (Map Ref. 3), where 43 m of cross-bedded quartz sandstones, siltstone and fine-grained sandstone, some containing sand-filled worm tracks, are exposed (Hjelle & Winsnes, 1972). A dark clay shale, coaly to carbonaceous, at least 10 m thick near the top of the exposed sequence, contains *Glossopteris*, *Gangamopteris* and *Vertebraria*. The presence of *Gangamopteris* spp., as the only representative of the reticulate-veined Glossopteridae at Heimefrontfjella, suggests that the lowest rocks in the sequence may be Upper Carboniferous (Plumstead, 1975).

No analysis of these coals is available; they seem to be too inferior to merit analysis (Winsnes, pers. comm.).

Buckley Formation (Map Ref. 4)

In the central Transantarctic Mountains, the Buckley Formation crops out at the west-side of the Upper Beardmore Glacier, alongside the Shackleton Glacier, the north-face of Mt MacKellar, the Buckley Nunatak in the Beardmore Glacier, the Supporters Range to the southeast, and the Keltie Range. In the Beardmore Glacier area, the Buckley Formation overlies the Fairchild Formation along a local disconformity and is intruded by several Ferrar Dolerite sills. Plant fragments, coal streaks and coaly shale of geographically restricted extent, occur in the Fairchild Formation (Barrett, 1969), but as they contain no coal beds or carbonaceous shale, have not been shown in Table 1. The Fairchild and Buckley Formations were formerly collectively mapped by Grindley (1963) as the Buckley Coal Measures. The Buckley Formation (750 m thick) is generally of similar character to the Weller Coal Measures (see below). It consists of coal measures comprising at least fifteen idealised cycles composed of basal sandstones, conglomeratic in places, grading upwards into grey siltstones, which in turn become more shaly, carbonaceous and coaly at the top. Generally, then, the lower 100 m of this 750 m-thick sequence consists mainly of sandstone, commonly conglomeratic, the remainder in most places being principally carbonaceous shale or mudstone. The Buckley Formation sandstones are mostly composed of zeolitised detritus of volcanic origin, which seems to be the case for the coal-measure sandstones over a wide area (Barrett et al., 1972). The sequence is intruded by several sills of the Ferrar Dolerite.

Leaf collections from the Beardmore Glacier area have indicated a Permian age for the Buckley Formation (Rigby & Schopf, 1969). The flora is very abundant (Grindley, 1963) including *Glossopteris indica* (most abundant species) *G. decipiens*, *G. cf. browniana*, *G. cf. angustifolia*, and *Noeggerathiopsis hislopi*, the latter being recorded for the first time in Antarctica.

The Buckley Formation was named for the Buckley Nunatak where the coal measures were discovered by F. Wild during the British Antarctic ("Nimrod") Expedition of 1907-09. From this locality, Dr E.A. Wilson collected the first Antarctic *Glossopteris* flora during the British Antarctic ("Terra Nova") Expedition of 1910-13 (Seward, 1914).

In the Shackleton Glacier area, at Mt Butters, La Prade

(1972) recorded a thickness of 467 m for the complete formation. Between the Shackleton Glacier and the Axel Heiberg Glacier, Barrett (1965) recorded a complete section of 259 m at Mt Surprise and incomplete sections of 253 m and 195 m, respectively, at Mt Wade and Mt Fridtjof Nansen. At this latter locality, at least four beds of impure limestone, each approximately 1 m thick, occur in the lower 60 m of the measures.

At Coalsack Bluff to the north of Buckley Nunatak, a 220 m section of the formation is exposed, containing an 8 m thick coal seam at the top of the boundary with the overlying Fremouw Formation. Two thinner seams, respectively 105 m and 130 m lower in the sequence, have been observed (Collinson & Elliot, 1984).

The descriptions of the coal seams are generalised, albeit usefully, as being throughout the area composed of "lenses of shaly coal" (at Beardmore Glacier; Grindley, 1963), "coal with a maximum thickness of 11 m" (general comment; Elliot, 1975), "dark shales . . . quite coaly in places" and "20 feet of coaly shale and fissile coal" (at Mt Fridtjof Nansen; Barrett, 1965), "one dark shale contains four coaly horizons" (at Cape Surprise; Barrett, 1965); "light coloured carbonaceous shales and coals", "fissile coaly shales and coals" (at Mt Butters; La Prade, 1972); "coal comprises 3 to 6% of most sections" (in Beardmore Glacier area) and "at least 10.7 m of coal in the formation" (at Mt Wild; Barrett, 1969).

The records of chemical analyses of raw coal (i.e. as sampled in the field) of the Buckley Formation are somewhat inconclusive as to stratigraphic positioning. Samples Nos. 115 and 116 in the table below from the Queen Elizabeth Range and Dominion Range, respectively (from Schopf & Long, 1966), probably are from the Buckley Formation. Barrett (1969) provided five coal analyses (floats at S.G. 1.6) with ash contents between 8.1% and 21.4% of samples from the Beardmore Glacier area. Representative analyses (i.e., Samples No. A321 and C203) of the "as received" type are also given in Table 2. (Note that selected examples in this table and other tables following do not cover the full range of values of all available analyses.)

TABLE 2. ANALYSES OF COAL FROM THE BUCKLEY FORMATION, QUEEN ELIZABETH AND DOMINION RANGES, AND BEARDMORE GLACIER.

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
115	3.9	12.8	68.0	15.3	26.38	0.5
116	6.5	16.2	61.1	16.2	24.17	0.5
A321	2.9	14.8	74.2	8.1	28.49	0.5
C203	3.5	12.2	77.4	6.9	29.31	0.8

Queen Maud Formation and Weaver Formation (Map Ref. 5)

A 660 m-thick section of sandstone, siltstone, shale, coal and minor conglomerate with dolerite intrusions, is exposed in the Queen Maud Mountains, Mt Weaver area, at the head of the Scott Glacier. No coal occurs in the lowest two of the three units of the Weaver Formation, although there are beds of black and carbonaceous shale interlayered with both massive and thin-bedded sandstone (Doumani & Minshew, 1965, fig. 3; Minshew, 1967).

The topmost unit of the Weaver Formation comprises 76 m of strata, mostly consisting of massive sandstone beds. Animal burrows up to 3 cm in diameter and a variety of other sedimentary structures characterise the unit. In the upper 15 m of the unit are two irregular coal seams intercalated with silty shales.

Disconformably overlying the Weaver Formation is the Queen Maud Formation, 433 m thick. The base of this formation is a massive conglomeratic quartz sandstone of substantial extent. Above this conglomeratic sandstone are abundant fossil leaves and fossil wood, including tree trunks up to 60 cm in diameter; the roots of some upright trunks extend downward into the underlying layers. Two thin beds of coal occur directly beneath the conglomeratic sandstone, but there are no less than 32 distinct beds of coal recognisable above this sandstone. Most of the formation comprises cyclical sequences of sandstone, shale and coal. The shales are generally black and rich in *Glossopteris* leaves.

The many coal beds which are dispersed through the shales vary in thickness from several cm to 8 m; in some cases coal beds 6 m or more in thickness pinch out to a trace or disappear completely within short distances. Two dolerite sills, the thicker being 40 m, intrude the coal-bearing sequence. Thirty analyses of coal samples from the Mt Weaver area have been published (Schopf & Long, 1966), mostly based on samples collected by V.H. Minshew in 1962-63.

Examples of typical proximate analyses of this material, as received, are given in Table 3.

TABLE 3. ANALYSES OF COAL FROM THE QUEEN MAUD FORMATION, MT WEAVER

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
45	2.7	13.6	66.2	17.5	25.14	0.6
54	2.9	18.4	72.8	5.9	28.66	0.7

The relationship between these analytical data of the Mt Weaver Coals and other coals is further discussed below (see also Fig. 2).

Mt Glossopteris Formation (Map Ref. 6)

The Mt Glossopteris Formation (Long, 1964, 1965a), 700 m thick in the Mt Schopf-Mt Glossopteris area of the Ohio Range, Horlick Mountains, consists of approximately equal proportions of medium grey arkose or feldspathic sandstone and ash-grey to black shale and siltstone together with at least eight coal seams, the latter from 1.2 to 3.6 m thick. An exploratory adit was blasted on Terrace Ridge, Mt Schopf, into the lowermost, thickest (3.6 m) coal seam. Analyses of the coals indicated a variation in ash content from 10 to 40%, commonly being 25 to 30%. A composite sample of coal from the adit showed 80.7% fixed carbon (d.m.m.f.); the moisture-free ash content being 25.3%. Therefore, it is low-volatile, bituminous coal. Typical analyses (Schopf & Long, 1966) of coals from Terrace Ridge, on as-received basis, are given in Table 4.

TABLE 4. ANALYSES OF COAL FROM THE MT GLOSSOPTERIS FORMATION, TERRACE RIDGE, MT SCHOPF, OHIO RANGE

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
71	8.0	14.3	67.5	10.2	25.26	0.4
77	6.5	15.0	62.6	15.9	23.86	0.5

The sequence is uninterrupted by igneous intrusions, but is overlain by a dolerite sill of presumed Jurassic age, as a capping to Mt Schopf.

Many of the shales contain fossil leaves, including a profuse assemblage of *Glossopteris* (five species), seeds (*Samaropsis*), fossil wood (*Dadoxylon* and *Antarcticoxylon*), small stems, spores and pollens, and also the

conchostracans *Leaia* and *Cyzicus*, the latter strongly indicating a Late Permian age for the sequence. *Glossopteris ampla* and fossil logs are, respectively, up to 33 cm and 7 m long. Unidentified animal trails are also present.

Unnamed Formation at Horn Bluff (Map Ref. 7)

At Horn Bluff in George V. Land, Mawson (1940) reported cross-bedded feldspathic sandstone with minor carbonaceous shale and some coal outcrops. The coal occurs as laminae and lenses in the sandstone. The carbonaceous shale contains plant microfossils assumed to be Permian in age, although some doubt appears to exist as to this age (Elliot, 1975).

Takrouna Formation at Rennick Glacier (Map Ref. 8)

In the Freyberg Mountains, Mesa Range Area, and the Morozumi Range Area in the Rennick Glacier region (ca 72°S164°E), some 300 m of Takrouna Formation sediments occur in scattered outcrops, resting unconformably on a metasediment/plutonic basement (Dow & Neal, 1974; Walker, 1983). The sequence is composed of alluvial plain sediments with minor carbonaceous shales and coal seams; Walker (1983) reported that the coal seams are on average 0.7 m thick and range up to 1.2 m in thickness. Ferrar Group dolerites overlie and intrude the Takrouna Formation and extensive block-faulting associated with their emplacement has tilted the generally almost flat-lying sequence, producing locally steep dips. *Glossopteris*, *Gangamopteris*, *Vertebraria* and *Paracalamites* in the Takrouna Formation indicate a Permian age.

The nearest-known Permian rocks to the south of this occurrence are some 600 km away in the Mackay Glacier region and the Horn Bluff rocks are a similar distance to the west.

Weller Coal Measures (Map Ref. 9)

The term Weller Coal Measures has been extended by McKelvey et al. (1977) to include the Mt Bastion Formation (Mirsky et al., 1965) (that is, the former Mt Bastion Coal Measures of Allen, 1962) at the heads of Victoria Valley and the synonymous Mt Fleming Formation (Matz et al., 1972) at Mt Fleming and environs. The Weller Coal Measures thus extend south from the vicinity of Allan Nunatak and Mt Gran in the north, via the heads of Victoria Valley and Wright Valley, Shapeless Mountain and Mt Fleming, the Quartermain Mountains (type area) and farther south, including the Lashly Mountains and Mt Portal, to the head of Deception Glacier.

Dolerite intrusions commonly disrupt the coal seams; this is graphically displayed on the southeast flank of Mt Gran, where about 200 m of sandstone and coal beds are broken into a most irregular mass by about 150 m of dolerite.

McKelvey et al. (1977) provided the most recent coherent account of the Weller Coal Measures, some 200 m thick. They divided the measures into three lithologic facies:

- Fining-upwards cycles of coarse feldspathic sandstone grading into shale and coal;
- carbonaceous shale with interbedded fine sandstone (with two or three limestone horizons near the top of this sandstone); and
- quartzose sandstone and conglomerate, which may contain fallen horizontally oriented logs or tree stumps in growth position.

Pyne (1978, 1979, 1983) has also offered facies concepts for the Weller Coal Measures. The compilations by Barrett (ed., 1971) and Barrett & Webb (eds., 1973) contain valuable records of measured sections of the Beacon Supergroup, including stratigraphic details of 27

occurrences of the Weller Coal Measures as well as 163 descriptions of the other formations of the supergroup.

The New South Wales Antarctic Coal Measures Study Group has recently mapped in detail (1:50 000 scale) the Weller Coal Measures in the Quartermain Mountains of the Olympus Range/Shapeless Mountain/Mt Bastion/Robison Peak area. This work has been complemented by detailed stratigraphic section (including coal seam section) measurement, including sampling and subsequent chemical laboratory analysis of coal seams at Kennar Valley, Mount Fleming and Shapeless Mountain (Whitby et al. 1983; Bryan, 1983; McElroy & Rose, 1987; Rose, 1985). McKelvey et al. (1977) stressed the lensoidal nature of individual beds and the abundance of washouts and scour-and-fill structures; and the resulting difficulty in correlating sections only a kilometre or so apart.

Many coal seams have been recorded from the Weller Coal Measures. Among the thicker seams are those recorded by McKelvey et al. (1977), 7.0m at Mt Fleming; Barrett (1971, p.53) 3.0 m at Mt Crean; Barrett & Webb (1973, p.40) 4.5 m at Kennar Valley; Matz et al. (1972) (based on Pinet, 1969) 4.6 m at Mt Feather; Mulligan et al. (1963a) who recorded five coal beds at Mt Gran, including one 4.5 m thick, but which apparently contains only about 2.0 m of coal. At Willett Range, fourteen coal beds were recorded by Mulligan et al. (1963b), the thickest being 4.5m but which contained only about 1.3m clean coal. It should be stressed that, in general, thicknesses recorded in the literature mostly refer to overall seam thickness, including bands of grey shale, carbonaceous shale and the like; the coal thickness in almost all cases is likely to be less than the stated seam thickness.

Within the geographic distribution of the Weller Coal Measures, the coal seam occurrences diminish from north to south. Examples of proximate analyses of the Weller Coal Measures at Mt Crean from Kyle (1976), which are properly related to measured sections in Barrett (1971), on as-received basis, are given in Table 5.

TABLE 5. ANALYSES OF COAL FROM THE WELLER COAL MEASURES, MOUNT CREAN

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
23447	4.8	10.1	77.4	7.7	28.94	0.94
23475	6.0	12.0	76.4	5.6	28.68	0.72

TABLE 6. ANALYSES OF COAL FROM THE WELLER COAL MEASURES, KENNAR VALLEY

Thickness (m)	Appt. R.D.	Yield %	Prox. Anal. (ADB)				Total S.%	S.E. (ADB) (MJ/Kg)
			Moist.	Ash	V.M.	F.C.		
0.90	1.59	67.2	7.2	9.6	9.6	73.6	0.68	26.84
0.44	1.49	96.9	4.5	8.5	10.4	76.6	0.72	27.85
0.17	1.48	94.1	7.2	9.2	10.9	72.7	0.74	29.10

Washed coal samples from Kennar Valley (obtained from measured stratigraphic sections) were analysed, yielding the results shown in Table 6 (McElroy & Rose, 1987; modified from Whitby et al., 1983). In this table, the analysed samples consisted in all cases of floats at S.G. 1.70 plus fines. (See later discussion in reference to Fig. 2, in which the results of many other analyses are included.)

Misthound Coal Measures (Map Ref. 10)

The Misthound Coal Measures crop out in the Darwin Mountains where poorly preserved *Glossopteris* and *Gangamopteris* indicate their Permian age. The unit is 93 m thick and principally consists of ash-grey cross-bedded sandstone in beds up to 1.5 m thick, intercalated with

carbonaceous sandstone, shale and coal beds up to 20 cm thick (Haskell et al., 1965). At the base of the formation are conglomerate beds up to 30 cm thick. Locally, the lower part of the formation consists of massive sandstone.

Bainmedart Coal Measures (Map Ref. 11)

The Bainmedart Coal Measures comprise most of the sedimentary sequence at Beaver Lake, Lambert Glacier, Prince Charles Mountains (Crohn, 1959; Mond, 1972). The estimated thickness of the formation is approximately 1800 m; the average dip is 11°.

Almost half of the sequence is light-coloured feldspathic sandstone, commonly cross-bedded. Siltstone and shale of varied colour, structure and texture constitute most of the rest of the unit; many of these beds are carbonaceous and grade into coal.

Abundant leaf and stem impressions throughout the formation include *Glossopteris* (6 species), *Gangamopteris*, *Vertebraria* and *Taeniopitys scotti* (petrified wood), recorded in detail by White (1969).

Evidence of the Upper Permian age was first determined, on the basis of plant microfossils, by Balme & Playford (1967) and Kemp (1969). There is a close lithological resemblance to the Mt Glossopteris Formation of Ohio Range (Long, 1965).

Some 65 coal seams distributed through the sequence range from 8 to 350 cm in thickness, averaging about 65 cm. They are laterally uniform in thickness over many hundreds of metres. In a few places, the coals have been severely baked where they have been intruded by basic to intermediate dykes.

The analytical studies of Bennett & Taylor (1972) are of special interest, in that the marked effects of heat alteration observed in most other Antarctic coals described to that date were absent in all cases except two.

Of the 65 coals sampled, the 12 that were analysed in detail were classified as high-volatile bituminous, with ash contents averaging about 25% and specific energies (d.m.m.f.) ranging from about 25 to more than 32 MJ/Kg. All 65 samples were weathered to some degree, influencing most analytical results.

Bennett & Taylor (1972, p.596) specifically commented in regard to the relatively high mineral matter content, that no real estimate of likely ash yield can be made in the absence of systematically taking of either channel, pillar or bore-core samples.

Examples of typical analyses (Bennett & Taylor, 1972) from these measures, on the as-received basis, are provided in Table 7. (See also discussion later under **Coal characteristics**, especially in relation to Fig. 2.)

TABLE 7. ANALYSES OF COAL FROM THE BAINMEDART COAL MEASURES, PRINCE CHARLES MOUNTAINS

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
AM20	5.0	34.2	42.3	18.5	21.47	0.56
AM105	3.5	33.4	48.0	15.1	25.26	0.62

Theron Formation (Map Ref. 12)

Stephenson (1966) described at least five coal horizons in the Lower Permian Theron Formation. Brown & Taylor (1960) concluded that coals from this formation had been altered by heat in the range 500°C to 1000°C due to dolerite intrusion under unusually high pressure, as suggested by x-ray analysis.

Typical analyses (Brown & Taylor, 1960) from this formation on as-received basis, are given in Table 8. (See

TABLE 8. ANALYSES OF COAL FROM THE THERON FORMATION, THERON MOUNTAINS

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
11333	7.3	7.8	75.3	9.6	26.77	0.40
11337	2.4	4.3	79.8	13.5	26.61	0.06

also discussion below under **Coal characteristics**, especially in relation to Fig. 2.)

Three horizons have yielded plant fossils including *Glossopteris* (7 species), *Annularia*, *Vertebraria* and *Phyllothea*. The flora represents a higher stratigraphic level than that found at Whichaway Nunataks, 240 km away, in which four species of *Gangamopteris* were also found, this genus being indicative of lowermost Permian (Plumstead, 1964).

Pecora Formation (Map Ref. 13)

The Pecora Formation (Schmidt & Ford, 1969) crops out in the Pensacola Mountains of East Antarctica; the outcrops are in isolated nunataks in the southern Forrestal Range and in the Pecora Escarpment where it is intruded by dolerite sills (Elliot, 1975). Thin-bedded fine sandstone, interlayered with thin siltstone and shale, dominate the sequence, but many of the interbeds are carbonaceous or coaly and locally contain *Glossopteris* leaves.

A single analysis of coal from the Patuxent Range in the Pensacola Mountains (probably from the Pecora Formation), representing floats at S.G. 1.85, was recorded by Schopf & Long (1966) on as-received basis, as shown in Table 9.

TABLE 9. ANALYSIS OF COAL FROM THE PECORA FORMATION, PATUXENT RANGE, PENSACOLA MOUNTAINS

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
114	1.0	5.9	87.2	5.9	30.38	0.3

The exceptionally low volatile matter of this coal should be noted; it is attributed to the close proximity to igneous intrusion. This analysis, accordingly, plots in the lower area in Fig. 2.

Polarstar Formation (Map Ref. 14)

The Polarstar Formation crops out in the Sentinel Range, Ellsworth Mountains, consisting of an interbedded

argillite/greywacke sequence. The formation is at least 1500 m thick, as reconstructed from three incomplete and isolated sections at Mt Ulmer, Polarstar Peak and Mt Weems (Craddock et al., 1964, 1965). These localities span a distance of about 15 km; *Glossopteris* has been collected from several of these exposures. For example, at Polarstar Peak, *Glossopteris* leaves were collected from six units throughout the formation. Coal beds up to 30 cm thick are common in the top half of the formation whereas some thin coal beds occur at lower levels.

Examples of proximate analyses of these coals (Schopf & Long, 1966) on as-received basis, are given in Table 10. (See also Fig. 2.)

TABLE 10. ANALYSES OF COAL FROM THE POLARSTAR FORMATION, ELLSWORTH MOUNTAINS

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
111	5.9	14.2	69.5	10.4	26.14	0.3
112	4.3	12.0	66.5	17.2	24.38	0.2

Triassic

The distribution of Triassic coal-bearing strata is relatively restricted; recorded outcrops are confined to the region between Rennick Glacier in the north and Beardmore Glacier in the south of the Transantarctic Mountains. Triassic beds without coal extend farther south to the vicinity of Scott Glacier, although older coals occur in that region. (See Table 11 for post-Permian coal measures.)

Lashly Formation (Map Ref. 15)

In southern Victoria land, in the Quartermain Mountains region, the Lashly Formation (McElroy, 1969) is over 500 m thick, predominantly consisting of light coloured sandstones and siltstones with thin coal beds, numerous carbonaceous intervals and abundant coaly streaks throughout (as recorded at Horseshoe Mountain, Mt Crean and Mt Dearborn; Barrett, 1971; Barrett & Webb, 1973). *Dicroidium odontopteroides* characterises many outcrops of this formation. Proximate analyses of some Lashly Formation coals are conveniently listed by Kyle (1976). Table 12 presents examples of the analytical results of samples from measured sections at Portal Mountain (Barrett, 1971; p.39) and Mt Bastion, Shapeless

TABLE 11. POST-PERMIAN COAL MEASURES

LOCALITY	S. Victoria Land	Beardmore Glacier Area-Dominion Range	Allan Nunatak	Priestley Glacier	Smith Island (Antarctic Peninsula)	Upper Rennick Glacier	Seymour Island (Antarctic Peninsula)
MAP REF	15	16	17	18	19	20	21
AGE	TRIASSIC	TRIASSIC	TRIASSIC (may range into Jurassic)	TRIASSIC	?JURASSIC/ TRIASSIC	JURASSIC	TERTIARY
FORMATION	Lashly Formation	Dominion Coal Measures Falla Formation Fremouw Formation	Allan Nunatak Formation	"Timber Peak Beds"	Unnamed Doubtful occurrence - See text	Ferrar Basalt (interbeds of coal)	Cross Valley Formation
REFERENCES	McElroy 1969 Barrett et al. 1972	Grindley 1963 Grindley, McGregor & Walcott 1964 Barrett 1969 Elliot, Barrett & Mayewski 1974	Gunn & Warren 1962 Townrow 1967 Matz et al. 1972	Skinner & Ricker 1968 Norris 1965	Dalziel 1977 Lovering & Prescott 1979	Gair 1967 Gair, Norris & Ricker 1965	Fleming & Askin 1983

NOTES: (1) A very useful general reference is Elliot (1975)

(2) Various carbonaceous sequences, Jurassic/Cretaceous in age, which are believed to be of less significance than most of those tabulated, occur on the Antarctic Peninsula; these have been briefly discussed in the text.

Mountain and Mistake Peak (Barrett & Webb, 1973, p.146, p.117, p.139, respectively).

TABLE 12. ANALYSES OF COAL FROM THE LASHLY FORMATION, SOUTH VICTORIA LAND

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
Portal Mountain (as received)	4.9	11.2	41.4	42.5	16.12	0.43
Mt Bastion (Floats SG 1.4 92.4% original)	5.7	9.6	70.7	14.0	26.61	0.48
Mistake Peak (as received)	4.7	8.0	54.3	33.0	20.33	0.74

Clearly the as-received coal samples are high in ash content; however, it is noted that in the Mt Bastion sample, when gravity separation is applied, a low-ash product may be achieved. This does not, of course, necessarily apply to all coals.

Dominion Coal Measures, Falla Formation, Fremouw Formation (Map Ref. 16)

At the Beardmore Glacier, the upper 100-200 m of the 650 m thick Triassic Fremouw Formation (Barrett, 1969, 1972) consists of volcanic sandstone containing coal beds. Fossil remains of the tetrapod *Lystrosaurus* have been discovered 76 m above the base of the Fremouw Formation (Barrett, 1969) and are relatively abundant at Coalsack Bluff (Elliot et al., 1970). *Dicroidium odontopteroides* occurs in the top 30 m of the type section at Fremouw Peak (Rigby & Schopf, 1969). *Dicroidium* and other plants, including logs up to 1 m in diameter, are present in the upper Fremouw Formation with the coals. (Note: This coaly sequence corresponds to most of the lower coaly part of the Falla Formation in the usage of that term by Grindley, 1963).

Details of the lower 270 m of the Fremouw Formation, exposed at Coalsack Bluff (West of Fremouw Peak), are described by Collinson & Elliot (1984). No coal seams are recorded.

In the Dominion Range on the southern side of the Beardmore Glacier, the Dominion Coal Measures are at least 365 m thick (McGregor, 1965); there are numerous seams of anthracite up to 4.5 m at Safety Spur.

The coal measures consist of cross-bedded grey sandstone and dark shale; silicified logs, intraformational breccias and carbonaceous beds are common. More recent work by Barrett (1969) and Elliot et al. (1974) indicated that these measures correspond to the upper part of the Fremouw Formation.

Although the published results of the few coal analyses from these formations are not quite clear in all respects, Barrett (1969, p.38) recorded an analysis of the Fremouw Formation from the Beardmore Glacier area (Table 13).

TABLE 13. ANALYSES OF COAL FROM THE FREMOUW FORMATION, BEARDMORE GLACIER

Sample No.	Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	S %
F328 Floats at S.G. 1.6	4.2	22.5	62.1	11.2	25.07	0.4

Allan Nunatak Formation (Map Ref. 17)

At Allan Nunatak, Gunn & Warren (1962, p.111) recorded irregular lenses of coal at several horizons, and Townrow (1967) noted some 20 m of grey siltstone con-

taining two impure coal seams 0.3 to 0.6 m thick, overlain by 25 m of massive sandstone. Townrow (1967) identified *Dicroidium odontopteroides* and *D. dutoitii* from this sequence, but Matz et al. (1972) applied the term Allan Nunatak Formation to it and suggested that the beds may range up into the Jurassic.

"Timber Peak Beds" (Map Ref. 18)

Triassic coal from Timber Peak and Eskimo Point, on the southern flank of the Priestley Glacier, occurs as thin layers in white sandstone and black siltstone. The coals, after manual separation from the host rock (Skinner & Ricker, 1968) were classified as sub-bituminous to bituminous despite the graphitic appearance, on the basis of the analysis given in Table 14 of a sample from Timber Peak.

TABLE 14. ANALYSES OF COAL FROM THE "TIMBER PEAK BEDS", PRIESTLEY GLACIER

Moisture %	V.M. %	F.C. %	Ash %	S.E. MJ/Kg	Sulphur %
13	33	34	20	15.53	0.8

Contrary to field observation, it appears that the closely associated intrusive Ferrar Dolerite has had little baking effect. This is further discussed below in **Coal characteristics**. Norris (1965) concluded that the microflora from the associated sediments indicated a late Triassic age.

In northern Victoria Land, the Triassic strata are generally relatively thin, from less than 15 m to more than 130 m, principally consisting of arkosic sandstone, quartzose sandstone and variegated sandstone with thin seams of coal and bands of carbonaceous shale.

?Triassic/Jurassic

Dalziel (1977) reported the possibility of a local occurrence of coal beds within an undeformed sedimentary sequence apparently resting on highly deformed and metamorphosed pre-Jurassic rocks on Smith Island of the South Shetland Islands (Map Ref. 19). "Good coal" mentioned at this locality was referred to in the US Hydrographic Office Antarctic Sailing Directions (The Antarctic Pilot, 1st Edition, 1930, p.69) (Dalziel, 1977; 1982). Lovering & Prescott (1979) indicated that the coal is probably Triassic or Jurassic in age, but suggested that the beds are merely of local importance. Dr R.J. Adie of the British Antarctic Survey has recently advised (pers. comm., 1982) that "This island is now known to be composed entirely of metamorphic rocks and therefore the possibility of coal in the sequence is extremely remote". This is as indicated on the British Antarctic Survey's Geological map of Northern Graham Land and South Shetland Islands.

Jurassic

Ferrar Basalt (Kirkpatrick Basalt) Interbeds (Map Ref. 20)

In the Upper Rennick Glacier region, the lavas of the Jurassic Ferrar Basalt (Kirkpatrick Basalt) contain at several horizons well-stratified sedimentary sequences of arkosic sandstone, siltstone and mudstone up to 20 m thick with thin coaly lenses, disseminated carbonaceous material, silicified wood, and penecontemporaneous mudstone-pebble conglomerates (Gair, 1967). Two microfloras from a mudstone bed, about 200 m above the base of the basalt, have been identified as being early Jurassic in age (Gair et al., 1965; Norris, 1965).

Jurassic/Cretaceous

On the Antarctic Peninsula, there are a number of occurrences of thin carbonaceous shales indicative of the coal-forming environment (R.J. Adie, pers comm). These include Middle Jurassic strata at Hope Bay (63°0'S; 57°W) near the tip of the peninsula and at various other localities on the east coast, including along the Lassiter Coast (Williams et al., 1972).

Elliot et al. (1978) referred to "plant-bearing sandstones" of Mesozoic age at Hope Bay and nearby Fleiss Bay; to Lower Cretaceous strata on Alexander Island (71°38'S; 69°W); and to Upper Cretaceous strata around James Ross Island (58°S; 64°30'W).

Tertiary

A coal seam about 1 m thick has recently been reported (Map Ref. 21) from the upper part of the Palaeocene-Eocene Cross Valley Formation on Seymour Island (64°17'S; 56°45'W) (Fleming & Askin, 1983). Thin discontinuous clay partings occur within the seam which is exposed over a distance of about 6 m. Fleming & Askin (1983) suggested the coal to be a lignite.

Correlation

In the early 1960's, a constructive attempt was made (Grindley, 1963) to correlate the Permian and Triassic coal measures of Antarctica to corresponding units in South Africa, South America, India and Australia — the land masses that were once joined together in the Gondwana supercontinent. In particular, the distribution of the Permian *Glossopteris* flora and the Triassic *Dicroidium* flora have been key parameters in supporting this correlation. The occurrence of glacial sediments within or at the base of Permian sequences in East Antarctica, on the Falkland Islands, Argentina, South Africa and Australia constitutes another resemblance in lithologic association. Additionally, Jurassic dolerite invades the coal measures both in Antarctica and some, but not all, other Gondwana land masses.

The discovery of amphibian and reptilian remains in the Triassic of Antarctica, similar to those in Africa and India (Elliot et al., 1970; Colbert, 1970), was hailed as positive evidence of a land connection between those continents. In addition, Doumani & Tasch (1965) and Tasch (1968) have drawn parallels between Permian rocks of the Ohio Range, Antarctica, and the Newcastle Coal Measures of Eastern Australia, equivalent beds in southern Africa and South America, on the basis of leaidd conchostracans (clam shrimps) common to all sequences.

Kyle & Schopf (1982) established diagnostic plant microfossil assemblages which allow correlation between Late Carboniferous to Triassic Beacon Supergroup sequences in the Transantarctic Mountains, and which also correlate with palynologic successions in Australia. This work complemented earlier work of Kyle (1977) which, on the basis of palynomorphs, correlated rocks of Late Carboniferous/Late Triassic ages of the Beacon Supergroup and similar sequences in Eastern Australia.

Harrington (1965) has produced strong argument in support of linking Antarctica with southern Africa and eastern South America and, to a lesser extent, with India and Australia. Craddock (1982) consolidated the evidence for the reality of Gondwanaland, although Grindley & Davey (1982) presented arguments both for and against the reconstruction of New Zealand, Australia and Antarctica. McElroy (1969) concluded that the lithostratigraphic record of Antarctica and Eastern Australia indicate

sedimentary environments common to both areas. However, the variety of environments in Eastern Australia is not known from Antarctica and precise time-equivalency has yet to be demonstrated. Elliot (1975) in a critical review of the Gondwana basins of Antarctica, stressed the incompleteness of sections, the wide separation of sequences, and the difficulty of tying sections to those elsewhere. Elliot saw little basis for comparison with most Australian coal basins.

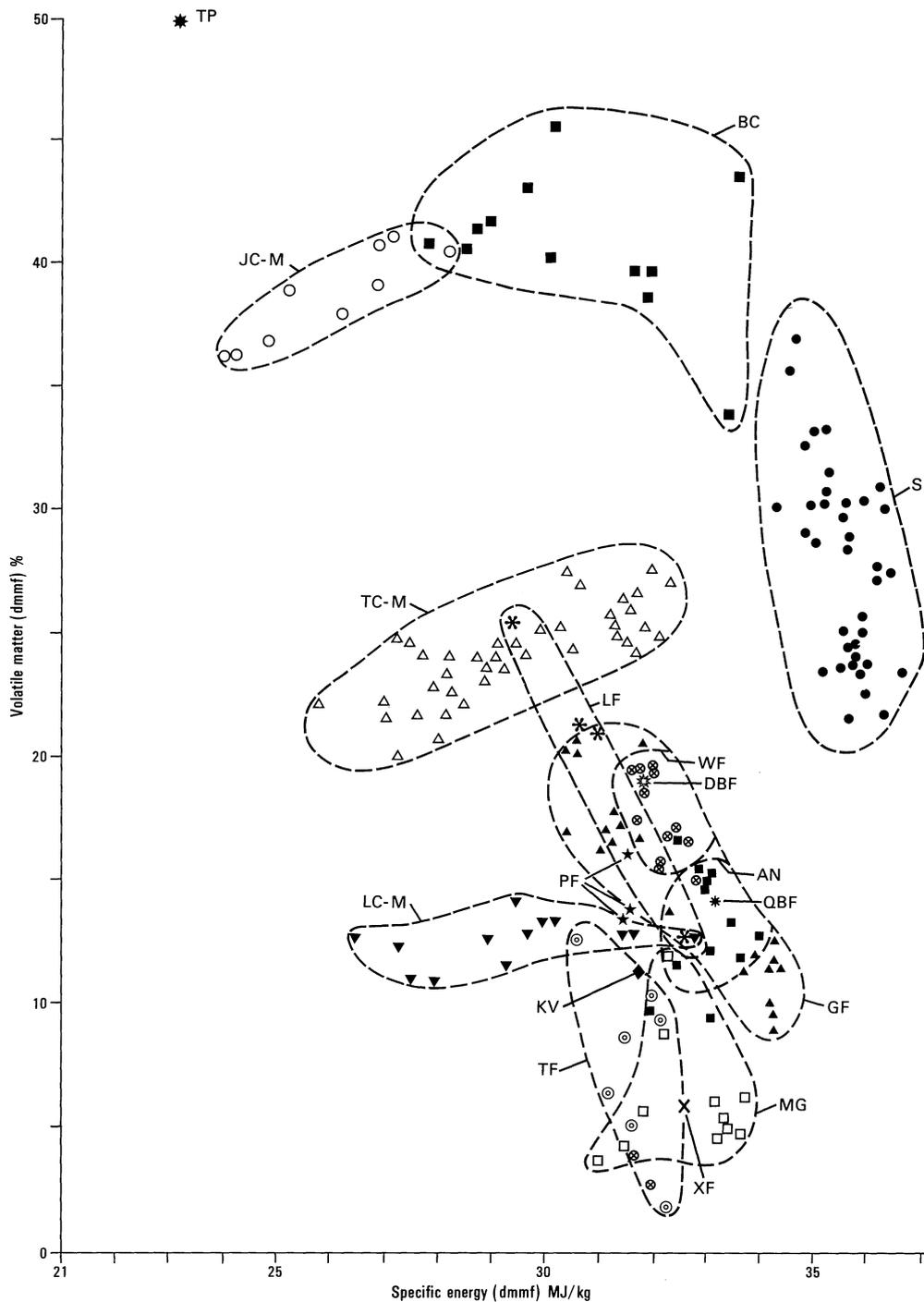
However, evidence is accumulating that sequences may be broadly correlated, but, on balance, we are aware that correlation of detailed subdivisions is not possible as yet. Between interconnected coal basins of Eastern Australia, where in places very detailed exploration programs have been carried out, the correlation of *whole* coal measure sequences, let alone individual seams, has yet to be established. Indeed, the same applies from sub-basin to sub-basin and within parts of basins in this region. The state of stratigraphy in Antarctica is such that, as pointed out below, a great deal of additional coalfield exploration must be carried out before correlations can be made in reasonable detail, this being a first basic step in the evaluation of any coal resource.

Coal characteristics

The present work is not an in-depth study of the various characteristics of Antarctic coals. As we have stressed elsewhere, the analytical data are generally too scattered for an overall assessment, and in most cases are based on samples which were not taken by a standard method. However, coals from certain areas and specific stratigraphic intervals have been studied in some detail. Many of these data have been incorporated into a major work by Schopf & Long (1966) on "Coal metamorphism and igneous associations in Antarctica", the scope of which is wider than the title suggests. It contains general information from coal studies in Antarctica and is a compendium of much, if not all, of the pre-existing data together with those authors' own valuable field and laboratory contributions. Amongst other contributions, they stressed that "no amount of laboratory technique can compensate for inadequacy in sampling" and emphasised that nearly all analyses were carried out on outcrop surface samples and hence subject to some degree of weathering, slight though this may be in many cases.

Petrographic and other physical properties of samples, provided by James Schopf and William Long from the Ohio Range and John Mulligan from Mt Gran, were determined by Schapiro & Gray (1966). Earlier, detailed work on optical, chemical and physical properties was carried out by Brown & Taylor (1960) on seven coal samples from the Theron Mountains, collected by the Trans-Antarctic Expedition in 1957 (Stephenson, 1966). Bennett & Taylor (1972) performed detailed chemical analyses and limited petrographic studies on 12 samples from a suite of 65 samples collected by A. Mond from the Bainmedart Coal Measures in the vicinity of Beaver Lake, Prince Charles Mountains. Kyle (1976) compiled the results of fifteen proximate analyses carried out by the New Zealand Coal Research Association, D.S.I.R., on coals from the Weller Coal Measures and Lashly Formation.

Recent studies by Whitby et al. (1983), Bryan (1983), Rose (1985), and McElroy & Rose (1987) have concentrated on mapping in detail (1:50 000 scale) the stratigraphy of the Beacon Supergroup in southern Victoria land. In particular, the mapping has aimed to delineate stratigraphic units to formation status so as to provide a *proper* framework for section measurement and specific



- * "Timber Peak Beds"
- Bainmedart Coal Measures (BC)
- Jurassic, NSW, Clarence-Moreton Basin (JC-M)
- Permian, NSW and Qld, Sydney and Bowen Basins (SB)
- △ Middle Triassic, NSW, Clarence-Moreton Basin (TC-M)
- * Lashly Formation (LF)
- ▲ Mt Glossopteris Formation (GF)
- ⊙ Weaver Formation, Queen Maud Formation (WF)
- * Dominion Range, Buckley Formation (DBF)
- Weller C.M., Allan Nunatak & Robison Pk & Mt Fleming (AN)
- ★ Polarstar Formation (PF)
- * Q.E. Range, Buckley Formation (QBF)
- ▼ Lowermost Middle Triassic, NSW, Clarence-Moreton Basin (LC-M)
- ⊙ Theron Formation (TF)
- Weller C.M., Mt Gran (MG)
- ◆ Weller C.M., Kennar Valley (KV)
- X Pecora Formation (XF)

PRINCIPAL DATA SOURCES
 Bennett & Taylor, 1972
 Joint Coal Board & Qld Coal Board, 1976
 Kyle, 1976
 McElroy, 1969
 Schopf & Long, 1966
 Whitby et. al. 1983

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Fig. 2. Diagram relating volatile matter and specific energy of some Antarctic and Australian coals.

coal-seam sampling. Individual seam samples from the Weller Coal Measures have been collected at Kennar Valley, Mt Fleming, Shapeless Mountain, Mt Bastion, and Mt Robison, and from the Lashly Formation at Shapeless Mountain.

A useful approach for comparing varying attributes of coals is presented in Fig. 2, where Volatile Matter (or, of course, fixed carbon if preferred) is plotted against Specific Energy on a dry, mineral-matter free (d.m.m.f.) basis. When this is done for a large number of more-or-less randomly selected groups of Antarctic coals, together with similarly selected Eastern Australian coals (from localities familiar to the authors), a positive grouping of coals according to stratigraphic and/or geographic setting is apparent.

Some groups within Fig. 2 are worthy of comment. For example, at first glance, it is obvious that most groups of Permian Antarctic coals plotted are low in volatiles compared with the Permian coals from both the Sydney Basin and the Bowen Basin of Eastern Australia. A notable exception is the group of high-volatile bituminous coals from the Bainmedart Coal Measures. It is reasonable to assume that, in contrast to the generally low-volatile, semi-anthracite coals of many other groups, the high volatile content of the Bainmedart Coal Measures is related to the lack of nearby major igneous intrusions.

At the bottom of the diagram we find the coals of the Weller Coal Measures at Mt Gran and the Theron Formation, the very low volatile content of these coals undoubtedly being due to the close association with dolerite sills about 200 m to 300 m thick.

The coals of the Triassic Lashly Formation plot more-or-less centrally in relation to most of the Antarctic coals, and generally intermediately between normal, moderately dipping, non-intruded Triassic coals of the Clarence-Moreton Basin, New South Wales, and the coals lower in the same sequence that have been crushed and sheared against a strongly deformed older Palaeozoic basement. This latter environment is apparently related to the lower volatiles of the last-cited group. The anomalous position of the very high volatile Timber Peak coal (top left, Fig. 2) is worthy of comment: it is possible that the high volatile content is related to the specific coal type, but in the absence of maceral analysis, this remains speculative. The high moisture content of this coal sample (13%) doubtless introduces anomalies into the analytical data.

Dolerites in the general vicinity of the "Timber Peak Beds" were considered, not unexpectedly, by the investigators (Skinner & Ricker, 1968) to have not affected the coals.

Argument has been presented (Schopf & Long, 1966) that the high rank of the coals is a combination of load and geothermal metamorphism plus the contact-metamorphic effects due to igneous intrusion. The resolution of these independent functions is a problem to which no general solution appears to be available at present.

Kyle (1976) concluded that the coal in South Victoria Land reached a rank no higher than sub-bituminous prior to the beginning of Jurassic volcanism. The rank was then substantially increased to its present unusually high rank as a result of both the increased geothermal gradient and increased overburden following the emplacement of basalts and dolerites in the Jurassic.

Sulphur content is generally less than 0.5%; random local variations, possibly due to pyrite or pyrrhotite, increase this content in a few cases to more than 1%.

Figure 2 demonstrates that it is not meaningful to discuss the range of variation in proximate analyses of Antarctic coals collectively. However, at least one can say that the bulk of Antarctic coals analysed to date are classifiable as medium volatile bituminous through semi-anthracite. On the basis of petrographic and associated work, it has been estimated (e.g. Bennett & Taylor, 1972) that on oxidation the coals show a decrease in fixed carbon (d.m.m.f.) and calorific value, and in many cases an increase in the volatile matter (d.m.m.f.) by 2-4%.

Similarly it is not practicable to generalise in regard to the petrographic characteristics of the coals. In the specific areas referred to above, the Theron Formation coals showed a predominance of structureless vitrinite with varying proportions of semi-fusinite, fusinite and micrinite; exinite, as such, was absent. Numerous fine mineral inclusions, mostly clay with some pyrrhotite, were usually scattered throughout the coals. There is a similarity in type to some Australian Permian coals. The Bainmedart coals from Prince Charles Mountains displayed an unusually high proportion of intermediate microlithotypes and, for the most part, a low content of vitrinite and clarite; pyrite is rare or absent; and the coals appear to be inherently high in mineral content. Virtually unique among Antarctic coals, the Bainmedart coals are classified as of high volatile bituminous rank (Bennett & Taylor, 1972). The coals, as mentioned by them, are similar, petrographically and in rank, to coals in various parts of the world. Many of the coals from the Weller Coal Measures at Mt Gran and from the Mt Glossopteris Formation in the Ohio Range, which were closely associated with igneous intrusions, have been described (Schapiro & Gray, 1966) as natural coke; gas vacuoles were common in half of the samples studied. All the normal macerals were present, but the exinoids and resinoids were not identified. The most striking difference, when compared with North American coals, was the abundance of semi-fusinoids, which is, however, common in other southern hemisphere coals.

Kyle (1976) has described the general lithologic attributes of coal in both the Weller Coal Measures and Lashly Formation in south Victoria Land. In the Weller Coal Measures, some coal beds are lensoid and of limited lateral extent, while others have a more sheet-like form. Hand specimens of the coals are typically banded and range from dull to bright. The bright coal consists of laminae 1 to 12 mm thick of highly lustrous material and bands of finely laminated mid-lustrous material with dull powdery fusinite films and flakes. A 1.3 m-thick coal bed on Shapeless Mountain consists approximately of 50% dull coal, 30% bright coal and 20% shale partings. In the Lashly Formation, coals occur as thin lensing beds averaging 0.2m in thickness and are of limited lateral extent. The thickest coal bed observed was 0.7 m at Mt Bastion. The Lashly coal is similar in appearance to the Weller coal, but is more finely banded and appears to contain a smaller proportion of vitrain.

References are common in the literature to the unsuitability of the thermally altered Antarctic coals for use as metallurgical coke. The fact that most of the coal samples have been collected from the surface, and therefore are affected to some degree by weathering, may also have a substantial affect on "apparent" coking properties. Either way, this is indeed an important factor in any consideration of the ultimate utilisation of Antarctic coal resources.

RESOURCE ASSESSMENT

As a general guide, mineral commodities (including coal) should only be classified as *resources* "if the commodity occurs in such form that its economic extraction is presently or potentially (within a 20-25 year time frame) feasible" (with a guideline defining several resource categories) (BMR, 1983). The categories of resources are based on the level of knowledge of the occurrence and the economic feasibility of exploiting it. This knowledge of coal in Antarctica is such that no recorded coal localities there should be classified as "resources" but should simply be referred to as "deposits" or "occurrences". It is of interest that in the state of New South Wales, Australia, where an integrated approach employing detailed geology, geophysics, drilling and analysis has been extensively applied to the evaluation of coal resources, only 7% of such resources are sufficiently well known to make positive decisions to proceed with economic development.

Terminology used in resource evaluation is often confusing. It is not uncommon in the literature on coal resources to find the words *resources* and *reserves* used interchangeably and without qualification as to the level of knowledge or understanding of the coal seams involved. There is also the problem of defining the degree of certainty in regard to resources. Qualifying words such as: "demonstrated", "indicated", "measured", "hypothetical", "inferred", "proven", "recoverable" and "economic" are used (Rose, 1978). The degree of confusion is one of national and international concern, and deserving of continued attention by such bodies as the International Energy Agency and other organisations referred to in BMR (1983). Recent efforts towards the development of a national approach to this issue in Australia has resulted in an "Australian Code for Reporting Identified Coal Resources and Reserves" (Galligan & Mengel, 1986).

As mentioned in the introductory section, any evaluation of the coal resources of Antarctica in quantitative terms, based on existing information, would be virtually meaningless. Information is lacking in respect to parameters normally used for coal resource evaluation, such as seam continuity, geological structure, true seam thickness, nature and thickness of inter- and intra-seam sediments, nature and thickness of overburden, and the number and separation of seams in any one stratigraphic unit, and above all the relationship of all the coal quality parameters to all of the foregoing. Some of these aspects have been recorded in detail by some workers (e.g., Barrett, 1971; Barrett & Webb, 1973; Whitby, et al., 1983;

Bryan, 1983), but in the absence of any consistent approach it is unlikely that any quantitative evaluation of the coal measure potential in Antarctica will be forthcoming for many years. Geological maps clearly delineating units to at least formation status, supported by precisely located, measured and sampled stratigraphic sections are an essential first step toward overcoming existing shortcomings.

The published data do not provide an adequate basis for the evaluation of *coal seams* in a normally accepted economic framework. A large number of analyses of coal samples are available which allow some broad conclusions as discussed in this paper (and presented specifically in Fig. 2) as to the character of Antarctic coals in general. However, as to any specific coal seam, no conclusion is possible as to quality and distribution (geographic and stratigraphic) because the information on the Antarctic coalfields is too meagre at present. This view differs from that of Wright & Williams (1974, p.2), who stated that ". . . Water and coal could constitute identified resources in Antarctica . . ." and further that ". . . The coal resources in the Beacon rocks have been sufficiently measured in places to permit estimation of volumes . . .". The sampling methodology *in toto* (frequency, localisation, recording) is unfortunately grossly inadequate. We recommend that analyses of coal should only be undertaken on samples which have been *properly* collected, although the difficulty of such sampling under Antarctic conditions is recognised. For outcrop collection, *proper* channel samples should be taken with, in the primary sampling of any seam, separation of plies and bands into separate samples. These samples should be keyed to *properly* measured seam sections and stratigraphic sections. Locality detail should be sufficient to allow repeatability of sample collection.

It is clear that as more information is gathered on the nature of the coal measures in Antarctica, it will be possible to undertake reappraisals of the coal resource potential. However, much of this information will be dispersed and unavailable. We believe that in the interest of coal geology generally, there is a need to establish a central repository of data. We would tentatively suggest that a suitable international data centre might be funded by an Australian or overseas source. A major first step would be taken if the national bodies of those countries active in coal studies in Antarctica were to establish central national resource repositories, where information was required to be lodged.

POSSIBLE FUTURE EXPLORATION METHODS

To our knowledge, no proper coalfield exploration has been undertaken to date in Antarctica. It is only recently, that an attempt has been made to undertake what we would call "normal coalfield mapping", i.e. on a scale of 1:50 000 (Whitby et al., 1983; Bryan, 1983; Rose, 1985; McElroy & Rose, 1987).

Elsewhere in this report (Potential for Utilization and Development), we consider the problems which may be experienced during mining and exploitation of the coal resources. These social, environmental and technical problems, mainly related to climate and remoteness, equally apply to exploration.

Coalfield exploration can be separated into four clear categories: (a) geological mapping (including stratigraphic, structural and sedimentological studies); (b) geo-

physical investigations; (c) drilling and exploratory openings; and (d) analytical studies.

There are no reasons, apart from climatic constraints, why normal geological mapping techniques cannot be applied in Antarctica. The ice and snow cover are equated to the masking effect of soil which exists in more temperate areas and can be treated simply as a Quaternary unit. It is conceded that sustained periods of detailed coalfield mapping in the Antarctic require a somewhat higher degree of dedication and tenacity by the field geologist and support staff than in many other areas of the world.

Geophysical methods are likely to play an important part in any future coalfield exploration in Antarctica. For regional investigations, including definition of sedimen-

tary basins and structures, airborne electromagnetic, magnetic and gravity surveys could be useful. Although any airborne surveys will be hampered by the lack of some normal navigational aids, inertial navigation systems and Global Positioning Systems (GPS) could be used to supply sufficiently accurate positioning in geophysical surveys.

Frequent magnetic storms may hinder magnetic surveys; however, gradiometric systems would be less adversely affected by the storms than simple-sensor systems. The effects of the widespread thick, interbedded Ferrar Dolerite in the sedimentary sequence may mask magnetic anomalies arising from basement sources and possibly can generate gravity anomalies that are indistinguishable from or mask those anomalies arising from the basement-basin interface.

Electrical methods have been used in permafrost mapping in the northern hemisphere and they may be useful in the definition of permafrost and glacial cover from bedrock in the coalfields in Antarctica. The main problems are those associated with the extremely high resistivity of frozen ground and ice.

Seismic techniques are probably the most effective geophysical aids in normal sedimentary basin mapping and should be useful in coalfield mapping in Antarctica. Problems in the use of seismic methods could arise because of the "shot effect" of ice breakup after using normal explosives or reverberation of the ice after the application of surface sources.

The opening of the small adit ("The Dirty Diamond Adit"), which was used specifically to obtain fresh material for chemical analysis from the lowermost coal seam on Terrace Ridge, Mount Schopf, Horlick Mountains (Long, 1964), is one of very few attempts to follow proper coalfield exploration practice in coal-seam sampling in Antarctica. Among others, Mulligan (1963 a,b) has made clear the necessity for adequate channel

samples in his study of the Mt Gran and Willett Range coals, even though conditions permitted only limited application of proper procedures.

Drilling programs have been undertaken in Antarctica although we are unaware of any case where these have been for coal. Exploration drilling is a normal adjunct of resource evaluation in the Arctic and, for example, northern Canada where cold-climate techniques have been successfully developed. Drilling fluids have been developed which are suitable for use in the Arctic/Antarctic low temperatures. In Antarctica, drilling rigs, personnel and supplies could be airlifted to the drilling site using a helicopter, a common practice throughout the world.

The drilling of a small number of appropriately stratigraphically located, fully cored, stratigraphic drill holes through the coal measures would be valuable in reaching a better understanding of the geology of these units and would provide basic information towards an evaluation of the coal resource potential of Antarctica. However, the siting of such drill holes should only be considered *after* more comprehensive geological mapping has been completed in order to gain the maximum information in a regional context.

Procedures for analytical studies as they relate to coal-field exploration, or coal seam evaluation, are relatively standardised and can be undertaken by laboratories specialising in these disciplines. Samples can be readily transported to such laboratories and this aspect of exploration need not pose any unique problems in the study of the coalfields of Antarctica. It is, however, of critical importance that the collection of samples of coal in the field must follow one of the established methods. If this is not done, then the considerable cost and effort involved in the collection and the subsequent analytical studies will be wasted.

POTENTIAL FOR UTILISATION AND DEVELOPMENT

Mining under arctic conditions

Discussion of the possibility of future coal mining in Antarctica must be preceded by reference to current practice and conditions in the Arctic region, where several mines for a variety of minerals have been established under climatic conditions and latitude generally similar to those of some of the Antarctic coal measures. There are, however, a number of important differences between these two scenarios.

The Polaris Mine at latitude 76°N in Canada is an underground mine working a relatively high-grade lead-zinc orebody which can be concentrated close to source to a low volume, high-value product. It is near shore and can be loaded directly onto a ship in the summer months; it is relatively close to major population centres and existing community settlements; it is within a relatively short distance of final market (Anon, 1981; Cominco Ltd, 1984; Harrop, 1984; Scales, 1982).

In Spitzbergen, centred about latitude 78°N 14°E and also with climatic conditions similar to Antarctica, there are at least six coal-bearing stratigraphic horizons. Devonian, Carboniferous, Cretaceous and Palaeogene ages are represented, although the richest deposits are of the latter three ages (Harland et al., 1976). The coals from the various seams are diverse in type and rank and it is inappropriate to try to deal with them in detail here. Some of these seams have been mined for many years, but like the Polaris Mine, when compared to Antarctica, there are significant variations: the coal is near to seaboard for ease

of transport, "civilisation" is close by, and markets are relatively more accessible.

Other mining ventures within the Arctic Circle include iron (Sweden, Norway); lead and zinc (Canada, Greenland); diamonds (USSR); tin, tungsten (USSR); complex ores of nickel, copper, cobalt, etc. (USSR) (Camillo Premoli, International Mineral Research, pers. comm.).

Clearly there is considerable mining activity in the Arctic, but for reasons expressed below the authors believe that, for the immediate future, the mining of coal under Antarctic conditions poses significant, if not insurmountable, difficulties.

Mining and mining methods

The coal resources of Antarctica will only be exploited if a satisfactory system of recovery can be devised. The two modern-day conventional systems of mining are open-cut (surface) or underground operations using a variety of extraction techniques. A less conventional method (and one with a possible future potential) is underground (or *in situ*) gasification, which is, as yet, in an early stage of development. It is also possible that *in situ* liquefaction techniques could be developed in the future.

Open-cut operations in Antarctica would pose insurmountable problems. It would be virtually impossible to work in winter because of climatic difficulties; operating equipment continuously in sub-zero conditions would introduce many problems. For practical purposes, summer may be considered as the three-months period from

November to January and winter the remaining nine months. It is also impossible to conceive that any normal workforce would accept such conditions except under cost-prohibitive or technologically impractical terms, e.g. enclosure of the whole operation. Doubtless any excavation would be filled by snow in the winter months; frozen ground could only be broken with difficulty. Indeed, perhaps stating the obvious, throughout the year the problems of accumulation of snow would be significant. In the summer, the conditions would be slightly more reasonable, but problems of the short summer period and sharp, sudden climatic changes of brief duration (such as blizzards) still leave the concept of open-cut coal recovery inconceivable.

Underground mining provides a more realistic alternative for the recovery of coal in this environment. A wide range of development and recovery techniques is available. Entry to the workings in the seam can be by way of shaft, drift or adit, or a combination of these. Development can be on the basis of either total extraction or partial extraction. Techniques include mobile extraction machines, such as continuous miners or cutters and loaders, semi-mobile longwall or hydraulic mining. Transportation from the face and the mine can be in rubber-tired vehicles, rail-mounted skips or by conveyors, or in the case of hydraulic mining, by pipeline. Diesel-powered mobile equipment, rather than electric-powered, would be greatly preferred for underground operation. Diesel equipment is more flexible and has the added advantage of transferring heat to the mine atmosphere. All scenarios which have been considered assume that entry to the seam would be in relatively ice-free areas, a situation existing in many of the areas in which coal is known to occur. Climatic factors would significantly detract from the effectiveness of any of the above possible combinations for underground coal-mine development, but these would not be as severe as with open-cut developments.

It is common practice in deep mines, where the geothermal gradient produces unacceptably high working temperature, to refrigerate the ventilating air. Mine air can be heated in a similar way as has, for example, been done in Canada, by oil or natural gas. Without this measure, airways would ice up. The geothermal gradient is unlikely to be high enough to overcome the need for heating, because of the relatively shallow depths at which coal mines can be worked and because of the large volumes of fresh air required for ventilation. Such heated air for ventilation, when emitted by the exhaust system, could be used to advantage to assist in keeping the surface works area relatively snow free. No data are at present available on the possibility of the occurrence of gas, coal dust or outburst hazards in mine development. The known degree of igneous activity indicates that there could be significant CO₂ emissions. These factors directly influence the ventilation requirements.

With any operation exposed to the Antarctic extremes of temperature, it would be mechanically more reliable for continuous-movement machinery to be used. For this reason, drift or adit development with conveyors would be preferable to shaft sinking or skip winding, if any interruption were more than momentary.

It is emphasised that extraction of coal should be as close to total as possible in this, at best economically marginal, mining proposition. Hydraulic mining should be discounted because of the problems associated with water freezing and subsequent remobilisation. Longwall operations are probably the most cost effective of underground mechanised techniques, given structurally simple conditions. Longwall mining, however, requires continuous operation once set up and is most certainly not suited to

seasonal, small-scale operations; and without the most detailed information on the seam, should not be considered as a preferred approach. Available geological data indicate that the coal seams are commonly disrupted by igneous activity and for that reason use of mobile machines may have a greater advantage. Clearly, because of the problems of operation and manning a high degree of automation must be considered. The maximum practicable use of remote control from an area, which is adapted for comfortable operations, would be desirable.

To cope with problems of low temperatures, high winds, snow accumulation, movement in ice sheets and the like, all installations should, as far as practicable, be developed underground, giving a reasonable measure of consistent and predictable control over the working environment.

In summary, the preferred conventional mining method would

- (i) employ underground mobile machines or longwall techniques, with entry by drift or adit;
- (ii) use high-productivity, automated, remotely controlled systems; and
- (iii) require as much of the associated installations as possible to be developed underground in controlled (heated) temperature conditions.

The less-conventional method of *in situ* (underground) gasification could merit consideration, although the method is still very much in the formative stages (being used, for example, in the USSR). While there would be extreme difficulties with the associated drilling programs, these could be undertaken in the summer months. The actual gas drainage could probably be undertaken on a completely automated basis with overall remote control and only occasional visitation for monitoring and removal of product. There would, however, still be many unknowns; for example, the effect of the heat generated on ice at the surface.

Stockpiling, transport and the environment

With conventional mining methods, stockpiling would be inevitable particularly if mining operations were conducted in the winter. This poses immediate problems. Firstly, the coal would be "comparatively hot" and moist having come from the warmer environment maintained in the mine and water-sprayed for dust suppression. Once it was frozen on the surface, it would have to be "re-mined", i.e., mechanically broken, before removal. Thermal-pollution effects on the environment would certainly occur and may be significant and require further evaluation. Because of the arid climate and high winds coupled with the abrasive nature of ice and "sand-blasting" by it, coal dust pollution would certainly produce adverse visual, if not other, environmental problems. Any surface structures, stockpiles and living quarters must have an immediate adverse effect on the Antarctic environment at that locality.

The transportation of coal in the Antarctic would pose serious difficulties. Road and railway construction and operation, over anything but very short distances, would be impossible, within a reasonable cost structure, as based on existing technology. Pipelining could be considered, but several problems would arise from damage to the pipeline itself: from abrasion by ice or foundation movement if on ice, from energy loss and internal abrasion as a result of flexure, or from freezing as a result of heat loss in the slurry. Once frozen, it would seem to be virtually impossible to remobilize the slurry using present technology. Any such land-based transportation system would have severe environmental effects.

Because of these basically obvious difficulties, it is

necessary to consider other methods, if the coal is to be utilised for anything but relatively small-scale on-site use. For example, air transport or the use of hovercraft could be considered, if the coal-energy content could be sufficiently concentrated. For these reasons, on-site beneficiation, giving substantial bulk reduction, must be considered. The normal method of beneficiation, using washeries, raises significant difficulties simply in maintaining the mobility of the washery fluids in the plant. This could be overcome by using a full enclosure with air conditioning. The supply of washery fluids constitutes a major problem. Water would almost certainly need to be derived from the melting of snow or ice by applied heat at great energy cost. The disposal of coal washery-discard at the surface would be extremely difficult because of possible freezing in the disposal circuit. In addition, it would produce adverse, probably unacceptable, environmental risks; disposal by stowage underground would be logistically difficult, because of freezing of the circuit mixtures, and impracticable from an economic viewpoint.

As an alternative, one could convert the coal to gas or liquids on site. This proposal could be considered in the same context as *in situ* (underground) gasification. The preferred method of relatively conventional beneficiation could, therefore, be conversion of the coal to gas or to methanol (freezing point -97°C) or ethanol (freezing point -114°C) by a gasification route. The gas could be produced either by an on-site gasification plant or by *in situ* gasification. The problems of construction of such conversion plants may well be insurmountable and the disposal of waste following surface conversion of mined coal to gas would, as discussed above, be environmentally adverse. One could consider the possibility of compressing the gas into tanks and airlifting to seaboard, but the transportation of liquids by airlifting would appear to be more feasible.

Manpower and sociological problems

Even with a highly advanced technology there would still be a need for manpower for any of the methods discussed above, i.e., underground and open-cut mining or for *in situ* gasification. Any of the conceivable methods of extraction require an experienced workforce as well as a number of unskilled personnel. The attendant problems of family disruption, the practicalities of human relationships in a mining camp in Antarctica and the need to pay salaries commensurate with these conditions must be recognised. Industrial disputation would undoubtedly be a common occurrence because of the psychological pressures in the mining camp and the simple human, physical and mental strains which would occur. It should be borne in mind, realistically, that a mining community in Antarctica would have an outlook or commitment to their work different from research workers, especially short-term research workers, for example.

Economics and energy balance

There are four potential situations which would lead to the development of a coal mining operation in Antarctica. These are —

Case (a) *For use by a self-sustaining community in the Antarctic:* This could range from simple lump coal for a “domestic fireplace” to the operation of a small-scale, steam electric power-generating plant. It would seem reasonable to assume that cooling water would not be necessary in such a case.

Case (b) *For use in a profit-motivated venture:* This could involve some locally based venture exporting the

coal in a raw or processed (including gas or alcohol) state to be sold at a profit outside Antarctica.

Case (c) *As an energy resource if a world shortage* became of such magnitude that profit was not a consideration, i.e. for strategic purposes.

Case (d) *Political expediency* could, for example, encourage a country with a territorial claim on the Antarctic continent, to establish an “operational mine” to reinforce its claim to that territory.

Of these four possibilities, (a), the small-scale local use could, we believe, eventuate as a logical first phase. The coal would be produced by the community itself as a part-time operation from very small mines and delivered directly in a raw state to the final nearby user. Case (b), the use for a profit motivation, requires consideration of the economics associated with such a venture. (As a guideline, in Australia, with an underground mine in an established community with the potential for all-year-round operation, established workforce and relatively few real problems with land or seaboard transport, the cost of mine development is in the order of \$40 to \$120 per annual tonne of production.) It is impossible to determine to any acceptable order of accuracy the economics of an operation in Antarctica. Even in the mining sector, the basic ignorance of the nature and characteristics of the coal seams makes it impossible to determine whether mining could be feasible, using known technology, even if cost consideration were not a factor.

It is nonetheless interesting to contemplate the *hypothetical* situation, whereby coal is assumed to be available at mine head at *no cost* and then determine if it would be profitable to market it. With the problems of beneficiation, land or air transport and sea transport, coupled with almost inevitable winter shutdown, it is our opinion that the economic incentive to engage in such a business would almost certainly be negative for the foreseeable future. From all the evidence available, we are unable to identify a scenario which would lead to the conclusion that coal mining in Antarctica would be viable from an economic viewpoint, given existing technology. Transport and loading to vessel are aspects which are relatively uncomplicated in most coal-exporting countries; ship movement is relatively unrestricted as opposed to the situation in the Antarctic where ships can at most times move only at peril, due to ice and weather. The size of vessel, type of construction and times of movement would impose severe constraints upon shipping operations. Coal exported would be competing in international markets with coal won in more temperate climates.

Development as in case (c) above (i.e., because of energy shortage) requires consideration of the energy balance of such an operation, i.e., whether or not the energy used in recovery of the coal is greater than the energy gained. The possible use of *in situ* gasification has not been considered either in respect of economics or energy balance due to the limited information that is available on this currently developing technique. It may provide a feasible method of utilising the coal. Considering a typical underground mining operation in Australia, with which the authors are most familiar, the energy required to produce coal compared with its “energy value”, is relatively low. This includes beneficiation by a washery. It is our intuitive feeling, bearing in mind the problems of extraction, transport, environmental control and provision for human comfort and working conditions generally, that the energy balance would be negative. In effect, it would mean that more energy would be used to bring coal into use in the international market than could be produced from it. The possibly feasible option of local use may well fall into the same category.

Case (d) involves political factors beyond the area of expertise of the authors and is not further discussed here. Quilty (1985), Tingey (1985), De Wit (1986), Shapley (1986), and Triggs (1986) have dealt with economic and political, among other, matters that also apply to coal exploration and mining in Antarctica.

CONCLUSIONS

We conclude that a great amount of basic exploration must be carried out in Antarctica before a first approximation of the potential of coal as a resource can be obtained. No assumptions should be made at this stage as to the continuity of coal measures or coal seams beyond the vicinity of known outcrops. An essential part of basic exploration is the *proper* sampling of the coal with *properly* related chemical and physical analyses.

On balance, we believe that the many logistic, environmental, political, sociological and marketing problems

would negate the economic mining of coal in Antarctica in the foreseeable future, certainly until well into the next century. We feel this applies with some certainty to the export of coal from Antarctica into competitive world markets and may also apply to local use in Antarctica.

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