DEPARTMENT OF THE INTERIOR

U.S. Geological Survey

The Undiscovered Oil and Gas of Antarctica

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ABSTRACT

Antarctica is divided geographically and geologically into two parts: East Antarctica, an early Paleozoic platform bounded by marginal and interior rift basins, and West Antarctica, a convergent margin facing the Pacific. With only little detailed geologic information on this ice-covered continent, petroleum assessment largely depends on geologic and petroleum-yield analogies to once-adjoining Gondwana sedimentary provinces. A final assessment is made by group consensus after two, not entirely independent, methods, play analysis and area-by-area analogy, are employed. It is estimated that, if recovery were made under conditions generally extant throughout the world, there would be resources of 19 billion barrels of recoverable oil (BBO) and 106 trillion cubic feet of gas (TCFG), amounting to 36 billion barrels of oil equivalent (BBOE) in Antarctica. Field size, however, is critical in this region of extremely difficult recovery conditions. Field-size analogies with other Gondwana sedimentary provinces suggest that in Antarctica: (1) no petroleum accumulations reach supergiant size (5.0 BBO), (2) giant-size fields (0.5 BBO, by international definition) exist in the rifted provinces and contain 40 percent of the rift-province petroleum, and (3) none of the convergent margin fields reach giant-size. If, as seems probable, the adverse commercial recovery conditions require as a minimum, giant-size fields, the recoverable petroleum resources would accordingly be 6 BBO and 32 TCFG or 11 BBOE. If supergiant fields are required, the Antarctic recoverable resources are probably nil.

INTRODUCTION

Size of Area

The Antarctic continent, a fragment of Gondwana, has an area of some 5.5 million mi^2 (14.25 million km^2) with an offshore continental shelf and slope area in excess of 3 million mi^2 (7.8 million km^2) (fig. 1). By comparison, the United States has an area of 3.6 million mi^2 (9.3 million km^2).

Premise and Problems of Petroleum Recoverability

For comparison with other regions, estimates are made for recoverable oil and gas as if normal recovery conditions prevailed, rather than for oil and gas in place. The unfavorable economic and technical problems for petroleum recovery in the hostile Antarctic environment are not considered in this assessment other than to suggest that, at a minimum, only giant-size fields may eventually be found to be economic.

The physical recovery problems should be noted, however; the foremost of these is the ice, which covers 98 percent of the continent and most of the continental shelf with a thickness of up to almost 3 miles and is constantly moving at rates of 30 to 60 ft (10 to 20 m) per year on the continent and up to a mile or more per year offshore (J. Behrendt, personal commun., 1988). Additional physical problems are the iceberg-scour of sea bottom to depths of at least 1,600 ft (500 m) (Behrendt, J.C., in press), presumed sea-bottom gas hydrates, and the effects of extreme cold on personnel and equipment. Other important considerations are the preservation of Antarctica's very fragile ecology and the present treaty limitations.

Previous Investigations and Petroleum Assessments

Some 18 shallow offshore DSDP (Deep Sea Drilling Project) or ODP (Ocean Drilling Program) stratigraphic holes and two onshore holes have been drilled. Approximately 30,000 to 40,000 mi (50,000 to 65,000 km) of multichannel reflection, augmented by some refraction, surveys have been accomplished (fig. 1). Gravity surveys have usually been made in conjunction with the offshore seismic surveys. Gravity reconnaissance land surveys, until recent improvements in technique, were of little value. Reconnaissance aeromagnetic surveys have been carried out over a considerable part of Antarctica; closer-spaced surveys were made over the Ross and Weddell Seas and in the vicinity of the Antarctic Peninsula. Studies of the sparse outcrops were limited to the continental edges, the Transantarctic Mountains, and the Antarctic Peninsula. While these studies yield an insight into the regional geology, they do not provide sufficient data for petroleum assessment without relying rather heavily on geologic analogies and informed judgments.

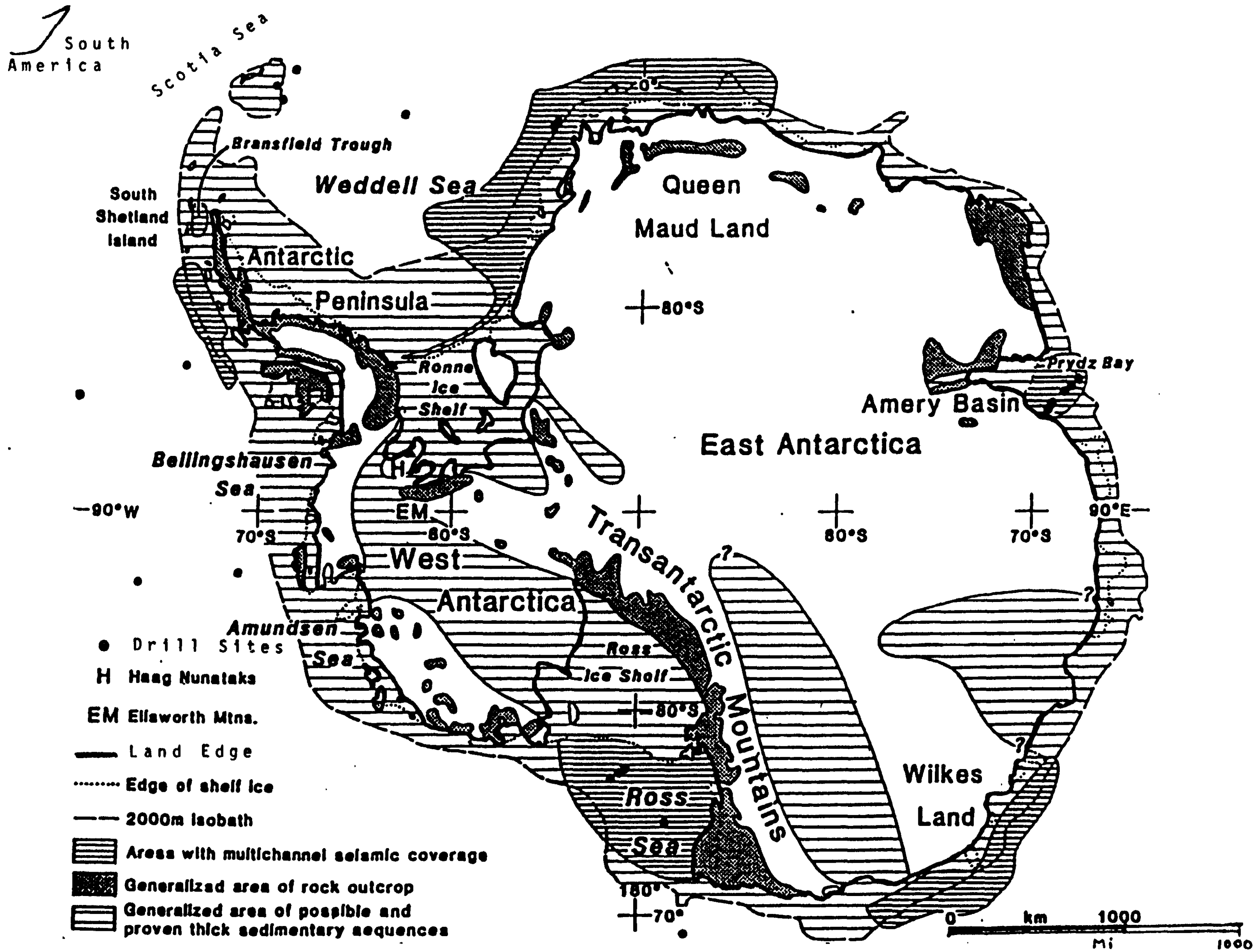

Figure 1.--Index map of Antarctica showing outcrop and sedimentary basinal area along with general location of drill sites and multichannel seismic surveys (modified from Elliot, 1988).

From such limited information several previous assessments of the petroleum potential of Antarctica, or parts of Antarctica, have been made (Deuser, 1971; Masters, 1975; Riva and Mielke, 1976; St. John, 1986; among others). Of these the most comprehensive, including a thorough study of the available data on the geology, is that by St. John (1986) who concluded, arithmetically, that Antarctica would have a potential petroleum yield of 203 BBOE if one considered the Antarctic petroleum yield to be equal to the average volumetric yield of world-producing basins, a consideration that he did not directly endorse, nor does this author.

Methods of Assessment

The basinal area of Antarctica is divided into 13 basins or provinces (fig. 2). These designated Antarctic provinces, as used here, are unusually extensive, containing a large number of basins and covering vast areas. For instance, the Antarctic-Australia marginal rift province of Antarctica covers some 554,000 mi^2 (1,434,000 km^2, over twice the size of Texas); it probably has six or more basins or depocenters, as does its Australian counterpart.

Initial detailed assessments are made following two separate, but not entirely independent, methods:

1. Play analysis of the Antarctic provinces, or superprovinces, using geologic petroleum-accumulation factors as observed in the adjacent southern Gondwana continent.

2. Estimates of the resources of the Antarctic provinces from area-by-area analogy to similar, once adjacent, nearby Gondwana provinces and their petroleum yields (reserves from Petroconsultants data).

In a final step, these estimates were summarized and, along with a description of the petroleum geology, were presented to a group of U.S. Geological Survey petroleum geologists (The World Energy Resource Program group). With this guidance, the group, through the modified-Delphi method (Dolton and others, 1981), arrived at a consensus for the final resource estimate, drawing on their individual backgrounds and experiences and considering all the geologic factors.

The Antarctic provinces, or groups of provinces, as assessed by the modified-Delphi method are extensive areas including unknown numbers of basins and plays. Each group of analog provinces being compared to the Antarctic group of provinces for assessment purposes, has at least one basin containing oil and gas fields. Thus, since we are assessing Antarctica's potential, for comparison purposes as if recovery conditions were normal, the marginal probability (probability of commercial quantities being present, Dolton and others, 1981) for each Antarctic

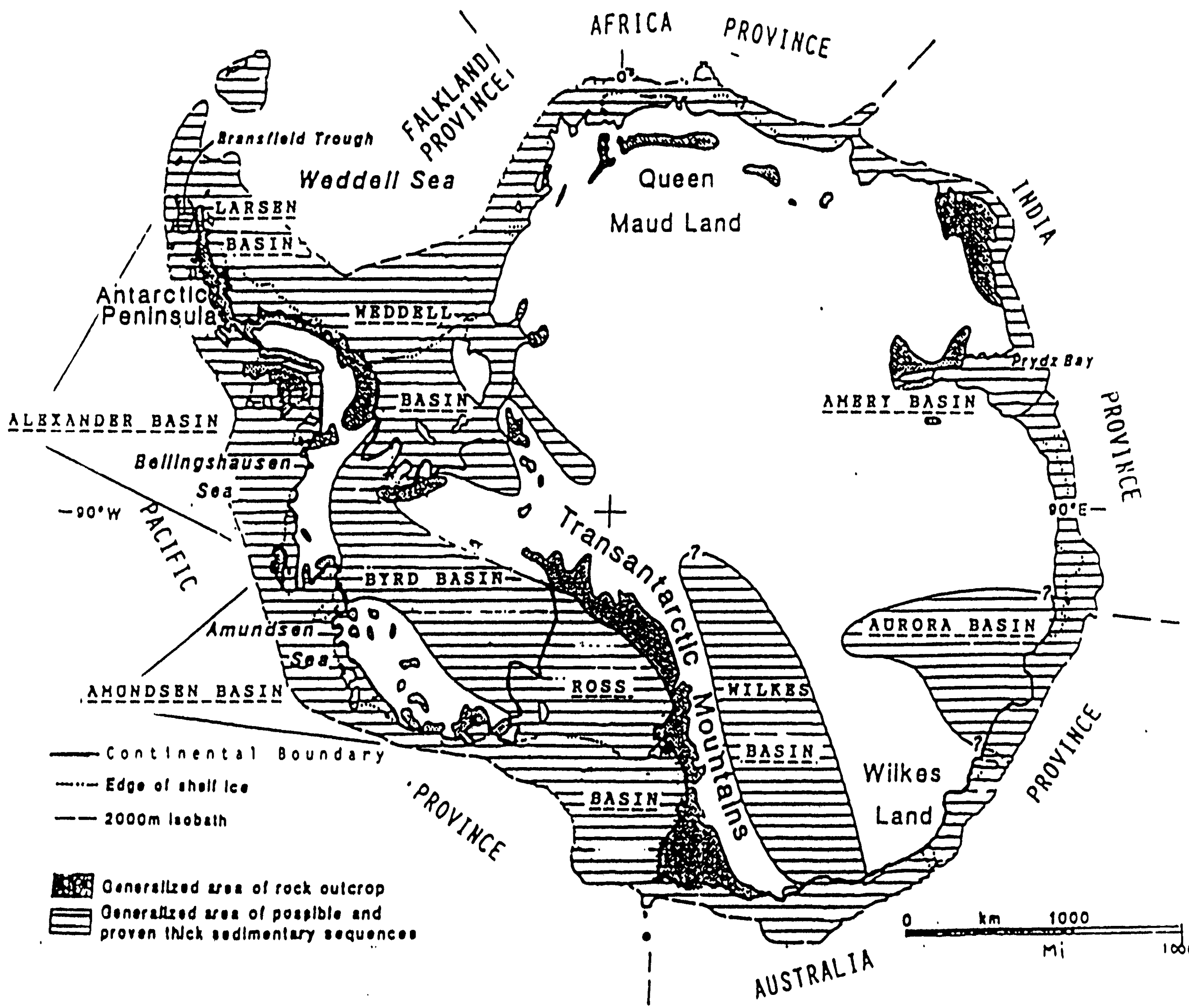

Figure 2.--Map of Antarctica showing designation of basins and marginal basinal provinces (modified from Elliot, 1988).

province would theoretically be 1.0. Actually, of course, conditions are not normal and certainly giant and possibly supergiant fields may eventually be required for commerciality.

REGIONAL GEOLOGY AND PETROLEUM OCCURRENCE

Antarctica was part of the supercontinent, Gondwana, which also included Australia, southern Asia, southern Africa, and southern South America and existed until middle Mesozoic when the supercontinent was broken apart (fig. 3). Antarctica is divided into two parts: the larger part, East Antarctica, is a high-standing, early Paleozoic shield covered by generally continental sediments and bounded by marginal and interior rift basins; and the smaller part, West Antarctica, is an accreted convergent margin facing the Pacific Ocean. The two areas are separated by the Transantarctic Mountains, part of a collision suture (the Gondwanides zone of Dutoit, 1937) that extends through the Gondwana continents separating the shield from the Pacific-facing, more mobile, convergent part (fig. 3).

The geology of East Antarctica and its bounding rifts is analogous to the high-standing Gondwana platform area, and bounding rifts, north of the Gondwanides zone. This Gondwana platform is distinct from the historically subsiding northern zone of the Gondwana continental area which is covered by marine Paleozoic and younger Tethyan strata and which contains the rich oil basins of the Near East, North Africa, and northern South America (fig. 3).

The East Antarctic platform is overlain by the Devonian to Jurassic nonmarine Beacon Supergroup, which is made up of two units, the Taylor Group (Devonian) and the Victoria Group (Carboniferous to Jurassic). From limited outcrops in Transantarctic Mountains the Taylor Group appears to be largely sandstone and siltstone (Davey, 1989) apparently lithologically similar to at least the partly age-equivalent South African Cape Series, which is also largely sandstone. The Victoria Group is lithologically and paleontologically similar to the Gondwana or Karoo Supergroup of India and South Africa, respectively, which extends over, and in part defines, the ancient Gondwana platform of Antarctica, Australia, India, southern Africa, and southern South America (fig. 3). The Gondwana or Karoo Supergroup of the Gondwana region, varies lithologically over this vast area, but as exemplified in the nearby Karoo basin, characteristically includes Carboniferous glacial beds, Permian coal measures, Triassic continental clastics, and Jurassic volcanics. The whole sequence is extensively intruded by voluminous Jurassic sills and dikes.

In Antarctica the Beacon Supergroup crops out mainly in the Transantarctic Mountains and their extensions to both coasts, and in a few scattered, isolated exposures over East Antarctica; it undoubtedly extends under large areas of the ice. Except for the extension of the Transantarctic Mountains to the coasts, Beacon formations are generally

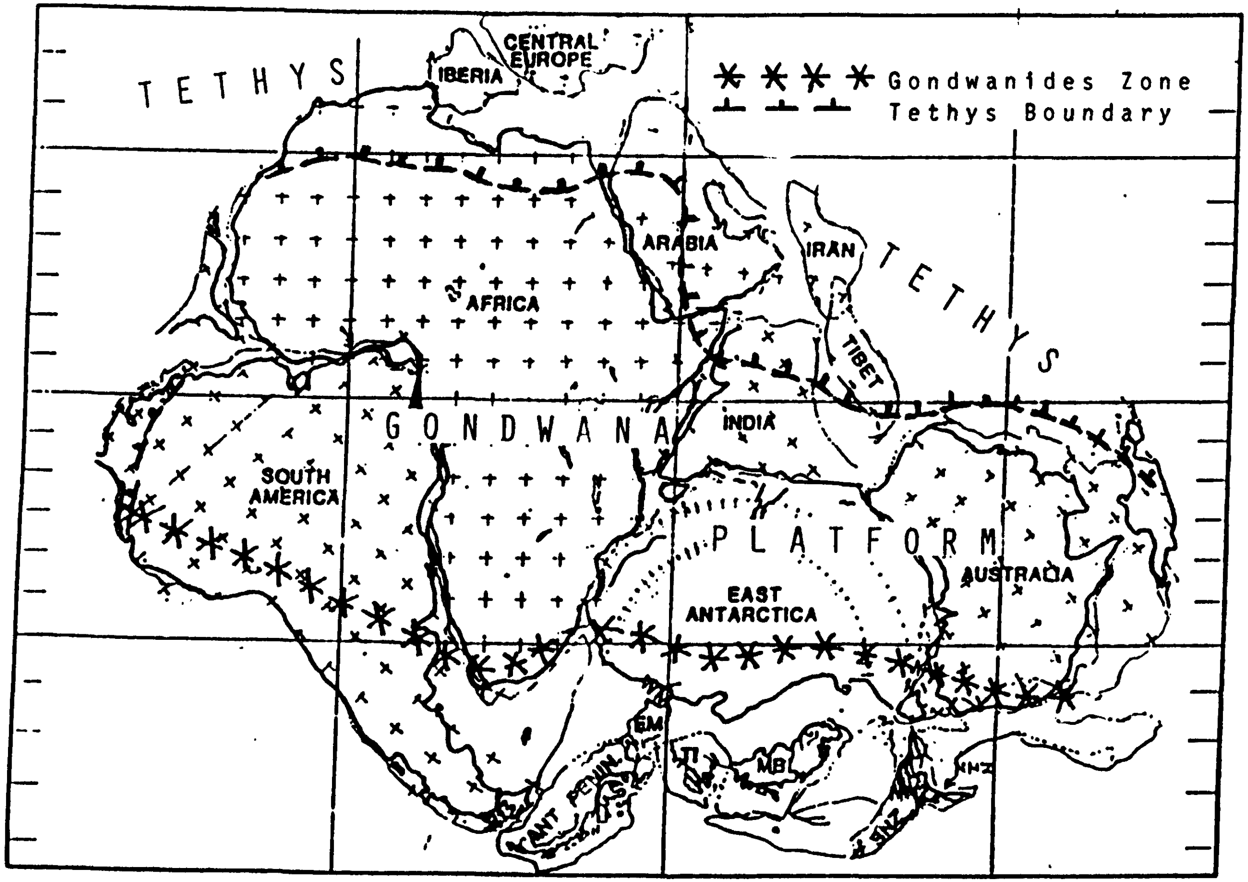

Figure 3.--Reconstruction of Gondwana, showing the high-standing Gondwana platform, or Southern Gondwana, as distinguished from northern Gondwana, which was lower, receiving thick Tethyan marine sediments. Also shown is the Gondwanides zone separating the platform from the convergent margin geology. EM = Ellsworth Mountains, TI = Thurston Island block, NNZ = northern New Zealand, and SNZ = southern New Zealand attached to Campbell Plateau indicate separate terranes (modified from Lawver and Scotese, 1987).

missing from the Antarctic coastal areas, as are their counterpart formations, for instance, in the once-adjoining south Australian margin. This suggests post-Beacon arching of the incipient interior rift and eventual continental separation, in a manner similar to the pre-rift arching of the Red Sea and East Africa rift zones.

Although the Beacon Supergroup may have petroleum source and reservoir capability, there has been generally little petroleum obtained from analogous equivalent units in other parts of the Gondwana platform areas. Two more analogous exceptions may be the productive provinces of the nearby interior sag, the Cooper basin of Australia, and the more distant interior sag, Solimoes basin of Brazil. However, the Cooper basin is somewhat anomalous in the lack of (1) the usually ubiquitous Jurassic intrusives and (2) a Devonian section. The sediments of the Solimoes basin, the only producing basin of several large interior sags of Brazil, is also somewhat anomalous to the largely continental Beacon Supergroup in containing sections of restricted marine (Permocarboniferous) and open marine (Devonian) shales. The estimated ultimate resources of the Cooper basin are 0.05 BBO, 4.4 TCFG, and 0.4 BBNGL and the estimated ultimate resources of the Solimoes basin are 0.08 BBO and 4 TCFG.

The subandaan basins of South America, extending from southern Peru to northern Argentina, lie within the southern Gondwana supercontinent area and produce petroleum from Beacon age-equivalent, tillite-containing sequences. These sequences, however, are largely of marine rather than continental origin and free of the usual, ubiquitous Jurassic intrusives, and therefore not considered sufficiently similar to the Beacon Supergroup of Antarctica to be used as analogs.

Synchronous with the Jurassic volcanics and intrusives was the initial large-scale, pervasive rifting of Gondwana, which extended into the Cretaceous where the final separation of the continents occurred, or into the early Tertiary where final continental separation failed to occur, e.g. the interior rifts of the Gippsland basin (0 of.fig 4) or of the Ross or Weddell basins (fig. 2). It is in these Late Jurassic and Cretaceous marginal rift basins and failed-separation Cretaceous-Tertiary interior rift basins where the oil and gas of the Gondwana platform region (i.e., exclusive of the Tethyan margin) is largely concentrated. Jurassic through early Tertiary rifts in Australia contain over 90 percent of the petroleum reserves (Gippsland basin, O of fig. 4); in India over 90 percent of the reserves (Bombay High and Cambay basins, J of fig. 4); in the rifted Gondwana platform area of Africa (exclusive of the Tertiary Niger delta), over 90 percent of the reserves (Niger basin, Gabon basin, and Congo basin of Zaire, Cabinda, and Angola, A of fig. 4); and, in the rifts of South America, over 90 percent of the petroleum reserves of the Gondwana platform region (Campos [B of fig. 4] and adjoining basins, Brazil).

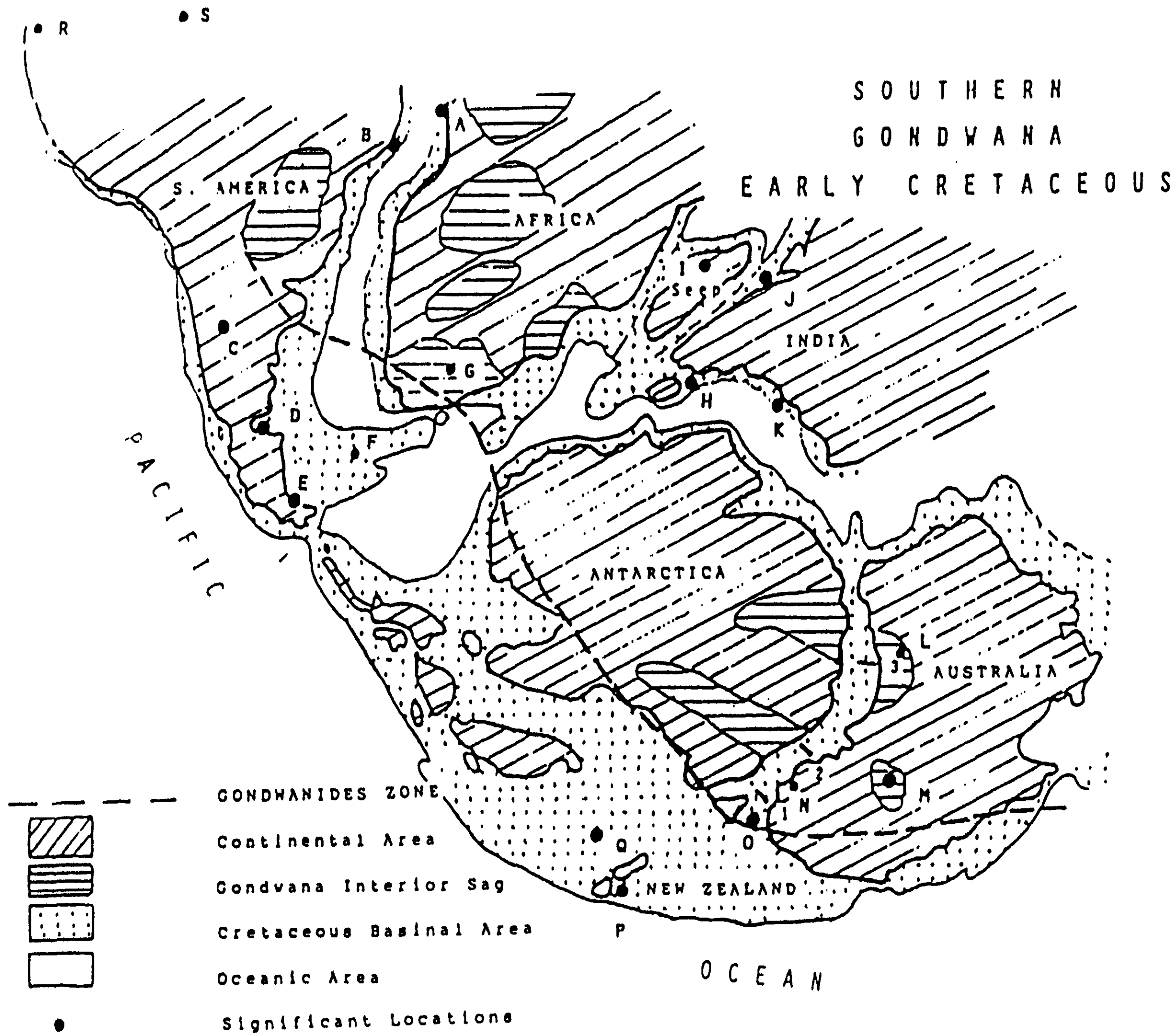

Figure 4.--Reconstructed map of Antarctica and adjoining continents, as of Early Cretaceous, (modified from Elliot, 1988), showing basinal areas and significant location referred to in text. A = Congo basin, B = Campos basin, C = Neuquen basin, D = San Jorge basin, E = Magallanes basin, F = Falkland plateau, G = Karoo basin, H = Cauvery basin, I = Madagascar seep, J = Bombay High and Cambay basins, K = Krishna-Godavari basin, L = Great Australian Bight basin, M = Cooper basin, N = Otway basin, O = Gippsland basin (Bass Strait), P = Taranaki basin, Q = Campbell plateau-Chatham Rise, R = Talara basin, Peru, and S = Solimoes basin, Brazil. 1, 2, and 3 = sections of the Antarctic-Australia Province in figure 5.

It appears that the petroleum resources of the rifted Gondwana platform, presumably including Antarctica, are largely in one type of play, that is, the rift-associated play. The remaining 10 or 15 percent or so of the resources is in the convergent Pacific margin, and even less resources are likely in the interior sags.

Gondwana's rifted basins are relatively high in petroleum resources largely because of the favorable conditions for source rock deposition and preservation that evolved largely prior to and during continental break up. During the rifting (Late Jurassic through early Tertiary), the grabens were sites of graben lakes and delta sediments (synrift sequence) and later narrow interior gulfs between the separating continental fragments into which there was restricted marine entry (early postrift sequence). In these sequences, rich organic matter was deposited and preserved. The rifting also provided fault and drape closures. The restricted marine phase often resulted in thick seal- and trap-forming salt sequences, which, however, are not likely in Antarctica.

Although the presence of some of these synrift rocks are indicated by the seismically-revealed geometry of the rift margin, these Upper Jurassic through lower Tertiary rocks do not crop out in East Antarctica. In a few instances their presence is confirmed, however, by findings in shallow holes or by erratics or reworked fossils in younger sediments. These instances, counterclockwise around East Antarctica, are:

1. A sea bottom core just offshore of Wilkes Land (approximately in the middle of the Antarctic-Australia province of fig. 2) revealed an in-situ Aptian (that is, synrift) siltstone (Domack and others, 1980). Abundant organic material was found in some nearby erratics of the same age.

2. Reworked palynomorphs in modern marine sediments were found in the eastern half of the Antarctic-Australia province (fig. 2), which ranges in age from Early Cretaceous to Tertiary (Veevers, 1987).

3. ODP hole, site 741, (one of five drill holes at Prydz Bay, fig. 1) revealed Eocene pre-glacial, nonmarine rock with carbonaceous and coaly material (Party, Leg 119, 1988).

4. The ODP drilled two holes, sites 692B and 693 (figs. 1 and 18), into the pre-glacial sediments off Queen Maud Land (at the Antarctic-Falkland and Antarctic-Africa provincial boundary of fig. 2). Site 692B penetrated Lower Cretaceous (Valangian, Hauterivian) organic-rich claystone (up to 8 percent organic carbon). The organic materials were types II and III, with a high source potential (50 Kg HC/ton of rock). The section is thermally immature. (Party, Leg 113, 1987) (See Antarctica-Falkland rift province discussion).

5. Cretaceous and Tertiary rock outcrop in West Antarctica and are best exposed in the Larsen basin of the Antarctic Peninsula. There, a complete section, from Upper Jurassic to Pliocene is exposed including Jurassic and Lower Cretaceous source rock (see Larsen Backarc Basin).

Reservoirs and seals in East Antarctic synrift or early postrift, that is, pre-Oligocene, sequences are, as is the case for source rock, unaccessible to observation. By analogy, however, to Australia's rifted margin (see "General; the South Australia Rifted Margin Analog") and other once-adjoining Gondwana rifted margins, adequate reservoirs may be presumed to exist.

The Oligocene and younger sequence of thick glacial deposits, on the other hand, are more accessible, and it appears that they contain potential reservoirs. CIROS-1 and the nearby MSS7-1 holes, in southeastern corner of the Ross Sea (fig. 1), penetrated Oligocene and younger sands with porosities ranging up to 46 percent (Cooper and others, 1988). However, as demonstrated by the probably relict hydrocarbon residue found at the base of the very porous Oligocene glacial beds in CIROS-1, the limiting factor to oil accumulation may be the presence of seals. A possible analog for glacial-deposit oil accumulation is the Permian-Carboniferous glacial Al Khlata Formation of south Oman, which contains some 3.5 BBO in place (Levell and others, 1988). In the main prospective belt of this formation, "there are multiple reservoir-and-seal couplets." These Oman reservoirs are glaciofluvial sands to proximal glaciodeltaic sands with porosities ranging up to 26 percent, but of rather erratic distribution; the seals are usually glaciolacustrine shales.

In West Antarctica there are some outcrops of Mesozoic and Tertiary possible reservoirs and seal strata of rather unknown quality (see Larsen Basin and Alexander Basin).

The geology of the convergent West Antarctica is more complicated and less understood than that of the East Antarctic region. According to the latest Gondwana reconstructions (Lawver and Scotese, 1987), the convergent margin is made up of a number of microcontinents (fig. 3) accreted against the East Antarctic craton at the Gondwanides collision zone of Triassic and earlier times. While convergence was apparently strong in those times, later in the Mesozoic and Cenozoic the West Antarctic area was the site of extension rather than compression, similar perhaps to the Tertiary basin and range condition of the convergent western United States. Oblique subduction of a hot Pacific spreading ridge in the Tertiary furthered this extension. West Antarctica was therefore affected by two overlapping extensional forces: (1) extension, largely backarc, associated with the subduction, and (2) in part, the intracontinental extension, which led to the rifting associated with the Gondwana breakup, including the Ross and Weddell failed-separation interior rifts.

The geology of West Antarctica is discussed in more detail under "Backarc Provinces" and "Forearc Provinces."

Figure 4 shows the significant oil and gas provinces of the Gondwana platform area (that is, northeast of the Gondwanides now marked by the Transantarctic Mountains), the petroleum occurring largely in rifts. The total estimated ultimate petroleum resources of the marginal and interior rift basins of the Gondwana platform area are 35 BBO and 148 TCFG (based largely on Petroconsultants data). Six of these rift basins each have resources of over 2 BBO and two rift basins, Campos and Bombay provinces, have individual fields of 3 or 4 BBO.

The accreted convergent Gondwana area, Pacific-wards of the Gondwanides, in the adjoining South America (fig. 3) has reserves of 7.1 BBO and 46.6 TCFG (based largely on Petroconsultants data) and estimated ultimate resources of 10.1 BBO and 62.6 TCFG (based largely on U.S. Geological Survey estimates). The closest, on-trend backarc basin of southernmost South America is the 71,600-mi^2 (185,400-km^2) Magallanes basin (E, fig. 4) with estimated reserves of 0.8 BBO and 14.2 TCFG (Petroconsultants, 1989) and has estimated ultimate resources of 0.9 BBO and 15.0 TCFG.

Only minor hydrocarbon occurrences have been encountered in the Antarctic, which is not unexpected in any case, given the general lack of ice-free outcrops of the potential petroleum-bearing sedimentary rocks and absence of any wildcatting. These occurrences are listed below.

1. CIROS-1, a drill hole at the southeast corner of the Ross Sea (fig. 1), encountered 2 meters of heavy hydrocarbon residue in a coarse sand near the base of a 2,300-ft (700-m) Oligocene and younger sequence of glacial and nonglacial marine sediments (Cooper and others, 1988).

2. Thermogenic hydrocarbon traces are reported to occur in Bransfield Trough (fig. 1) emanating from presumably Pleistocene strata (Cooper and others, 1988). However, given the volcanic nature of the fill and the recent volcanic activity in the area, those shows may be the result of local pyrolysis of shallow organic shales by hot intrusive igneous rock.

3. Gas shows, including minor amounts of ethane and higher hydrocarbon homology, have been encountered in several holes of DSDP (Deep Sea Drilling Project) and successors IPOD (International Phase of Ocean Drilling) and ODP located in the Ross Sea (sites 271, 272, and 273); off Queen Maud Land (Antarctica-Falkland province) (sites 692B and 693) and near Prydz Bay (site 742, very slight). These shows may have little significance as regard to petroleum potential as such occurrences have been "essentially the same in DSDP coring worldwide" (Claypool as quoted in Behrendt, J.C., in press).

ASSESSMENT BY PLAY ANALYSIS

Play analyses (or superplay analysis, since the play, as used here, involves an unknown number of basins, or depocenters, within an extensive province) of each of the basinal trends or provinces were made involving the principal geologic factors required for the accumulation of oil and gas. These factors were estimates based on analogies to the same factors in more accessible, more-explored ex-Gondwana provinces, which were adjacent or nearby, in Cretaceous and earlier times. These analogs involve the amount of trap area, the percent of trap area that is productive, the pay thickness, the percentage of oil versus gas, and the amount of oil and gas recoverable per acre/foot.

Details of these analyses are shown in the play analysis sheets in Appendix A, but the highlights and critical concerns are briefly discussed below. In the discussion, several alternate estimates and interpretations may be covered, but the first-discussed estimate in each case is deemed the most likely.

Rifted Continental Margin Provinces

General; the South Australia Rifted Margin Analog

The East Antarctic craton is ringed by rifts; continental margin rifts on the eastern perimeter and interior rifts, or incipient marginal rifts, on the west that separate the craton from the orogenically active West Antarctica.

Prior to early to mid-Cretaceous times, the continental margin rift provinces of Antarctica were interior rift provinces, one half of each of which is now in Australia, India, Africa, and South America. These drifted halves (fig. 4), now in more accessible environments, have been relatively well explored and provide pertinent analogs for the play factors, which are lesser known in the ice-bound Antarctic marginal basins. Particularly good analogies appear to exist between the play factors on the Australian side of the Antarctic-Australia rift province and those on the Antarctic side, and consequently, to a certain degree, provide analogs to factors affecting the other marginal rift basins of Antarctica. The geology of the south Australian margin is therefore worthy of particular study in the assessment of Antarctica. Rifting of the Antarctic-Australia rift province began around mid-Jurassic and finished in mid-Cretaceous when the two continents separated. A northeastern branch of this rifting, the Bass Strait, between Australia and Tasmania, including the Gippsland and Bass basins (O, fig. 4), was not included in the continental separation, and rifting continued into the Eocene. The major part of the rifting, basinal fill, and we would judge most prospective part of the Australian margin is under the deep, upper continental slope (as indicated in fig. 5) where present-day economic and technical limitations have prevented adequate testing. This apparent

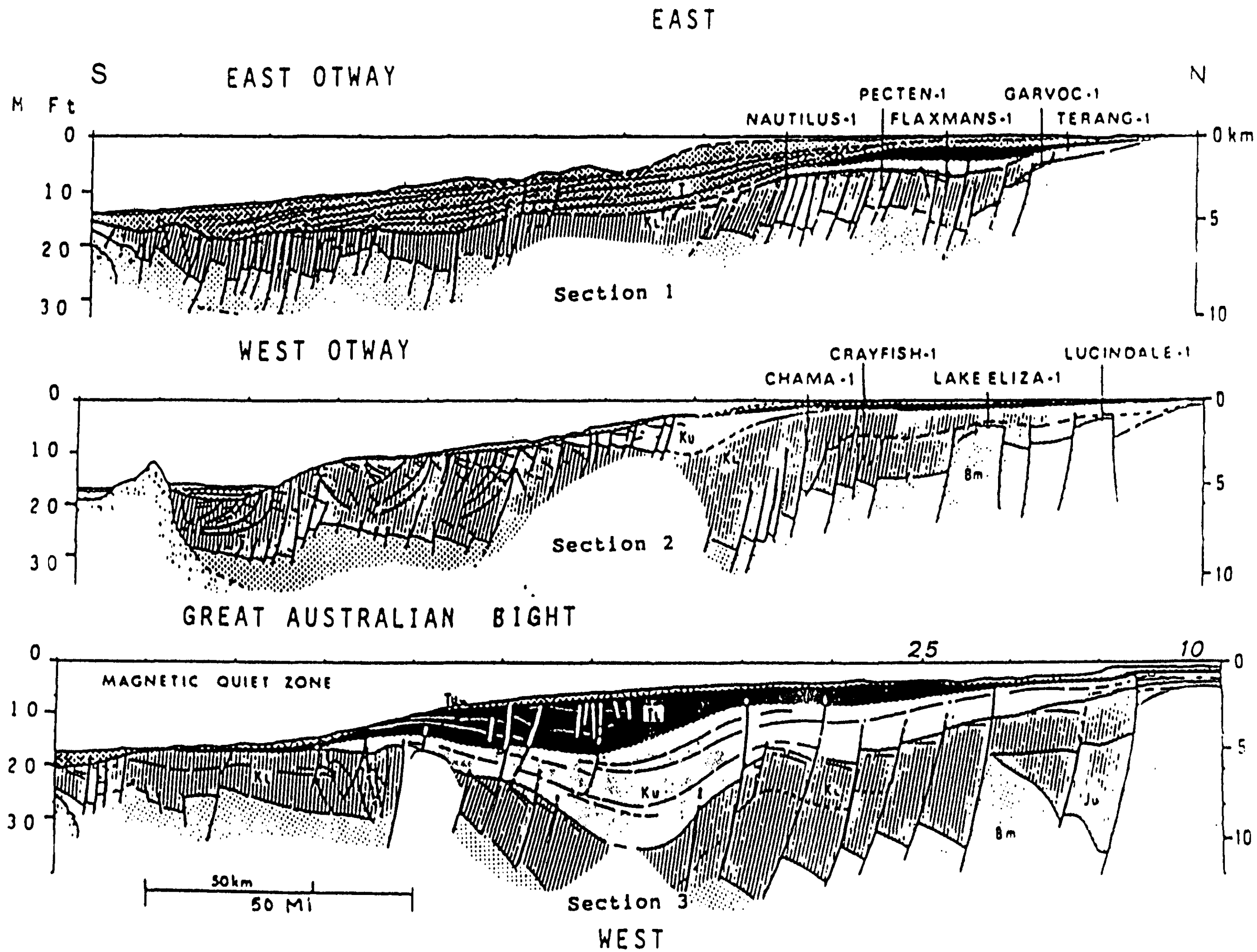

Figure 5.--North-South geologic sections across Australian south margin from east to west (East Otway to Great Australian Bight basins). T and Ku = Tertiary and Upper Cretaceous post-rift sediments; Kl and Ju = Low Cretaceous and Upper Jurassic synrift sediments; Bm = basement; pre-rift sediments only in isolated faulted inliers. Location of sections, figure 4 (from Boeuf and Doust, 1975).

petroleum potential of the Australian slope augurs well for the prospects of the opposing rifted Antarctic margin where a depocenter is also under the slope rather than, or additional to, the ice-bound shelf, and therefore possibly accessible to exploration under present technology.

Exploration drilling of the south Australian margin, largely limited to the continental shelf, has yet to be encouraged by any discoveries. Enough exploration has been done, however, to establish three groups of strata: (1) prerift, which is largely basement with pre-Jurassic or Early Jurassic sediments in small, isolated graben basins, (2) synrift, which is sediments of Late Jurassic to mid-Cretaceous age along the continental margin (but ranges through the Cretaceous into the Tertiary in the Bass Strait where rifting continued longer), and (3) postrift, Late Cretaceous and younger sediments (fig. 5). Since these rock groups are recognizable by their relation to the rifting that can be observed in seismic profiles, much of the subsurface geology may be surmised with only a relatively few key wells.

Exploration of the southern Australian margin and the Bass Strait has established that the essential factors for oil and gas accumulation do occur in the synrift and postrift strata and provide analogies that may be applied, within the rift framework, to the counterpart Antarctic margin, and to a lesser degree, the other Antarctic rift basins.

Traps.--The only available map of individual structures in the vicinity is that of the Bass basin of the Bass Strait (O, fig. 4) (Williamson and others, 1987) where structural closures, fault traps and drapes, appear to make up 5.8 percent of the basin (play) area. This percentage is used in play analysis of the marginal rift basins even though the Bass basin interior rifting did not cease in mid-Cretaceous, but continued into the Early Tertiary; while more closures may have formed, they would be in smaller traps and the total area of the closures may be similar. The 5.8 percent compares fairly closely with the 5.0 percent closure area estimated for other rifted continental margins of Africa and India (Kingston, 1986, 1988).

Percent of Trap Area Productive.--There is available only one producing basin, the Gippsland basin of the Bass Strait (O, fig. 4), as an analog for this factor. There, it appears that about 4.5 percent of the mapped trap area may produce oil and gas (on the basis of an estimated 15 percent discovery rate and assuming the general average of 30 percent by area trap-fill).

Reservoirs.--Stratigraphic studies of the southern Australia margin (Franklin and Clifton, 1971; Denham and Brown, 1976; Bein and Taylor, 1981; Ellenor, 1976; Fraser and Tilbury, 1979; Whyte, 1978) indicate that the average synrift Upper Jurassic-Lower Cretaceous reservoir sandstones combined thicknesses in that region range from 200 ft (61 m) in the east, Otway basin (N, fig. 4), to 225 ft (69 m) in the west, Great Australian

Bight (L, fig. 4). While synrift Upper Cretaceous reservoirs are up to 209 ft (64 m) in the Gippsland basin interior rift, the reservoir combined thickness is assumed to be around 100 ft (31 m) in the marginal rifts. Porosities range from 18 to 25 percent, perhaps averaging 20 percent.

Source Richness.--The synrift nonmarine sediments of Late Jurassic to Early Cretaceous age (but ranging through the Cretaceous to Paleogene in the Bass Strait) appear to be the principal source rock of the south Australia margin. The synrift total organic content (TOC) in Bass basin of the pre-Maastrichtian shows a "good to very good" source potential, but gas prone (Williamson and others, 1987). Oil and gas shows indicate the synrift strata to be a source in the Otway basin (N, fig. 4). The TOC of the synrift, Upper Jurassic and Lower Cretaceous, strata of the Great Australian Bight (L, fig. 4) ranges from 1.3 to 2.0 percent; and synrift oil and gas shows are present (Bein and Taylor, 1981).

The synrift Upper Cretaceous and lower Tertiary nonmarine sediments of the Bass Straits appear to be the principal source of the Bass and Gippsland petroleum (Williamson and others, 1987) with the Lower Cretaceous being a contributing source. Although these principal source rocks are younger than the Upper Jurassic-Lower Cretaceous synrift sediments of the continental margin basins, they reflect a prolongation of the earlier synrift environment that continued through the Cretaceous and into the Paleogene in the Bass Strait area.

In the Great Australian Bight "good ... hydrocarbon source potential was encountered in postrift strata" (Bein and Taylor, 1981). In this area, the postrift sediments become increasingly marine westward. In general, the lower postrift sediments, deposited over a horst and graben topography in a narrow interior sag basin with a restricted entree for the sea, would appear to be a likely source rock.

Conditions for Maturity of Source Rock.--From an average present thermal gradient of 1.4°F/100 (25.5°C/km) (Willcox, 1981) as established in some wells, and from the present rate of subsidence, it is estimated that the average depth to the top of the thermally mature source rock for oil (that is, the oil window) for the southern Australian margin averages about 10,000 ft (3 km) and the bottom of the oil-window is estimated at about 18,000 ft (5.5 km).

Oil Versus Gas.--The sole available analogy for the oil versus gas content of petroleum in the south Australian margin is the Gippsland basin, an interior rift province where oil and gas production has been established. The source shales (Eastern View Coal Measures) are of Late Cretaceous and early Tertiary age; they appear to be synrift sediments and probably equivalent lithologically to the presumed Early Cretaceous synrift petroleum-generating beds of the continental margins. Source rock analysis by kerogen type in the Bass basin indicates that while the Upper Cretaceous, Lower Tertiary Eastern View Coal Measures shales are a mixture of oil- and gas-prone kerogen, the Lower Cretaceous sediments of a similar lithology, the Otway Group, are only gas prone. Pyrolysis suggests, however, that both oil-prone and gas-prone source rock are present through the entire synrift section (Williamson and others, 1987). The Gippsland reserves are about 3.0 BBO, 7.8 TCFG, and 0.762 BNGL (Shanmugam, 1985) or approximately 59 percent oil, 26 percent gas, and 15 percent natural gas liquids. The indicated condensate yield is 97.7 BNGL/MMCFG. The proportion of oil and natural gas liquids appears to be unusually high for humic coal-generated petroleum. It is estimated, however, that the oil content would be lower in the Lower Cretaceous-sourced, deeper deposits of the Antarctic slopes, ranging from 34 to 60 percent depending on the geology. The natural gas liquids would also be lower, averaging about 50 BNGL/MMCFG.

Oil and Gas Recovery.--By analogy to the porosities of the Australian margin, which average 20 percent, and assuming water saturations of about 25 percent and an oil recovery factor of 30 percent, the average estimated volume of oil recoverable from Antarctic reservoirs, under normal conditions, would be about 240 barrels per acre/foot. Gas recovery varies with depth but might average around a million cubic feet per acre/foot.

Antarctica-Australia Rift Province

This province directly opposed the Australian south margin in Cretaceous times (figs. 1, 2, 3, and 4) and is taken to extend from the Antarctic coast to the continental-oceanic crust boundary (COB), a distance of 100 to 200 mi (160 to 320 km). It has a gross area of some 554,000 mi^2 (1,435,000 km^2) of which, by analogy with its Australian counterpart, about 20 percent is play or prospective area.

Part of the Antarctic margin of this province, offshore Wilkes Land, has been covered by sufficient reconnaissance seismic survey to indicate its boundaries, general shape, and sedimentary tectonic sequences (Eittreim and Smith, 1987). By correlation of these sequences with geometrically similar sequences in the relatively well-explored Australian margin, the geology and age of the sequences may be surmised, including their prerift, synrift, and postrift tectonic settings. Figure 6 shows the Antarctic sequences A, B, C, D and the position of the oil window as approximated from the thermal gradient. It will be noted that a good part of sequence D has subsided into the oil window. Sequence C is only partly in the oil window (and therefore thermally mature) in the downdip and deeper areas. Figure 7, a sample area off Wilkes Land, indicates that in 52 percent of the area (over the continental crust), sequence C is above the window and still immature.

According to Veevers (1987), sequence D correlates with the Australian Upper Jurassic to Lower Cretaceous synrift unit. On the basis

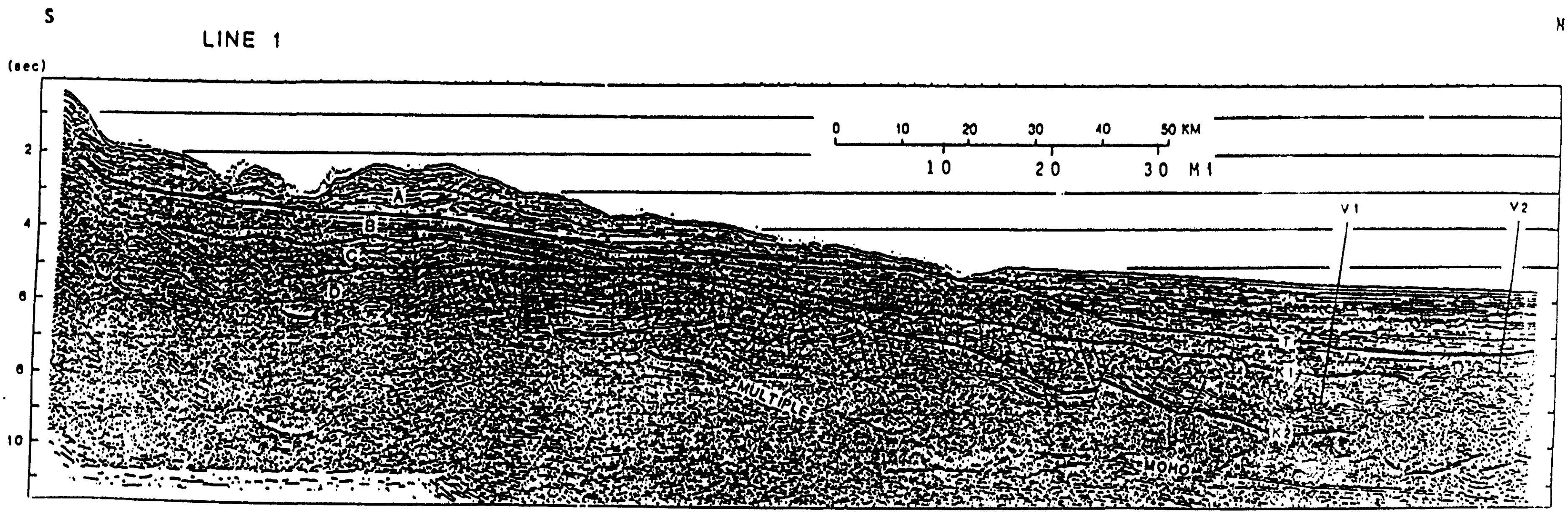

Figure 6.--South-north migrated seismic time section offshore Wilkes Land, showing seismostratigraphic sequences A, B, C, and D (and oceanic sequences V1, V2, and V3) as interpreted by Eittreim and Smith (1987). Dotted lines indicate approximate top and bottom of the oil-window inferred herein. Location of line in figure 7.

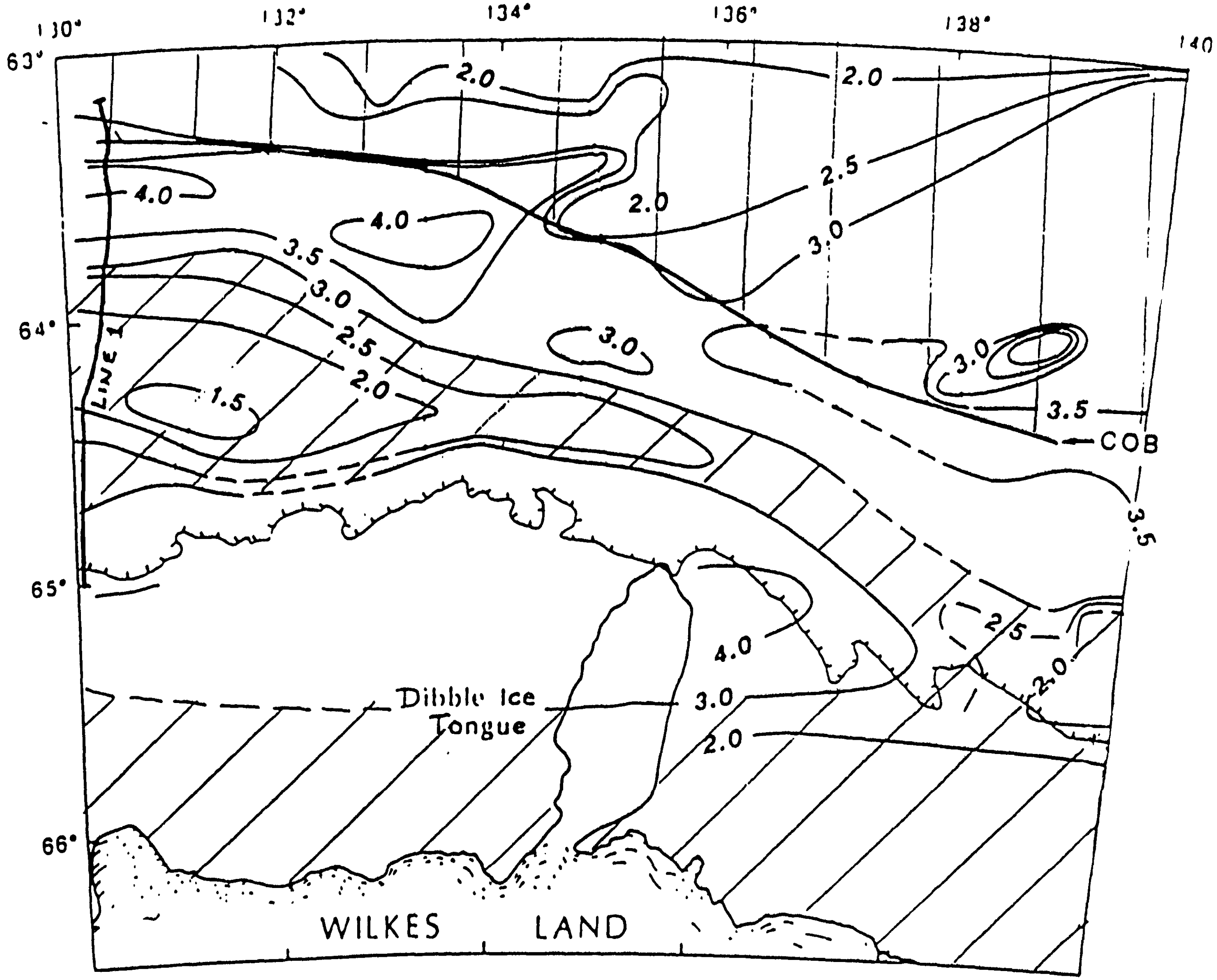

Figure 7.--Isopach of sediments of offshore Wilkes Land above horizon K_2, the Sequence C-D interface. Cross-hatched portion is area where Sequence C is above oil window and immature. Vertical hatch is area of oceanic crust and considered out of the play. Profile, Line 1, is shown on figure 6 (modified from Eittreim and Smith, 1987).

of this correlation and of associated geologic analogies where synrift strata have good source potential, play analysis (Play Analysis Summary 1, Appendix A) indicates resources of 2.7 BBO, 17.0 TCFG, 0.9 BBNGL, and 6.4 BBOE. This estimate assumes 40 percent oil in the petroleum mix, two-thirds the percentage of oil in the unusually oily Gippsland basin production.

An alternate, and in my opinion somewhat less likely, correlation (Eittreim and Smith, 1987) indicates that the mature sequence D is pre-rift, rather than synrift, which would presumably equate it with the Devonian to Middle Jurassic Beacon Supergroup or older units. The prerift Beacon Supergroup has some Permian coal beds, but is deemed to have relatively poor source potential. By analogy to the nearby Cooper basin of Australia, where the source is Beacon-equivalent strata, the resources for the Antarctica-Australia rift province, which were sourced from sequence D, would amount to 0.11 BBO, 10.0 TCFG, and 0.9 BBNGL. Under this correlation, the presumably organic-rich synrift sediments (that is, sequence C) would be mature in less than half the area and would generate resources of 1.3 BBO, 8.5 TCFG, and 0.3 BBNGL. Together the resources of the basin under this alternate interpretation would be: 1.4 BBO, 18.5 TCFG, 1.2 BBNGL equaling 5.9 BBOE. If the source potential of the Beacon Supergroup strata are assumed analogous to the equivalent strata of the Karoo basin, rather than the Cooper basin, the resources would be less, and if assumed analogous to the Solimoes basin of Brazil, they would be more.

Antarctica-India Rift Province (including Prydz Bay)

This province opposed India in Cretaceous times (figs. 2, 3, and 4) and extends from the Antarctic shore to the COB. It has a gross area of some 490,000 mi^2 (1,270,000 km^2) and, by analogy to the Antarctica-Australia marginal rift province, a play area of 20 percent.

The cross-section character of this rifted margin is shown in figure 8 and some details of the geology of the once-adjoining India-Sri Lanka margin may be seen in figures 9 and 10. A resource estimate of the Antarctica-India Rift province, with a play area of some 98,000 mi^2 (254,000 km^2), may be arrived at by drawing two separate analogies. The first analogy is to the resource estimates (Kingston, 1986) of the once adjoining margin of India, the Cauvery, Palar, and Godavari-Krishna basins (fig. 9) indicating resources of 1.3 BBO and 5.6 TCFG (Play Analysis Summary 2, Appendix A). The second analogy is to the resource estimates of the on-trend Antarctica-Australia Rift province, indicating 2.4 BBO and 15.2 TCFG (Play Analysis Summary 2, Appendix A) (or if, in the less likely case, the source is the Devonian to Upper Jurassic Beacon Supergroup, 0.1 BBO and 7.0 TCFG). Weighting the two resource estimates in favor of the India analogy, because of the province's proximity to the Indian basins in Cretaceous and earlier times, an estimate of 1.7 BBO, 10.0 TCFG is obtained.

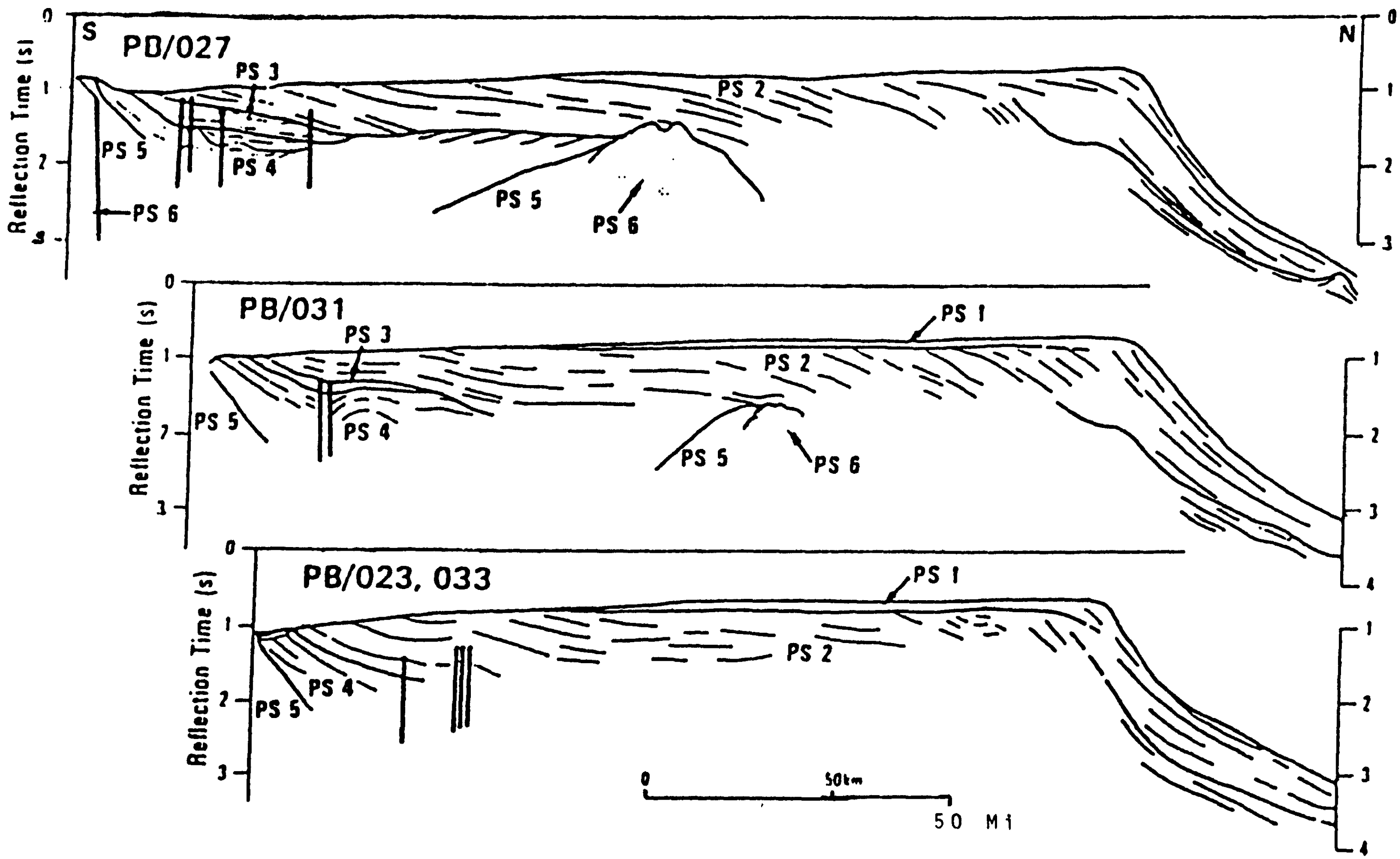

Figure 8.--Line drawings of seismic dip sections across Prydz Bay showing indications of rifting along the Antarctic-India province (from Stagg, 1985). Sequences PS5 and PS6 appear to be pre-rift. ODP drilling in the vicinity indicates that non-marine unit PS4 could be either pre-rift (Permian?) or synrift. PS3 and the lower part of non-marine PS2 (Lower Cretaceous?) are probably synrift. The upper part of PS2 and PS1 are post-rift and largely of glacial origin. Position of lines shown on figure 9.

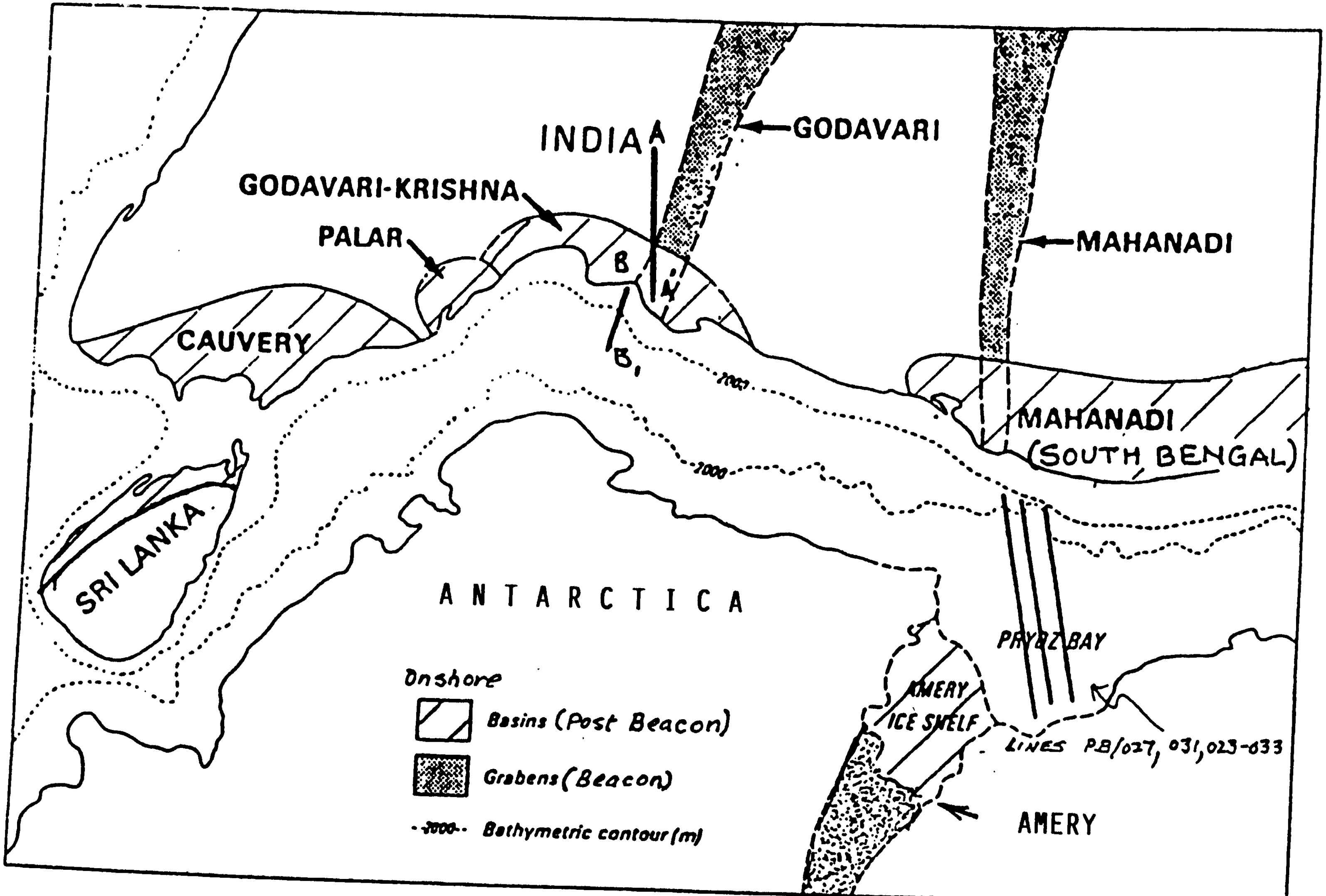

Figure 9.--Reconstruction of India (and Sri Lanka) against Enderby Land, or Queen Maud Land, Antarctica showing the Cretaceous-Tertiary coastal basins and the older, perpendicular-to-coast grabens of largely Beacon-equivalent fill (modified from Stagg, 1985).

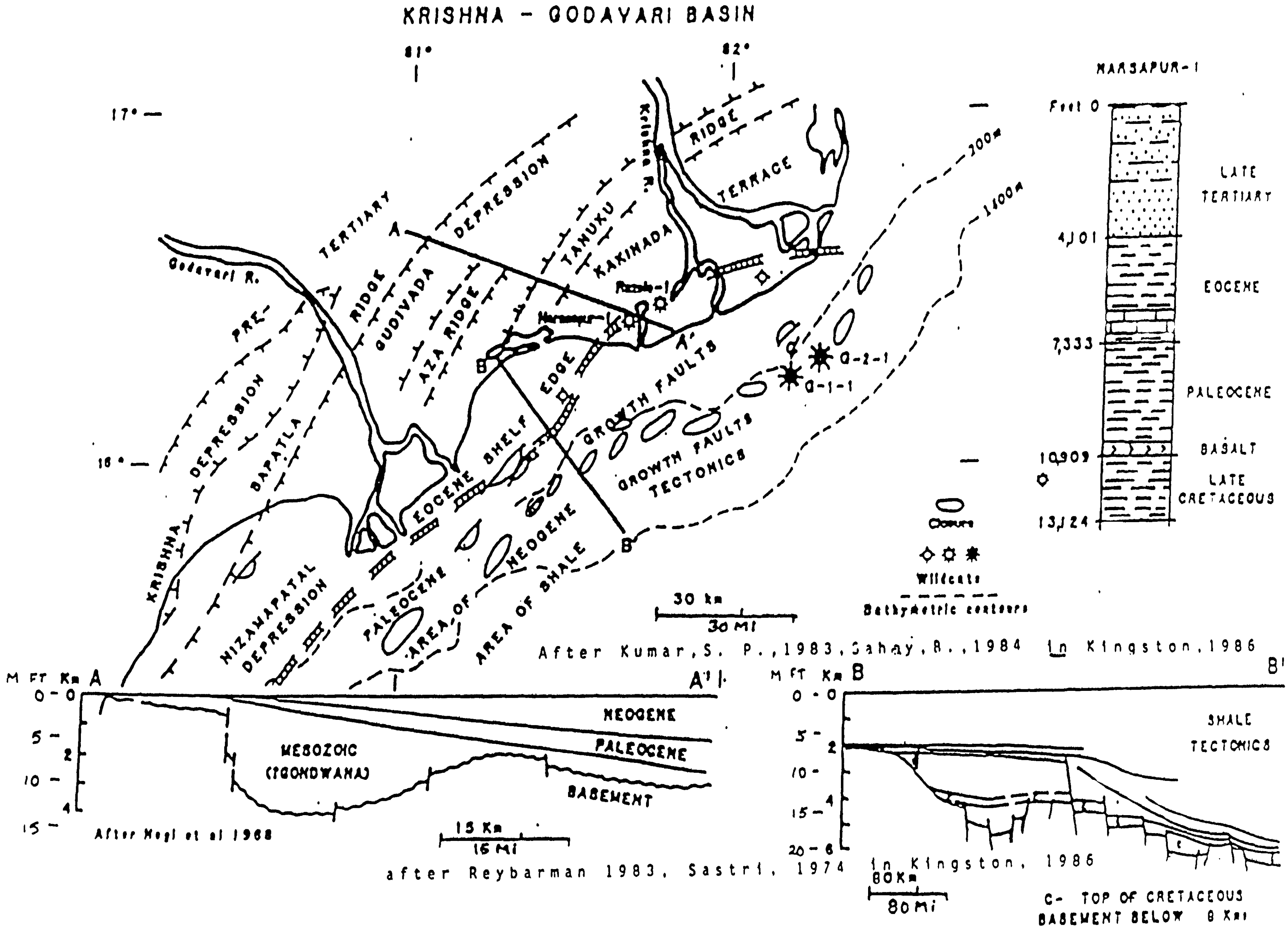

Figure10.--Basement tectonic map and geologic sections, Krishna-Godavari basin showing character of the eastern rifted continental margin of peninsular India (from Kingston, 1986).

Antarctica-Africa Rift Province

This province has a gross area of some 291,000 mi^2 (754,000 km^2), which by analogy to the other marginal rift provinces has a play area of about 20 percent or 58,000 mi^2 (150,000 km^2) and appears to have opposed Mozambique of southern Africa in pre-separation times (fig. 11). The absence of faulting or other evidence of Late Jurassic-Early Cretaceous extension along the African continental margin (see seismic line B-B', fig. 12) indicates that this portion of the African margin (and consequently, the opposing Antarctic margin) may have been largely wrenched rather than rifted during separation.

By analogy to the resources of the once-adjoining Mozambique basin (Kingston, 1986), the resources are 0.12 BBO and 2.9 TCFG (Play Analysis Summary 3, Appendix A). Another, perhaps less likely, analogy is to the on-trend Antarctic-Australia province; assuming (1) a wrenched margin at the shelf edge and thus restricting the province to the shelf (81,000 mi^2 of which 20 percent by analogy would be play area), and (2) that the shelf is otherwise comparable to the Antarctic-Australia Rift province, resources of 0.39 BBO and 2.5 TCFG are indicated.

Antarctica-Falkland Rift Province

This rifted margin province, which presumably opposed the Falkland plateau in the Cretaceous, has an area of some 118,000 mi^2 (306,000 km^2) (figs. 2 and 11), of which 20 percent is deemed basinal play area by analogy to the other Antarctic marginal rift provinces. Within this province are a number of large-volume, seaward-dipping sedimentary wedges (for example, the Explora wedge), which appear to have a typical synrift geometry (figs. 13, 14, and 15). On the basis of the findings of ODP hole 692B, which shows the strata above the wedge to be Lower Cretaceous or older, and the more tenuous evidence, that is, magnetic signatures, seismic velocities, and analogies to similar geologic settings around the Atlantic, the lower part of these wedges are Jurassic volcanics or Devonian to Lower Jurassic Beacon Supergroup sediments extensively invaded by Jurassic intrusives. Since either such rock group would contain relatively poor source rock and since the depths of these wedges entirely span the oil window, little petroleum may be expected from the province. The post-wedge sediments are generally too shallow to generate appreciable amounts of hydrocarbon. In this case, assuming an optimistic analogy to producing basins, i.e., the Cooper basin of Australia or the Solimoes basin of Brazil, which are filled with Beacon-equivalent sediments, the resources of the Antarctica-Falkland rift province would only amount to some 0.03 BBO, 2.65 TCFG, and 0.2 BBNGL, or 0.08 BBO and 4.0 TCFG, respectively, a negligible amount for such a large and hostile area.

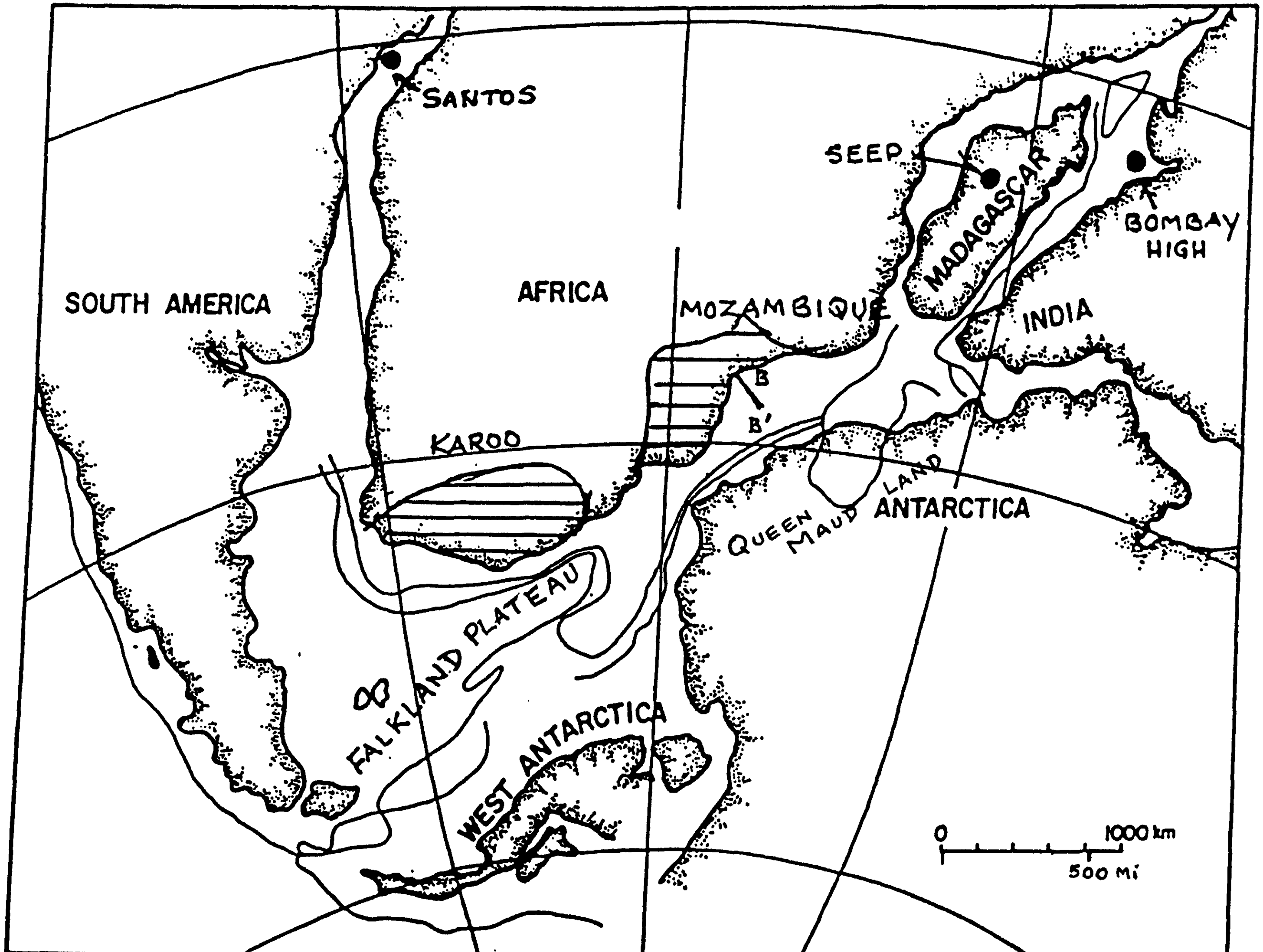

Figure 11.--Reconstruction of Africa against Antarctica showing the Mozambique basin opposing Queen Maud Land (other reconstructions show the Mozambique basin opposing peninsular India or Madagascar). Major petroleum occurrences, African basins, and seismic line B-B' are indicated (modified from Martin and Hartnady, 1986, after Norton and Sclater, 1979).

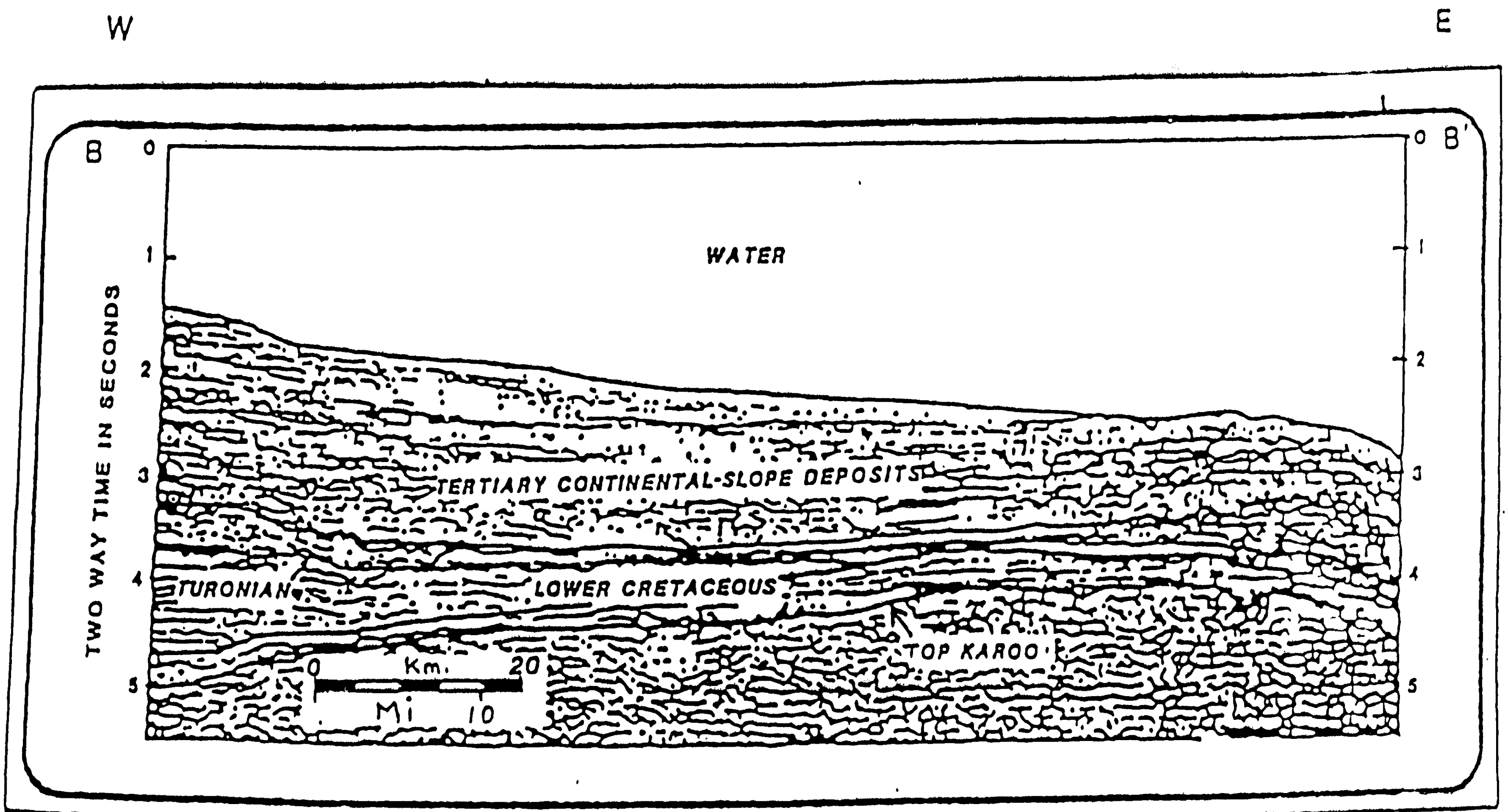

Figure 12.--West-east seismic profile across the continental slope offshore Mozambique (from De Buyl and Flores, 1985). Location shown on Figure 11.

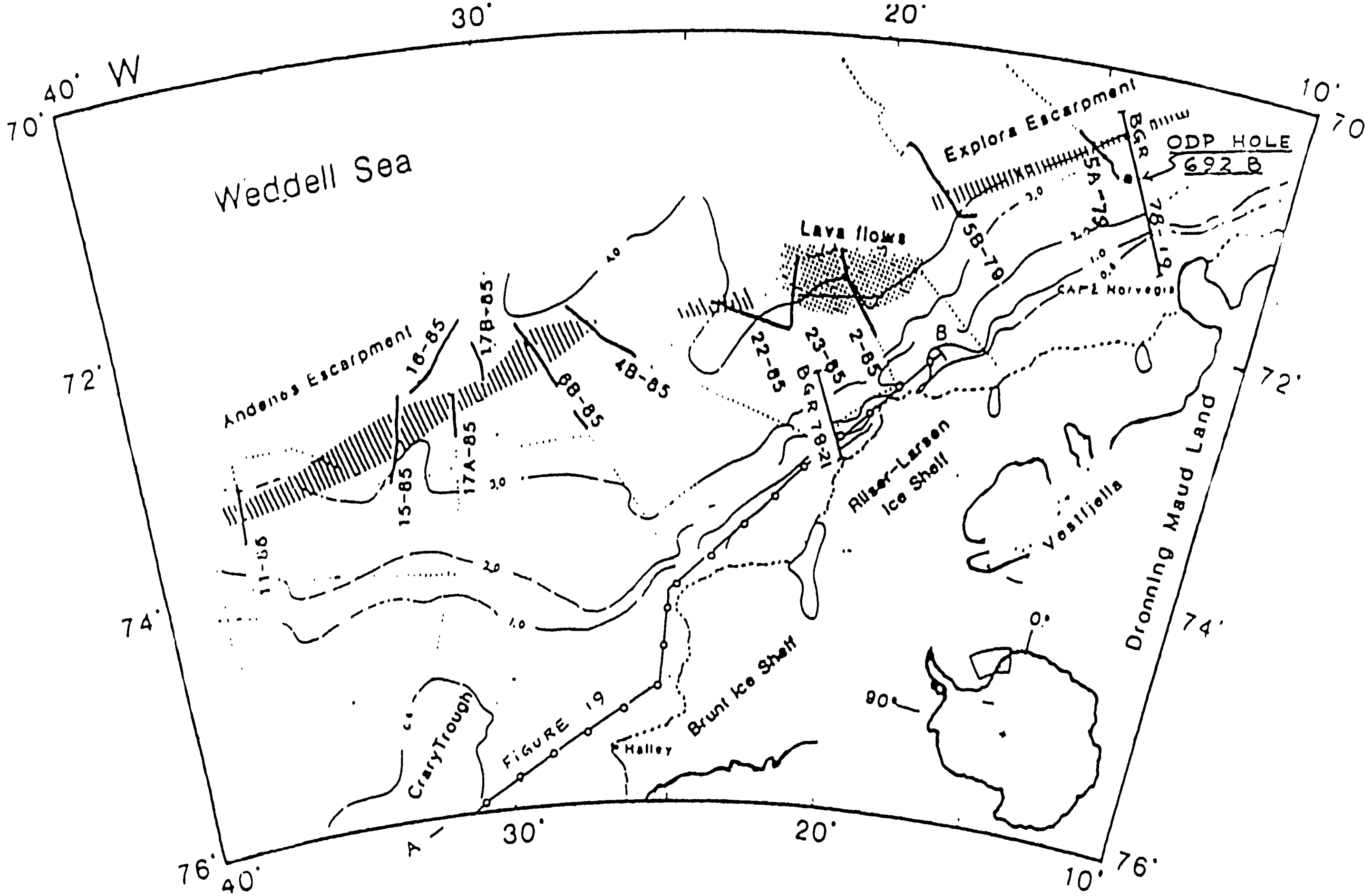

Figure 13.--Map of Antarctic continental margin off Dronning Maud, or Queen Maud Land, showing location of ODP Hole 692B, Norwegian Antarctic Research Expedition (fig. 14) and BGR (fig. 15) seismic lines, and seismogeologic line (fig. 19). Mapped escarpments and basement ridges (diagonal ruling) and regions of seaward-dipping lava flows (stippling). Bathymetry in kilometers. Position of ice shelf (dashed) and grounding line (solid line) (modified from Kristoffersen and Haugland, 1986).

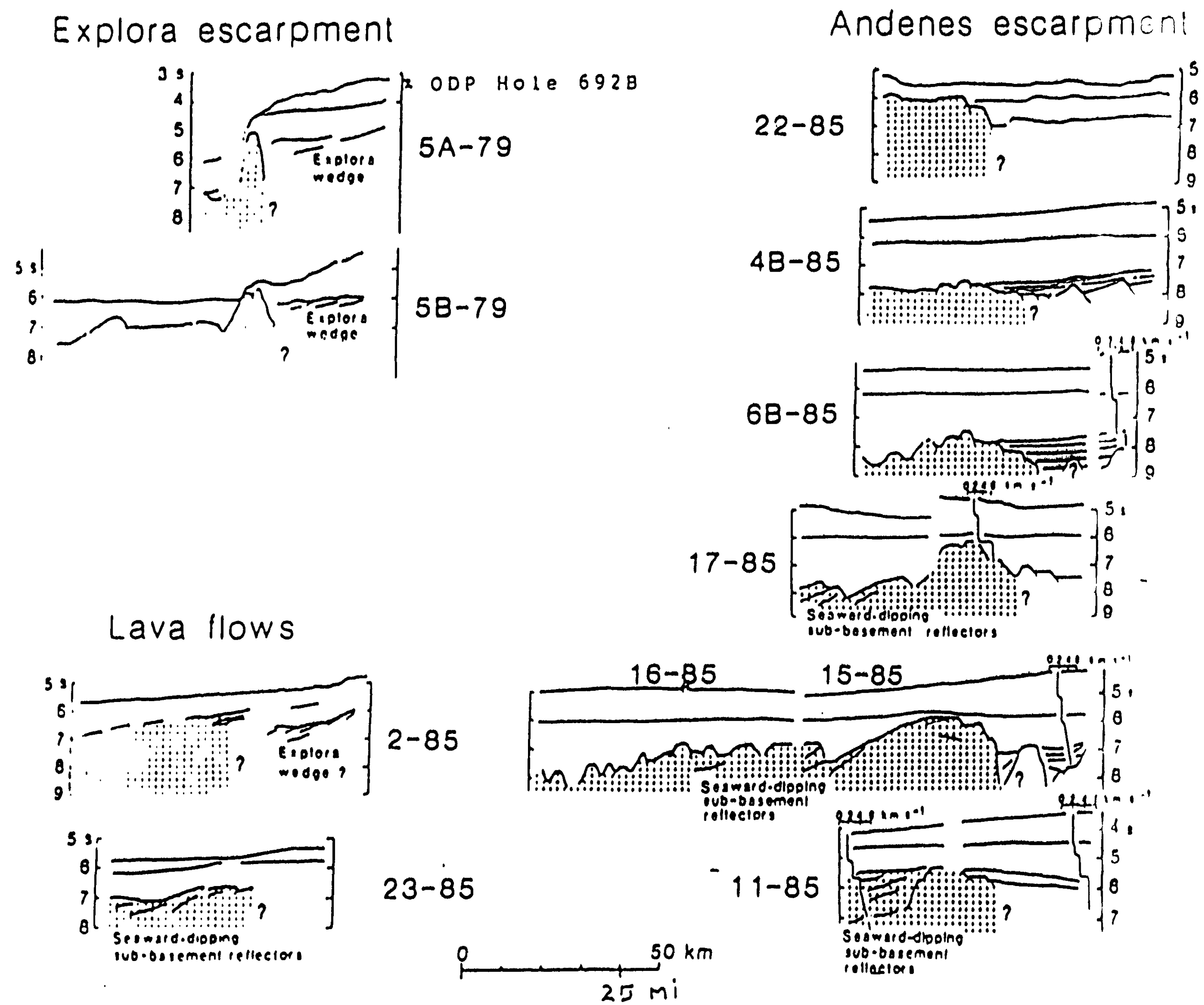

Figure 14.--Line drawings of seismic profiles shown on figure 13. Interpreted oceanic crust indicated by dot pattern (Kristoffersen and Haugland, 1986).

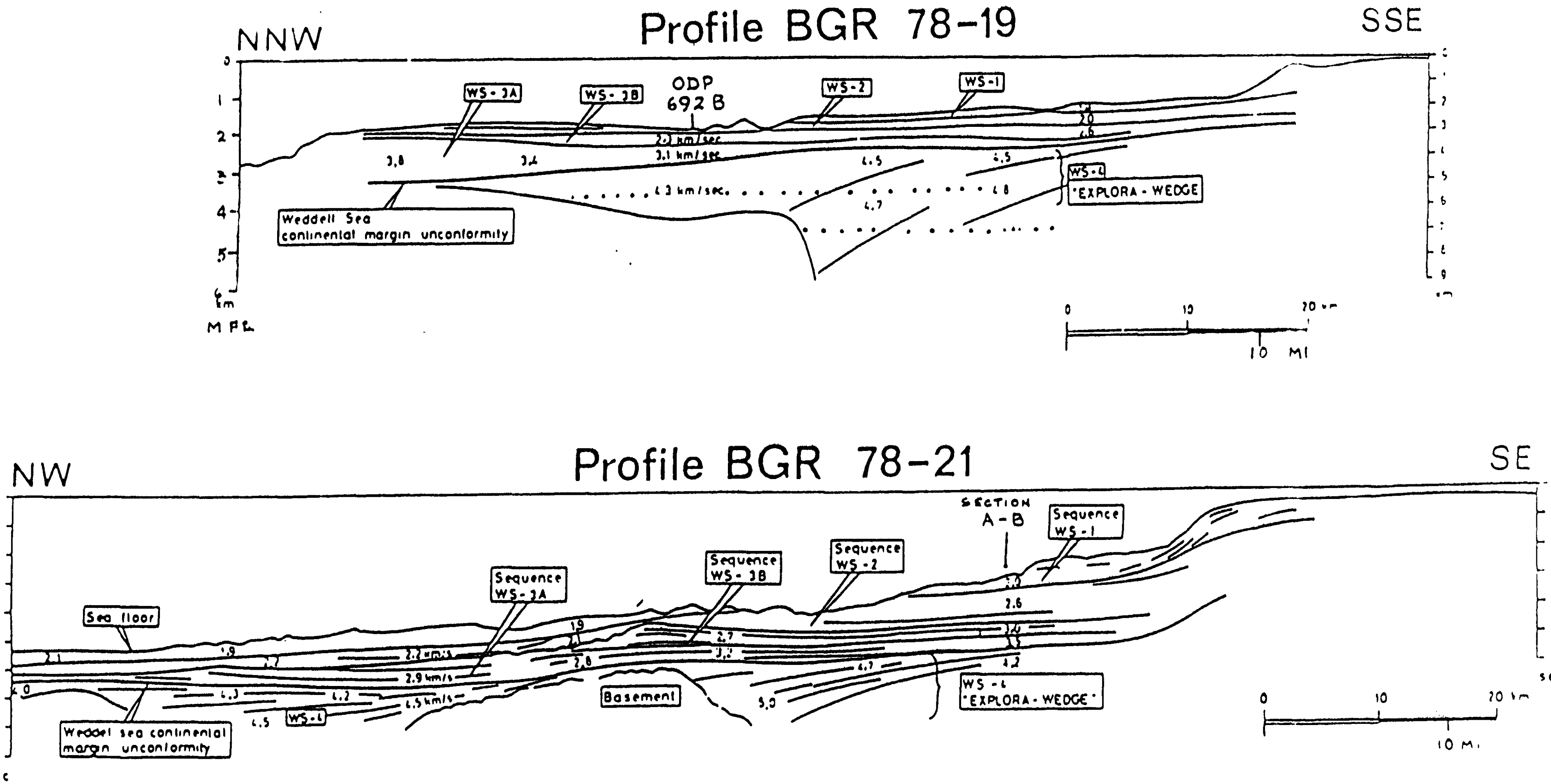

Figure 15.--Detailed line drawing of BGR seismic lines off Dronning Maud Land, or Queen Maud Land, showing Explora-Wedge sediments, basement fault blocks, Weddell Sea unconformity, the various seismic sequences along with the NMO velocities in kilometers per second, and ODP hole location. Limits of oil window shown by dots. Location of profiles shown on figures 13 and 18 (modified from Hinz and Krause, 1982).

Interior Rift Provinces

General

There are three principal interior rift provinces: the Ross Sea, Weddell Sea, and Amery basins (fig. 2). The Ross Sea basin or province is the most explored. The on-trend Ross Sea and Weddell Sea rift provinces separate the craton, East Antarctica, from the orogenic part of the continent, West Antarctica. The rifting trend is discontinuous, however, interrupted by the Ellsworth Mountains and other continental blocks (fig. 1) the tectonics of which are not clear (fig. 1).

The initiation of substantial interior rifting is presumed to be synchronous with that of the continental margin rifting during the Jurassic. I assume, in the absence of much data, that the tectonics, sedimentation, organic content, and thermal histories of the interior and of the marginal rift provinces are closely analogous, since both were interior rifts systems (that is, in synrift facies), up to the time of continental separation. The present interior rifts continued in a synrift setting through the Late Cretaceous and Paleogene while the marginal rift synrift setting ceased with continental separation in mid-Cretaceous.

Ross Sea Interior Rift Province

The Ross Sea Interior Rift province or Ross Embayment (Ross Sea plus Ross Ice Shelf, fig. 1) (572,000 mi^2, or 1,480,000 km^2) is essentially a mid-Tertiary (14-40 m.y.) peneplaned shelf or platform at a depth of 3,000 ft to 6,000 ft (900 m to 1,800 m), incised by a number of older grabens or rift basins (figs. 1, 16, and 17). The grabens, which occupy about 24 percent of the Ross Embayment area, are by analogy to the continental margin rifts deemed to have essentially begun in mid-Jurassic. However, instead of ceasing in mid-Cretaceous with continental separation, rifting continued into the Paleogene. The fill appears to be of a corresponding age, Late Jurassic to Paleogene, rather than down-dropped Devonian to Jurassic Beacon strata as many of the faults appear to be older than the fill and there is a smooth increase in seismic velocities from the beds above the Tertiary planation down into the graben fill. Recycled microfossils in younger beds support the presence of Cretaceous and Paleogene rock in the area, but no in-place sediments older than early Oligocene have been actually observed.

By analogy, mainly to the Antarctic-Australia rifted margin province estimates, but allowing for better Paleogene reservoir development owing to the likely greater quartz content provided by the nearby Eocene-rising Transantarctic Mountains, the average net pay is estimated to be 200 ft (61 m). This is supported by the 209 ft (64 m) net sand thickness reported from the Halibut field of the Gippsland basin of the analogous Bass Strait. Trap area (5.8 percent of play area) is derived by analogy from the Bass basin of the Bass Strait (only nearby available structural

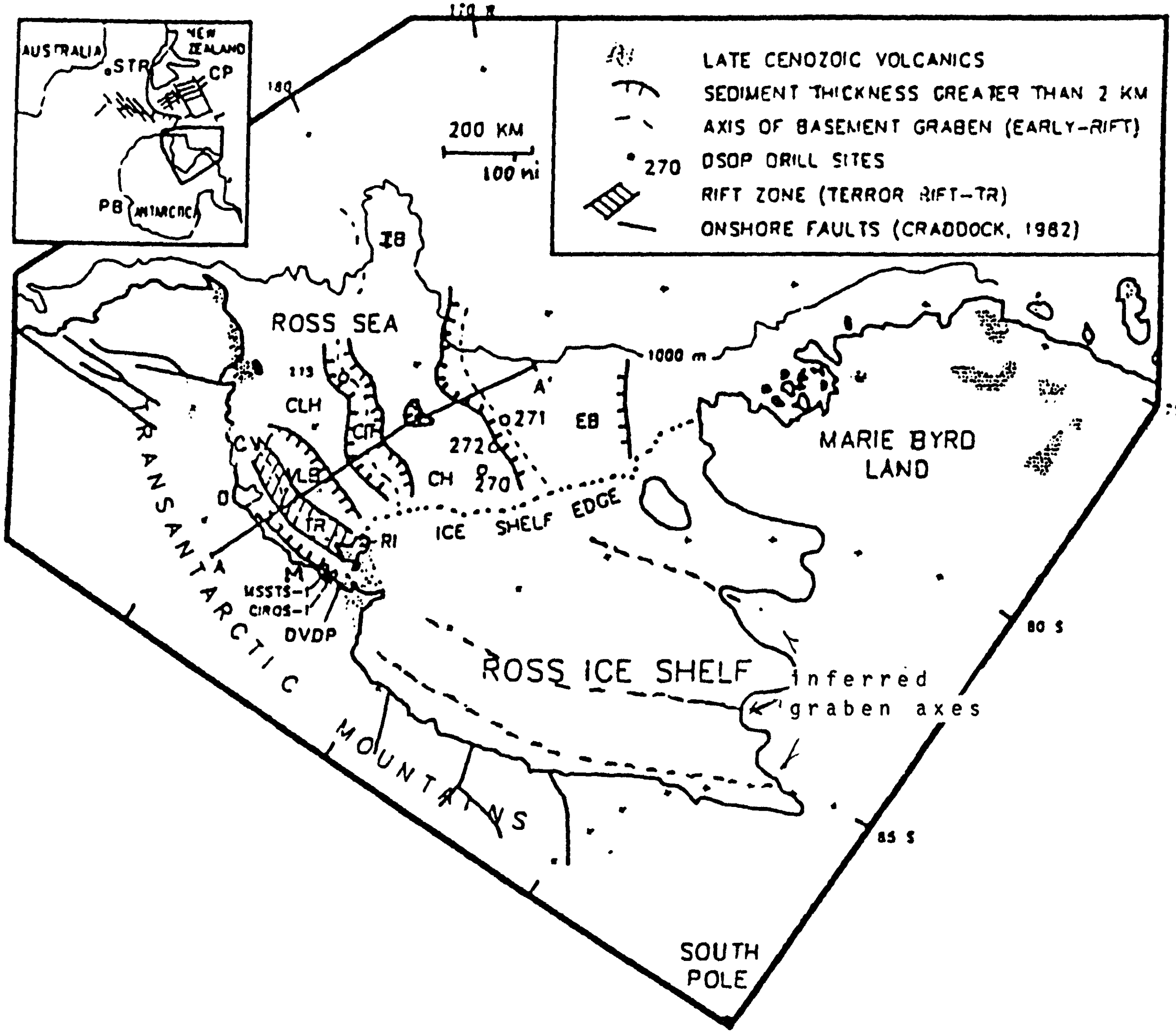

Figure 16.--Map of Ross Sea showing major grabens and inferred axes beneath the shelf ice. CH = Central High, CLH = Coulman High, CT = Central Trough, CW = Cape Washington, EB = Eastern Basin, IB = Iselin Bank, M = McMurdo Sound, TR = Terror Rift, RI = Ross Island, VLB = Victoria Land Basin (modified from Cooper and others, 1988).

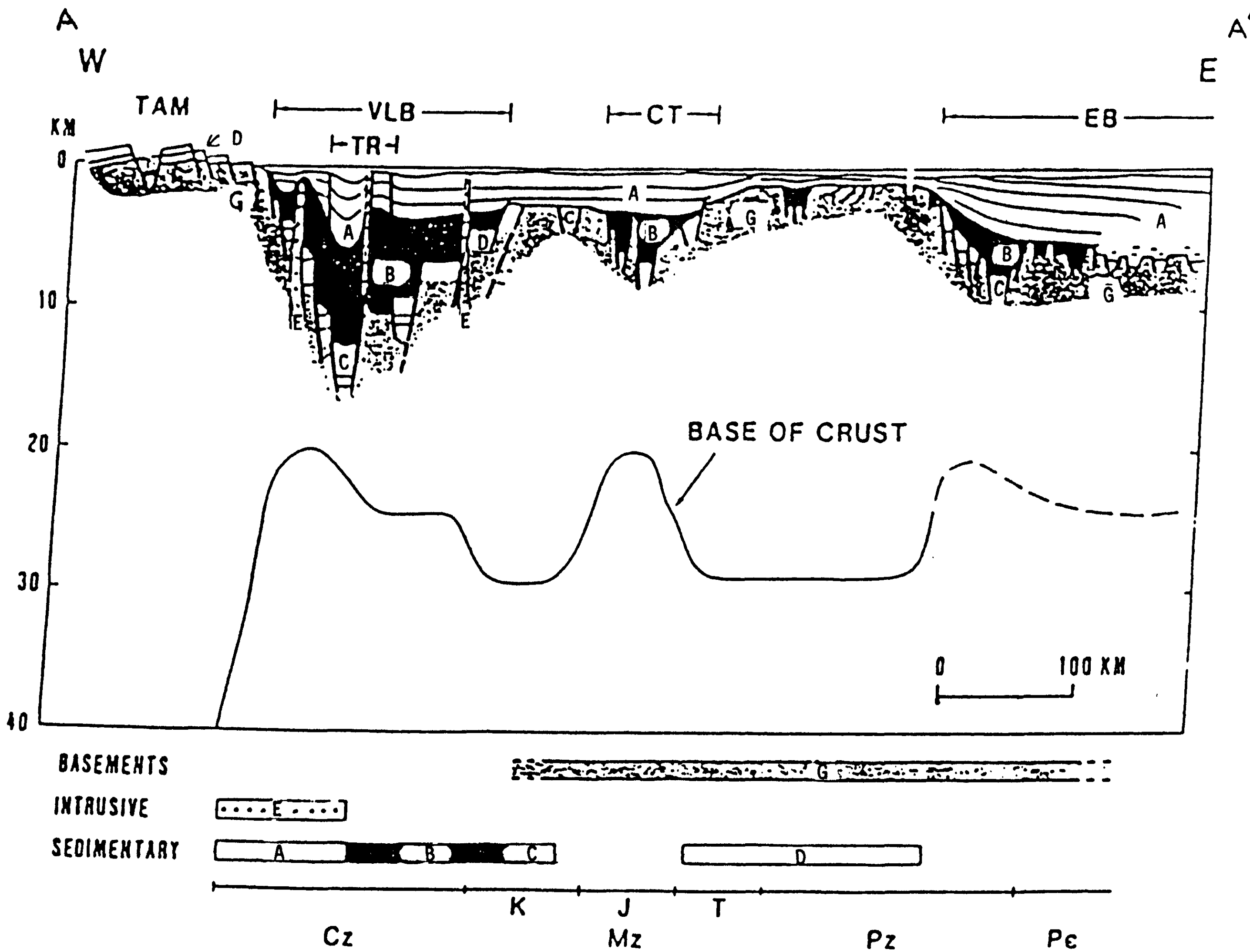

Figure 17.--Generalized profile across the Ross Sea. Letters refer to inferred-time scale. CT = Central Trough, EB = Eastern Basin, TAM = Transantarctic Mountains, TR = Terror Rift, VLB = Victoria Land Basin. Location on figure 16 (from Cooper and others, 1988).

data, Williamson and others, 1987) and trap productivity and reservoir characteristics from the Gippsland basin. On this basis, estimates of the Ross Sea Interior Rift province petroleum resources amount to 5.4 BBO, 27.8 TCFG, and 1.4 BBNGL, assuming 45 percent oil in the petroleum mix, which is three-fourths of the very oily Gippsland production (Play Analysis Summary 5, Appendix A). (If the oil content is assumed to be 59 percent, as in the Gippsland basin, the resources are 7.1 BBO and 20.7 TCFG).

Another apparently less likely interpretation is that the lower part of the graben-fill is down-dropped Devonian to Jurassic Beacon inliers and, therefore, analogous to the Beacon-equivalent sedimentary fill of the gas-producing Cooper basin or to the Solimoes basin, indicating resources of 0.14 BBO, 8.00 TCFG, and 0.61 BBNGL or 0.09 BBO and 4.7 TCFG, respectively.

Weddell Sea Interior Rift Province

The Weddell Sea Interior Rift province, or Weddell Embayment (Weddell Sea plus Ronne and Filchner Ice Shelves), of 300,000 mi^2 (780,000 km^2) (figs. 1, 18, and 19) is assumed to be generally analogous to the Ross Sea Interior Rift province, except that it is generally deeper, overall, with a thicker sedimentary section probably including a thick section of Devonian to Jurassic of Beacon strata, seismic sequence III of figure 19. Seismic sequence II appears to be, at least in part, Lower Cretaceous by correlation with the Lower Cretaceous found in ODP hole 692B (figs. 15, 18 and 19) but presumably includes Upper Cretaceous and Paleogene strata as well. The province can be considered a single, or at most, two rift basins (corresponding to the Ronne and Filchner Ice Shelves, fig. 18, and their seaward extensions) rather than a number of narrow individual troughs incised in a platform as in the Ross Embayment. The Paleogene reservoirs are deemed poorer than those of the Ross Sea province being further from the presumed quartz provenance of the Eocene-rising Transantarctica Mountains. Further, the oil content of the petroleum is estimated to be only about three-fourths that of the Ross Sea province since the potential source is deeper and probably includes more gas prone strata (for example, the Beacon coal measures). On this basis, the resources of the Weddell interior rift province are estimated to be 6.7 BBO, 69.5 TCFG, 3.5 BBNGL, amounting to 21.8 BBOE (Play Analysis Summary 6, Appendix A). A second, apparently less likely but more optimistic, analogy could be made by directly comparing the Weddell Sea province with the Ross Sea province on an areal basis, which would indicate resources of 11.8 BBO, 60.7 TCFG, and 3.1 BBNGL. The Weddell Sea play area appears enormous; a third interpretation might be that part of the shelf, particularly the area under the ice, is not sufficiently deep for petroleum generation. Assuming the source strata in only about half the indicated basin area (fig. 18) are deep enough to generate petroleum, the resources would be 3.3 BBO and 35.2 TCFG.

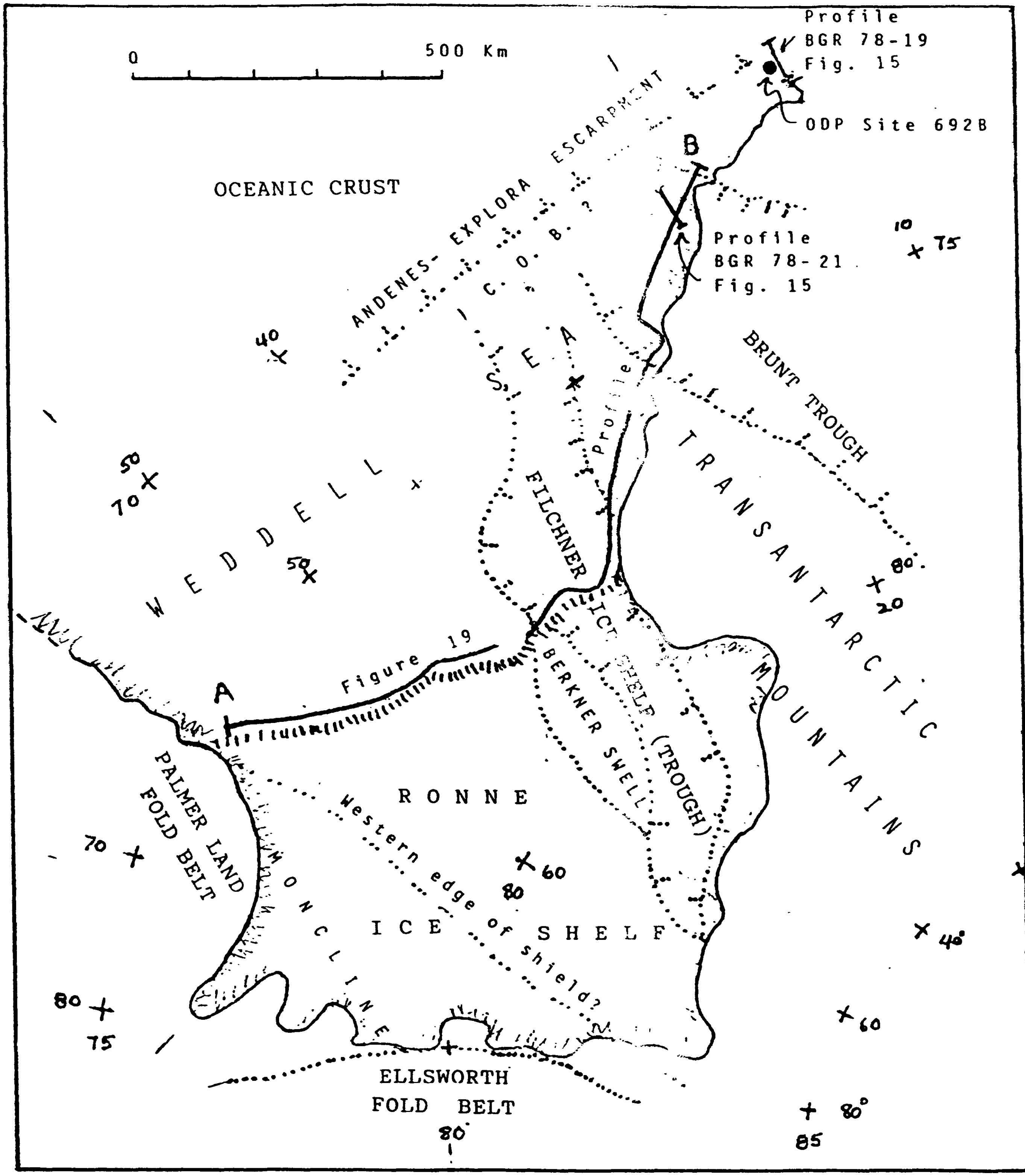

Figure 18.--Sketch map of Weddell Sea Province showing major tectonic elements and position of seismic profiles and ODP hole 692B. Area being considered is the Ronne and Filchner Ice Shelves and their seaward extensions, including the Berkner Swell, but not the monocline and the adjoining foldbelts, nor the Transantarctic Mountains. (Modified from Kamenev and Ivanov, 1983).

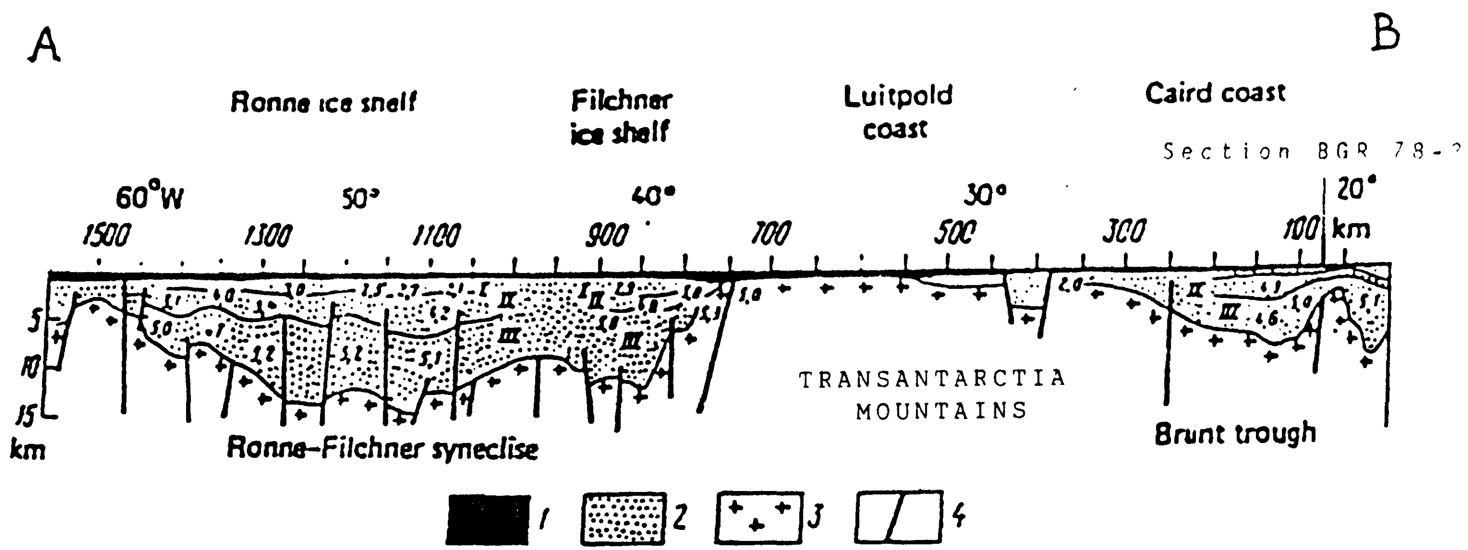

Figure 19.--Diagrammatic seismogeologic section along the southern shores of the Weddell Sea: 1) water layer, 2) sedimentary section, 3) top of acoustic basement, 4) faults based on geophysical data. Seismic sequence I has seismic velocities of 5,500 to 10,000 ft/sec; sequence II, 10,000 to 15,000 ft/sec, and sequence III, 15,000 to 18,000 ft/sec. Numbers indicate velocities in km/sec. Location of section shown in Figure 18. (from Ivanov, 1985).

Amery Interior Rift Province

The Amery Interior Rift province (28,000 mi^2 or 73,000 km^2) is here considered to be the onshore and ice shelf extension of the geology of the India-Antarctica marginal rift province area, exclusive of Prydz Bay (figs. 1, 20, and 21). Judging from the lack of petroleum indication in the Gondwana (Beacon equivalent)-filled, once-adjacent, on-trend rift basins of India (Godavari and Mahanadi, fig. 9), the principal petroleum source of the province would be limited to the shallower Cretaceous strata. The depth of the Cretaceous strata is conjectural; figure 20 suggests the entire sedimentary sequence may be generally shallower than 5 km, while figure 21 indicates the Cretaceous strata to be as deep as 7 km in the central part of the basin. I estimate that only in the seaward two-thirds of the rift province would the Cretaceous sediments be sufficiently deep to generate petroleum, indicating a play area limited to about 18,700 mi^2 (48,000 km^2). The Amery rift province is considered an analog of the incised, narrow grabens of the Ross Sea; on this basis the resources are: 0.74 BBO, 3.82 TCFG, 0.2 BBNGL, 1.58 BBOE (Play Analysis Summary 7, Appendix A). If one makes the perhaps less likely assumption of greater depth, to the extent that the source rock of the whole area of the rift province is generating petroleum, the resources would be correspondingly higher, namely: 1.11 BBO, 5.73 TCFG, 0.30 BBNGL, 2.37 BBOE. If depths are assumed to be less and/or the fill is entirely Beacon sediments, the amounts of petroleum become negligible.

Backarc Provinces

Larsen Backarc Province

The Larsen basin (117,000 mi^2 or 303,000 km^2) lies to the east of the Antarctic Peninsula (figs. 2 and 22), which has been the site of volcanic arc activity since at least early Mesozoic as the result of the eastward subduction of the Pacific or proto-Pacific plate. As has been discussed (Regional Geology and Petroleum Occurrence), the principal tectonic forces affecting the convergent margin of Antarctic since at least Triassic times, appear to be extensional.

Jurassic and lower-most Cretaceous anoxic marine potential source rock with TOC averaging 1.8 percent of type II kerogen, and middle Cretaceous marine fan and slope apron strata averaging 0.8 percent TOC of type III kerogen have been identified by Macdonald and others (1988). Reservoirs are likely to be poor to fair due to high proportion of volcanic lithic grains sourced from the Antarctic Peninsula volcanic arc. The Cretaceous to Paleogene sandstones, in presumed drape and fault closures of this region of extension, are the play of the province (fig. 23). The potential of this basin appears to be limited by the likely poor quality of the reservoirs. The outline of the basin assumed by Macdonald and others (1988) confines it to the eastern offshore of Graham Land with a play area of 117,000 mi^2 (303,000 km^2) (fig. 22). The estimate of the

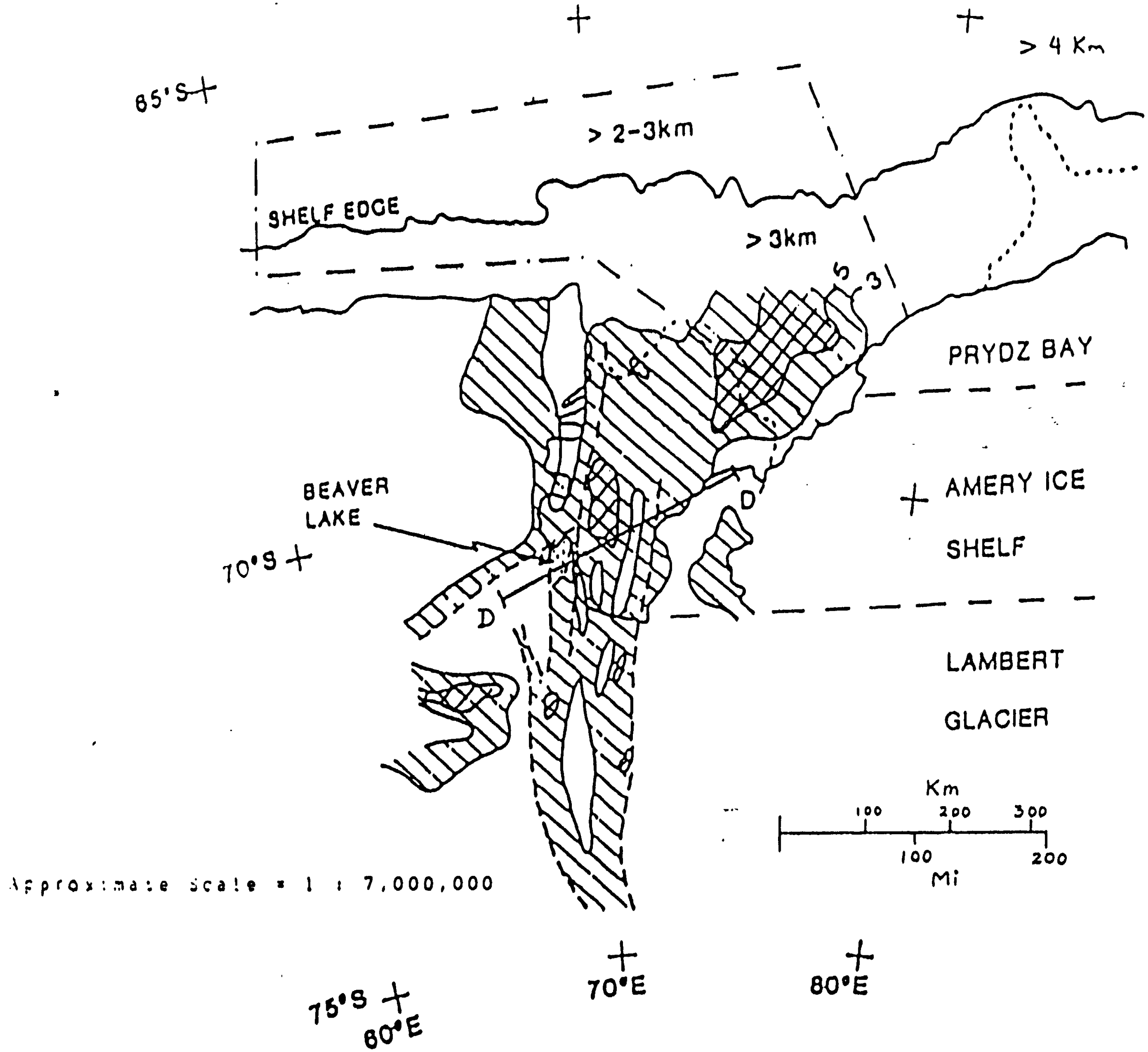

Figure 20.--Map of Amery Interior Rift province showing depth to magnetic basement: 3km = diagonal shading, 5 km = crossed shading (Federov and others, 1982), Beacon Supergroup sediments = dot shading. Seismic survey area (Stagg and others, 1983) = dashed line. Shore and shelf edge = solid line and dotted line (from Davey, 1985).

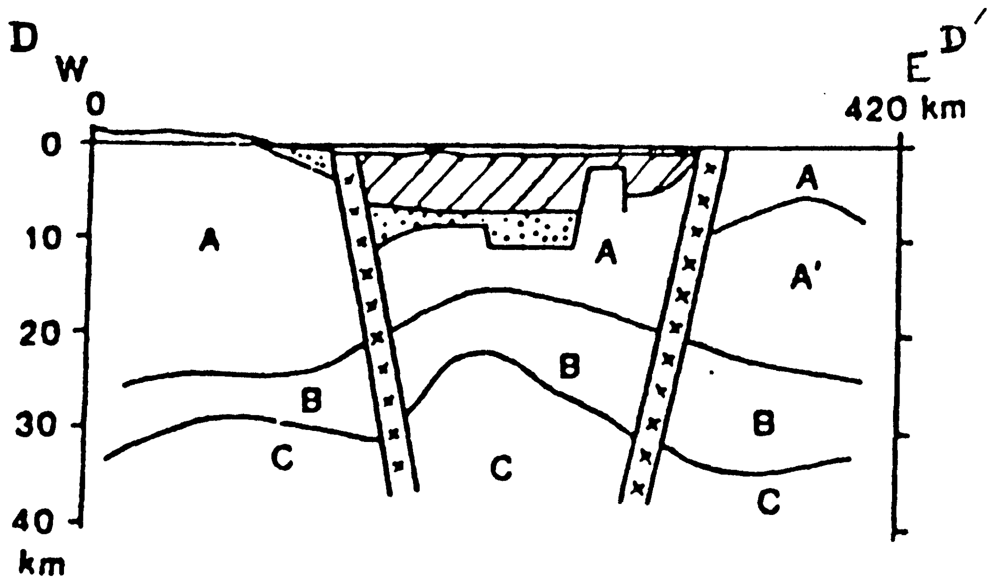

Figure 21.--Profile interpreted from geophysical data across the Amery ice shelf (after Masolov and others, 1981, and Kurinin and Grikurov, 1982). A,B = crustal layers, C = mantle, Mesozoic-Tertiary sediments = diagonal shading, Beacon Supergroup sediments = dot shading (from Davey, 1985). Location shown on Figure 20.

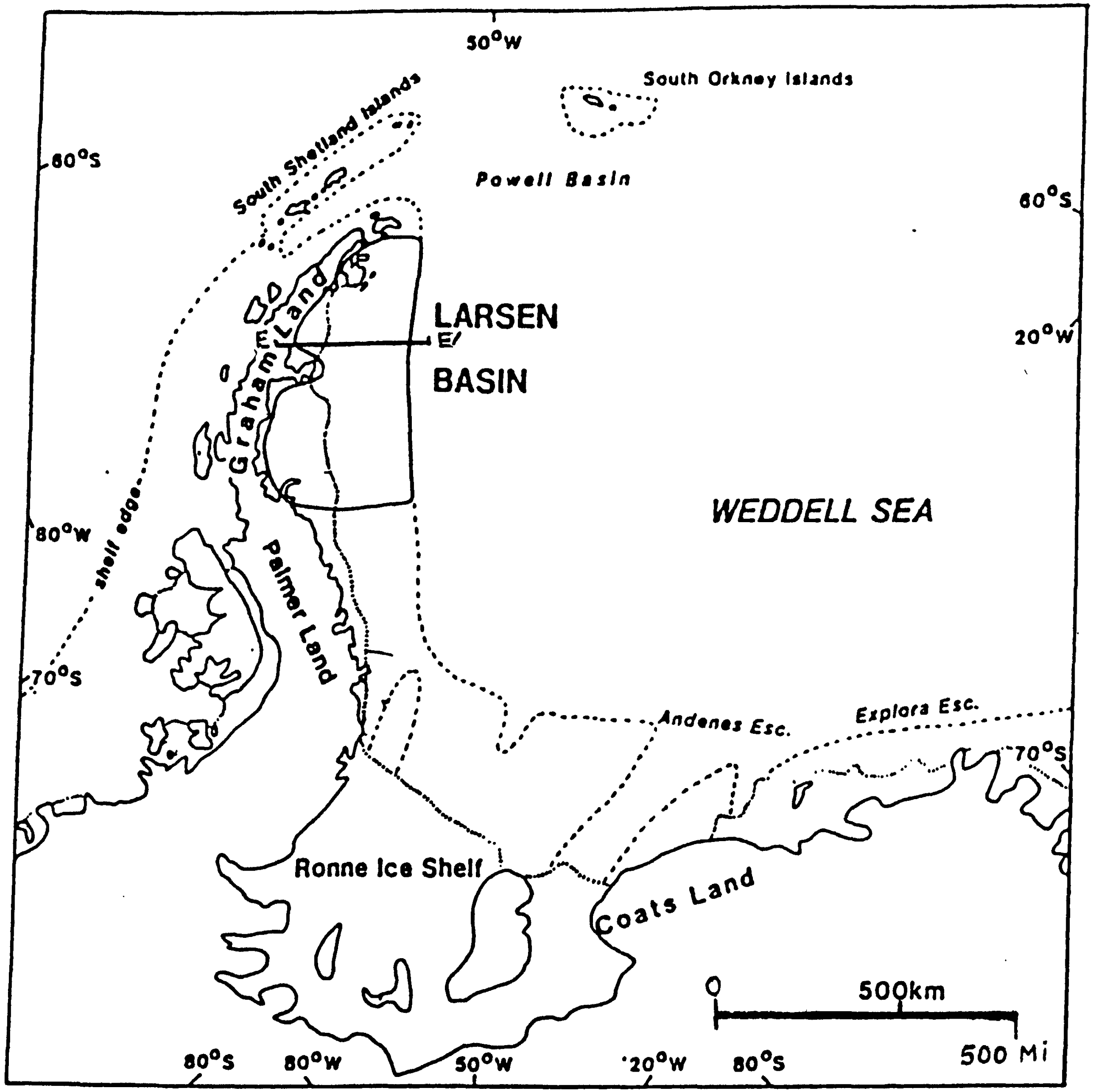

Figure 22.--Map showing location of the Larsen basin (outlined) (from Macdonald and others, 1988).

basin resources are: 1.7 BBO, 5.1 TCFG, 0.3 BBNGL, amounting to 2.9 BBOE (Play Analysis Summary 8, Appendix A). If, however, the basin is considered to extend southward along the length of the Antarctic Peninsula to the Ronne Ice Shelf, the resources would increase proportionally (that is, 66 percent) to 2.8 BBO, 8.5 TCFG, 0.5 BBNGL, amounting to 4.8 BBOE.

Byrd Backarc Province

Very little is known about the geology of the Byrd basin or basins. Its existence is surmised from reconnaissance aeromagnetic, gravity, and radio sounding surveys (figs. 2, 24, and 25). The area is very loosely defined as 80,000 mi^2 (200,000 km^2) but could be much larger or smaller. The Byrd basin appears, from the little data at hand, to be analogous to the on-trend Larsen backarc basin. Using the Larsen geologic factors, play analysis indicates 1.15 BBO, 3.5 TCFG, 0.2 BBNGL, and 1.9 BBOE (Play Analysis Summary 9, Appendix A).

Forearc Provinces

Alexander Forearc Province

This forearc province (190,600 mi^2 or 494,000 km^2) lies along the west, or Pacific, side of the volcanic arc, which forms the backbone of the Antarctic Peninsula and extends somewhat into Ellsworth Land (figs. 2 and 26). The arc is formed by the eastward subduction of the Pacific plate beneath the accreted continental crust of West Antarctica. Although there may have been compressive tectonics associated with this convergent margin, its latest deformation was by Mesozoic and Tertiary extension, as in the Larsen basin. Cretaceous-Tertiary sedimentary thickness ranges from 3,000 ft (900 m) on the shelf edge (fig. 27) to over 16,000 ft (4,900 m) in eastern Alexander Island (Taylor and others, 1985). The petroleum potential of most forearc basins is considered negligible, largely owing to presumed low heat gradient, poor reservoirs (derived from the volcanic arc), and often severe tectonization. It appears, however, that oblique subduction of the Pacific spreading ridge, starting in early Tertiary, may have not only caused the Tertiary extension, but added heat to the system (fig. 28). Given the heat, the province may have petroleum potential; Play Analysis Summary 10, Appendix A assumes that the reservoirs, though poor, are analogous to Larsen basin reservoirs, which are also volcanic, and that owing to more severe forearc tectonics, the percentage of trap area is half that of the Larsen backarc basin. Based on these assumptions, resources amount to 0.29 BBO, 1.24 TCFG, 0.06 BBNGL, amounting to 0.55 BBOE. If the subducted spreading ridge center did not contribute sufficient heat, as theorized, the resources of the province are deemed negligible.

Bransfield Strait between the South Shetland Islands and the Antarctic Peninsula is at the northern extension of the Alexander Sea forearc basin, but is not closely related tectonically (figs. 1 and 26). It appears to be a isolated backarc spreading center, the tectonics of

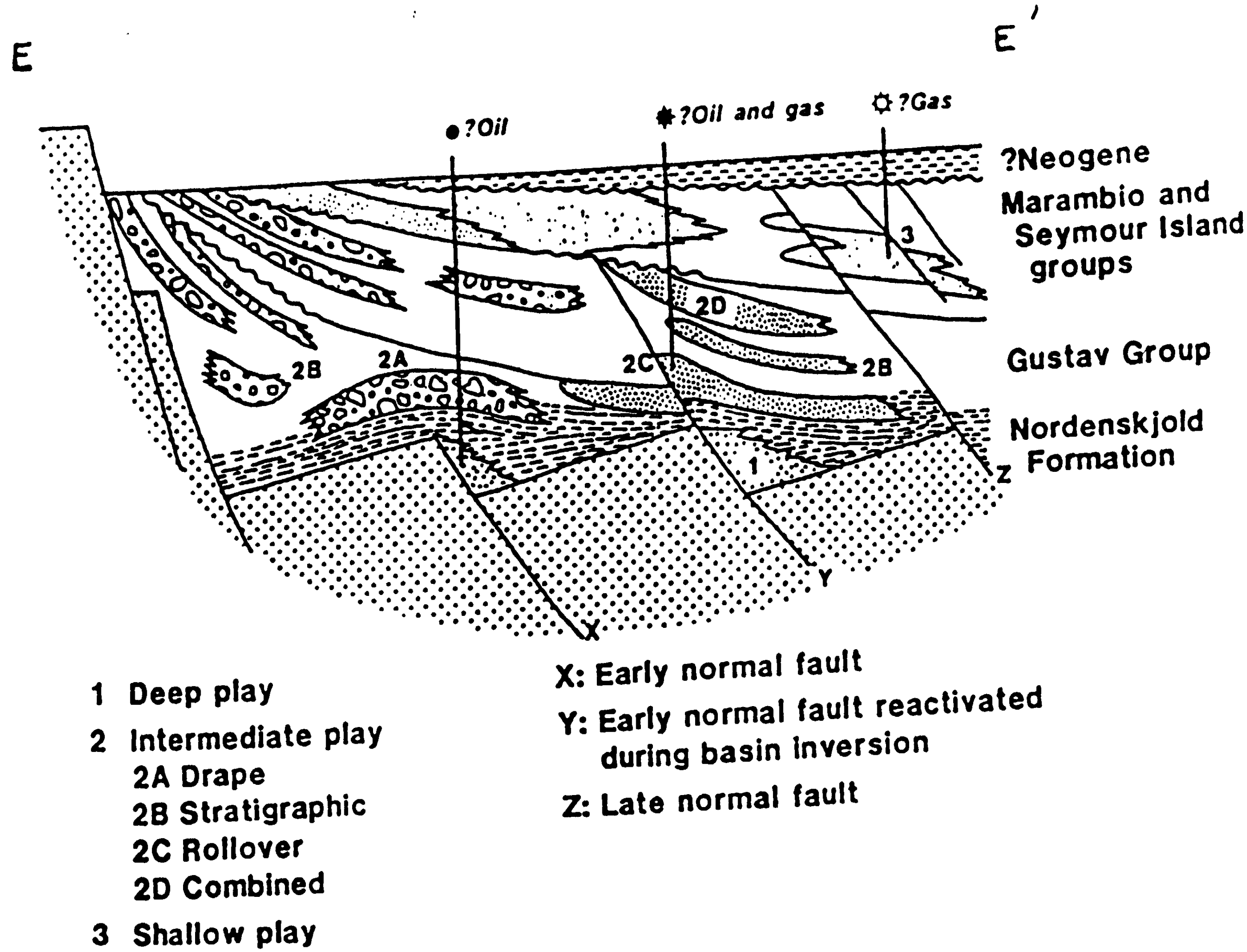

Figure 23.--Diagrammatic section across Larsen basin showing possible plays. Hypothetical location of section shown in Figure 22 (from Macdonald and others, 1988).

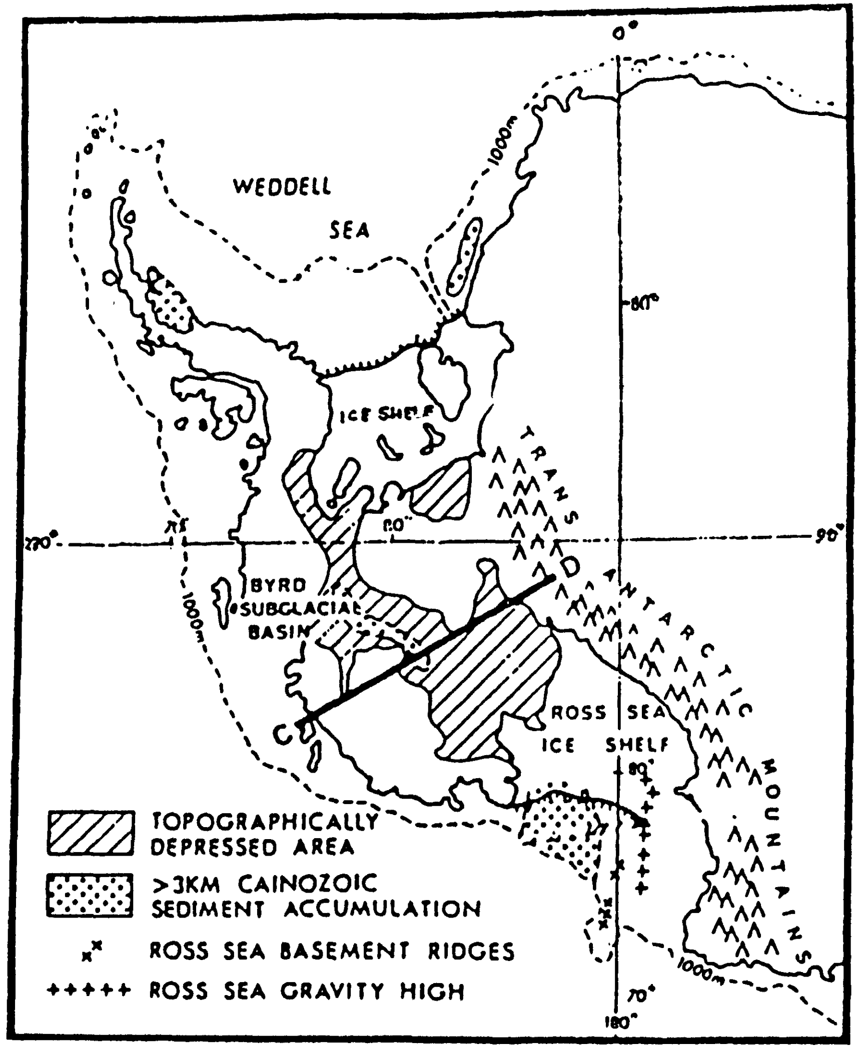

Figure 24.--Map of Byrd subglacial basin, showing the topographically depressed area between the Ross and Weddell Seas and areas of Cenozoic sediment accumulations (from Cameron, 1981).

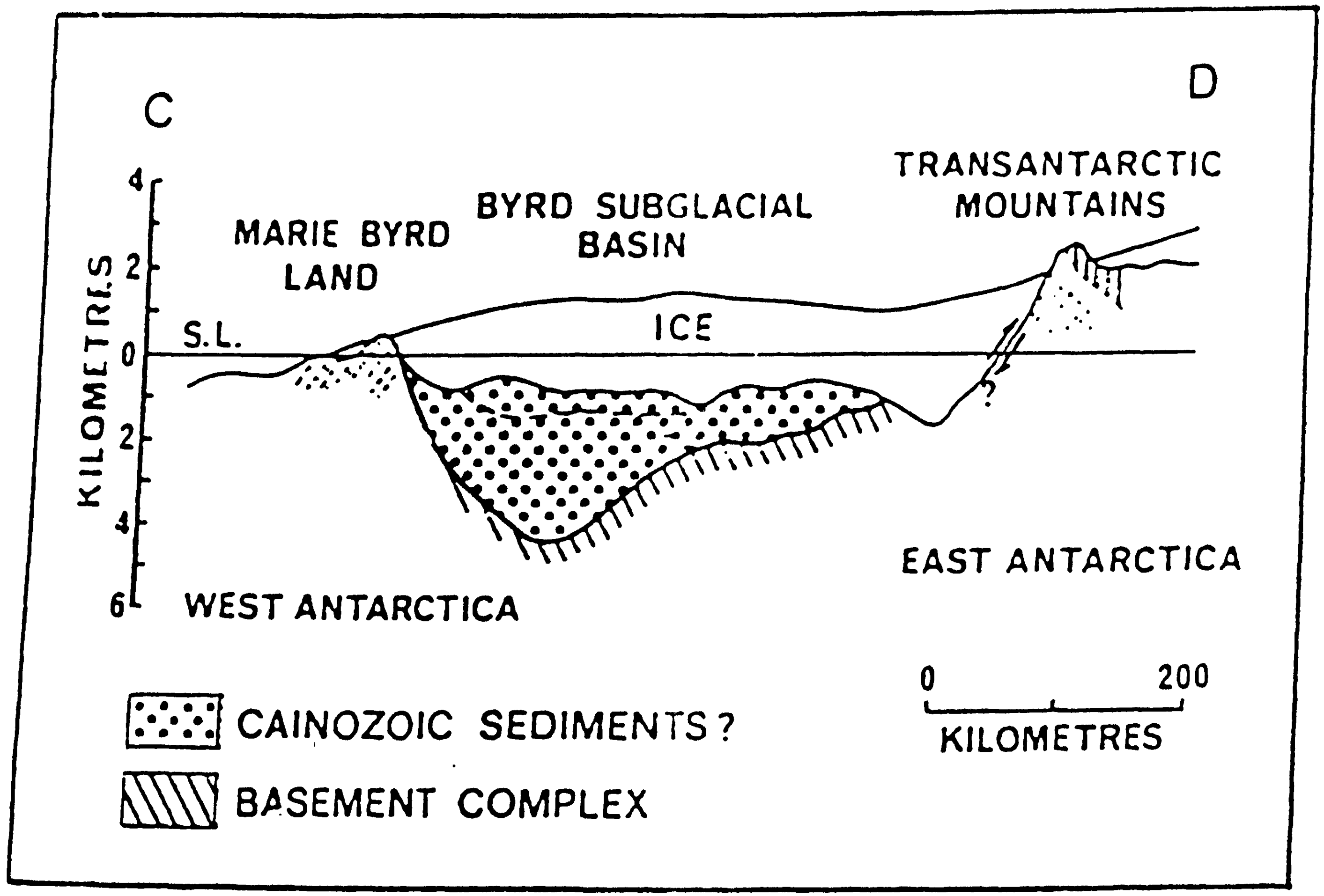

Figure 25.--Speculative cross-section of the Byrd subglacial basin. Location of section shown in Figure 24 (from Cameron, 1981).

which are obscure. It presumably has a high thermal gradient and some 16,000 ft (5,000 m) of strata (figs. 26 and 27), but the strata are apparently largely tuffs, flows, and volcanic-derived sediments. Although some hydrocarbon shows have been reported, they are deemed the result of local pyrolysis of shallow organic shales by hot intrusive igneous rock and the petroleum resources of the Bransfield Strait area are considered negligible.

Amundsen Forearc Province

The Amundsen forearc province approximately occupies the area of the Amundsen Sea and has an area of some 234,000 mi^2 (630,000 km^2) (fig. 2). Little is known of the geology, but it is assumed to be essentially analogous to the on-trend Alexander basin. In one respect the geology is different, however, in that the ocean margin is rifted and probably wrench faulted, having once adjoined the Campbell Plateau, which is attached to southern New Zealand. The effects of this rifting on the petroleum potential of the Amundsen basin, however, are unknown and this play analysis assumes all the petroleum factors to be approximately analogous to those of the Alexander basin. The analysis indicates resources of 0.36 BBO, 1.54 TCFG, 0.08 BBNGL, or 0.62 BBOE (Play Analysis Summary 11, Appendix A).

Another analogy may be made with the once-adjoining Campbell Plateau-Chatham Rise Paleozoic platform (Q, fig. 4) of 640,000 mi^2 (1,720,000 km^2), which now adjoins eastern New Zealand. It is covered by a thin section of Middle Cretaceous and younger strata and the thickness of sediments sufficient for thermal maturity is only reached in a few, isolated, deeper basinal areas of some 40,000 mi^2 (108,000 km^2), about 6 percent of the platform area (Anderton and others, 1982). The platform, rifted during the Early Cretaceous, was the site of graben-fill of synrift, nonmarine strata, which by mid-Cretaceous time became marine. The synrift strata are organically rich (over 1 percent TOC, commonly exceeding 2 percent), but gas prone, with some oil and gas shows. Adequate reservoirs were encountered in the five wildcats drilled to date. No oil or gas has been discovered. However, there is some potential for the few deeper depocenters of the Campbell-Chatham Rise plateau, but it is undoubtedly fairly minor. The analogy not only indicates a low potential for the Amundsen forearc basin, but points out that it may be generally shallow, and that the play analysis based on Alexander and Larsen basin analogs may therefore be high.

Interior Sag Provinces

Wilkes Land Interior Sag Province

The Wilkes Land Interior Sag province (approximately 100,000 mi^2 or 260,000 km^2) is very poorly defined under the thick Antarctic ice (figs. 2 and 29); it appears to be a relatively shallow (less than 10,000 ft

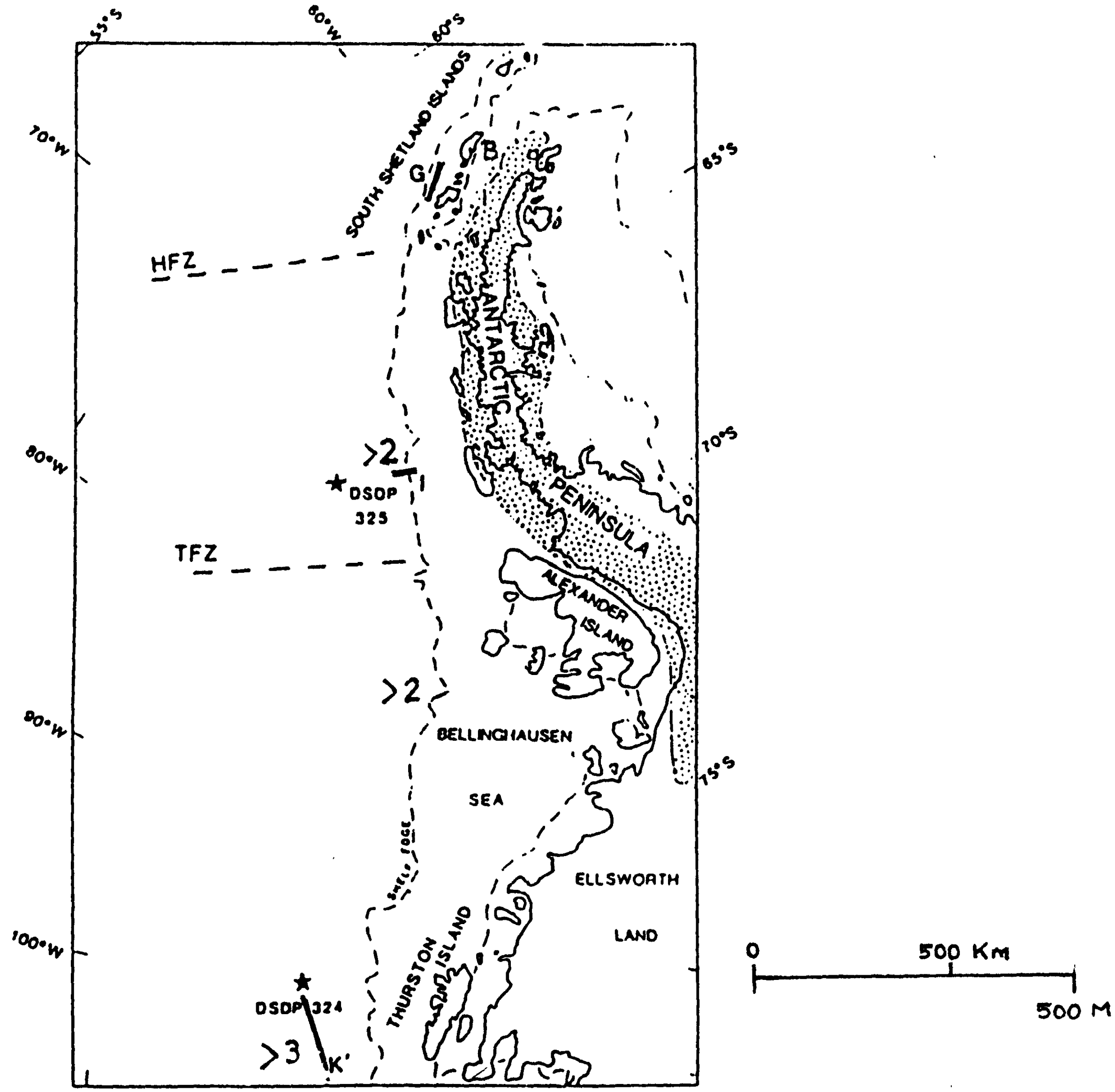

Figure 26.--Index map of Alexander province (volcanic arch to shelf edge). Volcanic arc = shaded area; seismic reflection profiles = heavy solid lines, DSDP sites = star, TFZ = Tula Fracture Zone, HFZ = Hero Fracture Zone. Sedimentary thickness in kilometers. G, I, K' profiles, figure 27, B = Bransfield Strait (from Davey, 1985).

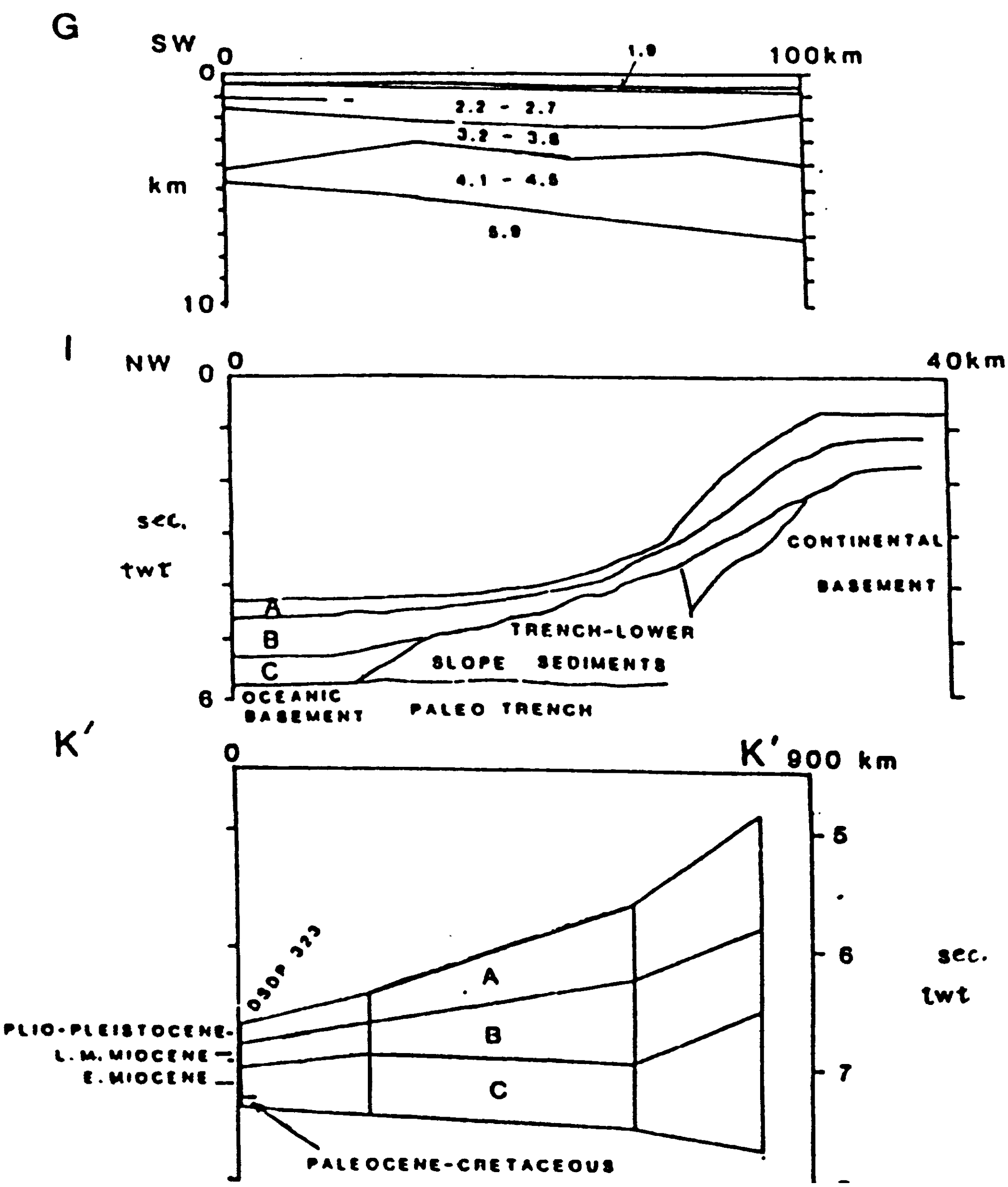

Figure 27.--Profiles along continental margin of Alexander province. Velocities in kilometers per second (from Davey, 1985). See figure 25 for locations.

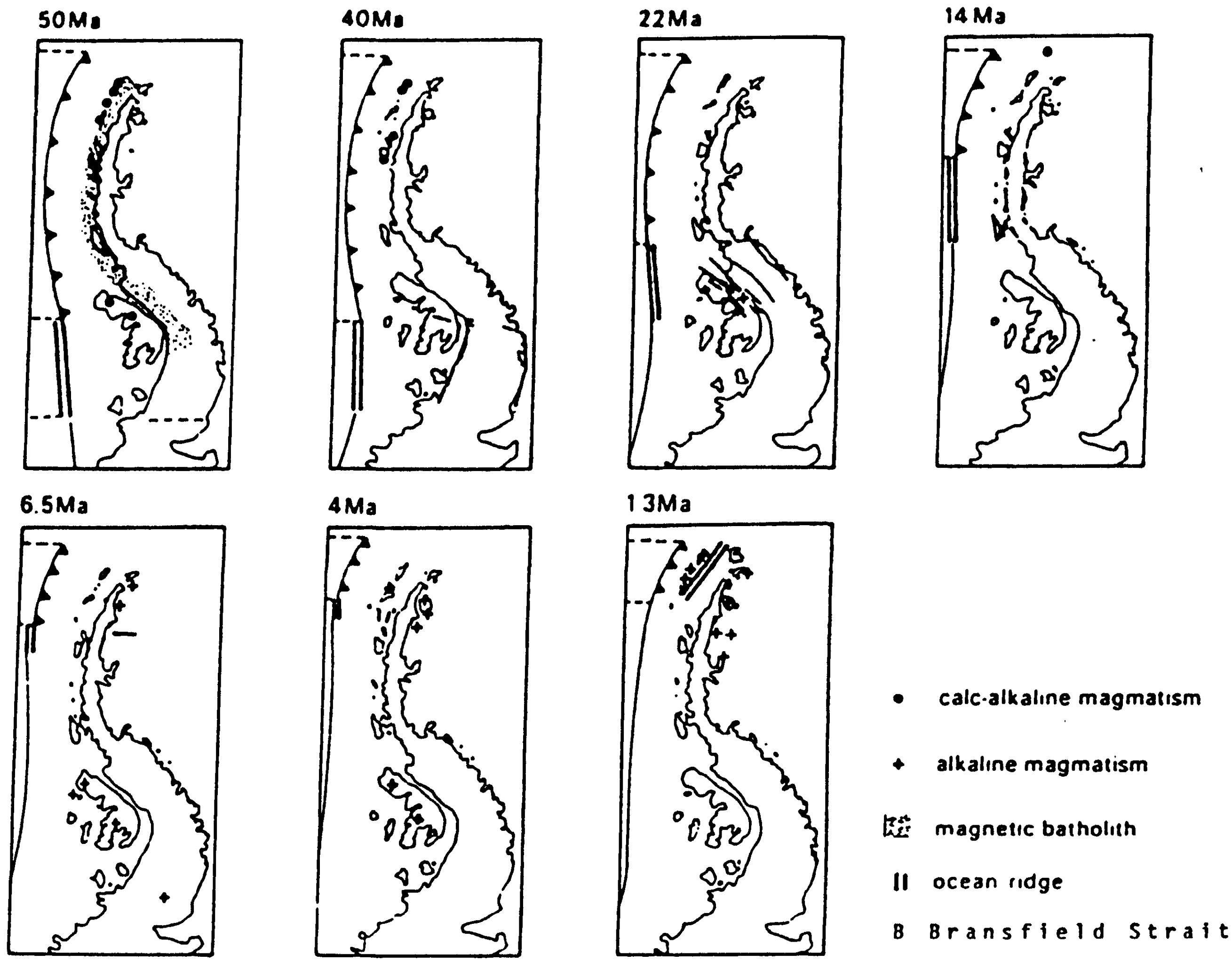

Figure 28.--A sequence of maps indicating the eastward subduction, through time, of the Pacific plate beneath the Antarctic Peninsula, and in particular, the position of the oceanic spreading ridge segments just prior to subduction and the consequent progressive northward cessation of relative subduction movement at the trench (from Garrett and Storey, 1987).

(3,000 m) deep) (fig. 30) interior sag or shelf lying just east of the Transantarctic Mountains near the coast. It is probably filled by Beacon Supergroup sediments. Given the shallowness of the basin and low thermal gradient type of basin, it appears that the potential source shale, probably generally limited to the upper Victoria group (since the lower Taylor group is largely sandstone and siltstone), would not be sufficiently mature to generate appreciable amounts of petroleum. I estimate negligible petroleum resources. There is a possibility, however, that Beacon sediments are deeper than supposed and would, therefore, generate some petroleum. Areal analogies with comparable producing basins of the Gondwana region, however, indicate that even in this case, resources would not be appreciable in this vast, hostile area (see Interior Sag Provinces under Resource Assessment by Areal Analogy to Provinces of Gondwana). Another possibility is that the basin, although cool, has been affected by biogenic action that could produce considerable gas under the permafrost and ice seal.

Aurora Interior Sag Province

The Aurora basin (estimated at about 390,00 mi^2 or 1,010,000 km^2) (figs. 2 and 29) is also very poorly defined. As far as can be determined from the sparse data available, it is a similar shallow Beacon-filled basin or shelf as the Wilkes Land basin. Similarly, it appears to be too shallow for the thermal generation of petroleum. If, however, it should be deeper than supposed, areal analogy to comparable Gondwana basins suggest that the resources would not be appreciable (see Interior Sag Provinces under Resource Assessment by Areal Analogy to Provinces of Gondwana). Biogenesis combined with a permafrost and ice seals could result in large gas resources.

RESOURCE ASSESSMENT BY AREAL ANALOGY TO PROVINCES OF GONDWANA

A further examination to check the validity of the resource assessment of Antarctic provinces, or groups of provinces, arrived at through play analysis may be made by making an area-by-area estimate of the resources of the play area being assessed by comparison to the area and resources of geologically similar, but ice-free and better known, play areas of other Gondwana continents. Table 1 shows these analog play areas in boxes along with the derived petroleum resources for each group of Antarctic provinces; also shown are the play analysis results and final estimates for each group of provinces.

Rifted Continental Margin Provinces

As discussed, the marginal rift provinces and their interior rift branches probably contain some 85 to 90 percent of the petroleum resources of the high-standing Gondwana platform areas, that is, areas exclusive of the northern zone covered by Tethyan marine sediments (fig. 3). The geology, petroleum reserves, and probable petroleum ultimate resources of

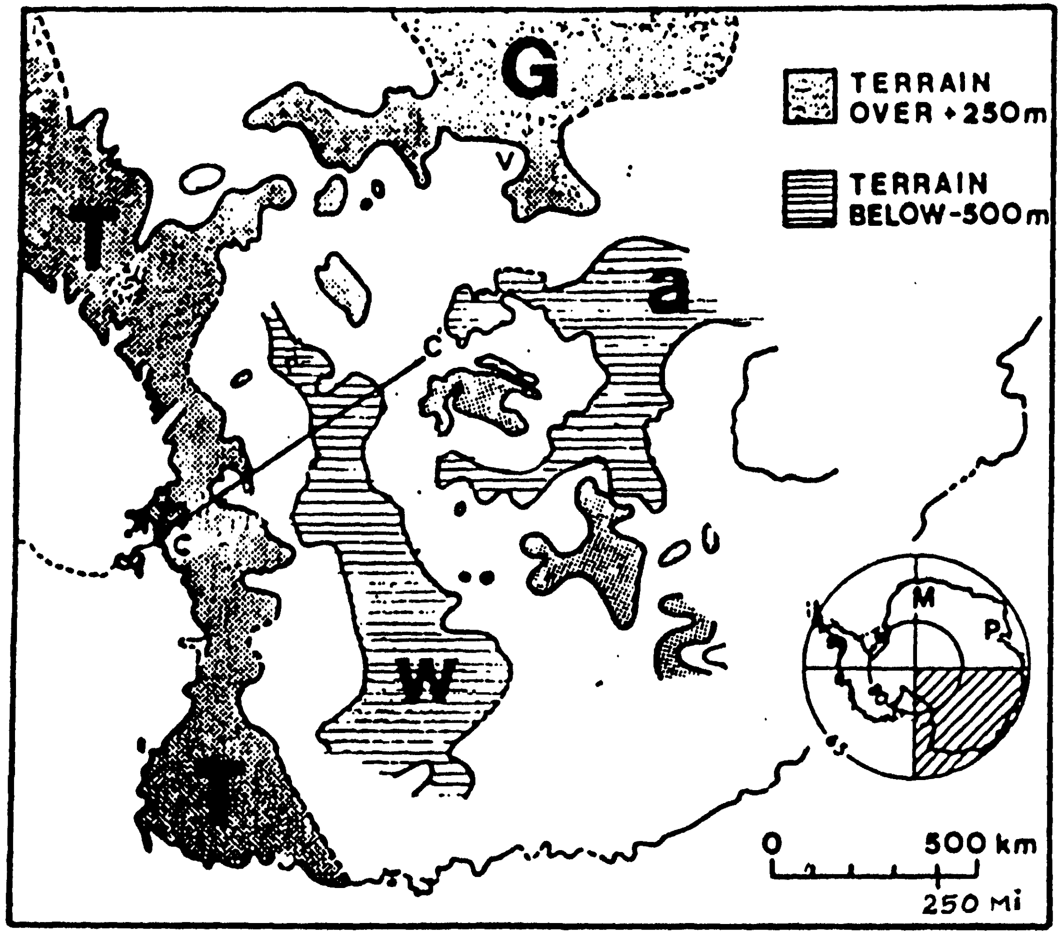

Figure 29.--Major terrain elements of East Antarctica from radio echo soundings indicating approximate position of Wilkes Land and Aurora basins. A = Aurora basin, W = Wilkes Land basin, T = Transantarctic Mountains, G = Gamburtsev Mountains (after Drewry, 1976).

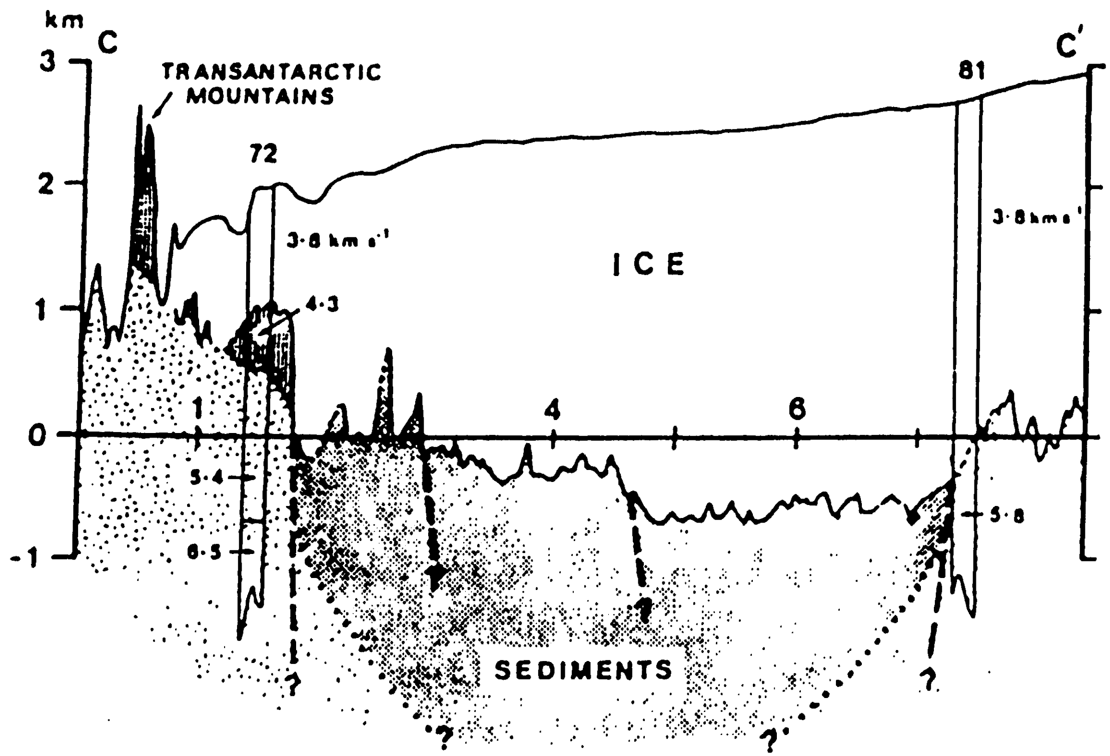

Figure 30.--Cross section showing inferred structure of the Wilkes basin. Ice sheet surface and bedrock profile from radio echo soundings supported by gravity data. Columns 72 and 81 show seismic refraction velocities in km/sec (Crary, 1963). Inferred sediments and basin are shown by appropriate shading. Sediments exposed in Transantarctic Mountains are of the Beacon Supergroup (after Drewry, 1976).

TABLE I

ANTARCTIC ESTIMATED PETROLEUM RESOURCES

(ASSUMING NORMAL RECOVERY CONDITIONS)

PLAY ANALYSIS

PROVINCE	PLAY AREAS SQ MI	BBO	TCFG	BBNGL	BBOE
RIFTED MARGIN					
Antarctica-Australia	111,000	2.7	17.0	0.9	6.4
Antarctica-India	98,000	1.7	10.0	0.5	3.9
Antarctica-Africa	58,000	0.1	2.9	0.1	0.7
Antarctica-Falkland	23,600	NEGLIGIBLE			
Antarctica-Campbell	NG.				
Area Total	290,600				
Derived Petroleum Resource		4.5	29.9	1.5	11.0
INTERIOR RIFT					
Ross	137,300	5.4	27.8	1.4	11.4
Weddell	300,000	6.7	69.5	3.5	21.8
Amery	18,700	0.7	3.8	0.2	1.6
Area Total	456,000				
Derived Petroleum Resource		12.8	101.1	5.1	34.8
BACKARC					
Larsen	117,000	1.7	5.1	0.3	2.9
Byrd	80,000	1.1	3.5	0.2	1.9
Area Total	197,000				
Derived Petroleum Resource		2.8	8.6	0.5	4.8
FOREARC					
Alexander	190,600	0.3	1.2	0.1	0.6
Amundsen	234,000	0.4	1.5	0.1	0.6
Area Total	424,600				
Derived Petroleum Resource		0.7	2.7	0.2	1.2
INTERIOR SAG					
Wilkes Land	100,000	NEGLIGIBLE			
Aurora	390,000	NEGLIGIBLE			
Area Total	490,000				
Derived Petroleum Resource		NEGLIGIBLE			
Grand Area Total	1,858,200				
TOTAL PETROLEUM RESOURCES		20.8	142.3	7.3	51.8

AREAL ANALOGS
SOUTHERN GONDWANA PROVINCES

EXAMPLE: BBO TCFG BBNGL BBOE — BASS STRAIT (PROVINCE NAME); (100,000 SQ MI) (AREA OR LENGTH); 3.5 10.0 1.0 6.2 (ESTIMATED ULTIMATE RESOURCE)

Province	Analog (area or length)	BBO	TCFG	BBNGL	BBOE
RIFTED MARGIN	Gondwana Rift Play Area (1,255,000 sq mi)	34.7	147.8		59.3
	Derived	8.0	34.2		13.7
	Gondwana Shelf/Slopes (2,850,000 vs 540,000 sq mi for Antarctica)	34.7	147.8		59.3
	Derived	6.6	28.0		11.2
	Gondwana Rift Length (19,500 vs 4,500 mi for Antarctica)	34.7	147.8		59.3
	Derived	8.0	31.0		13.6
INTERIOR RIFT	Gondwana Rift Play Area (1,255,000 sq mi)	34.7	147.8		59.3
	Derived	12.6	53.9		21.6
	Gondwana Rift Length (19,500/2 vs 2840 mi for Antarctica)	34.7	147.8		59.3
	Derived	10.0	43.0		17.3
	Bass Strait (100,000 sq mi)	3.5	10.0	1.0	6.2
	Derived	16.0	45.5	4.6	28.3
BACKARC	So. American Backarc (607,000 sq mi)	10.2	63.9		20.8
	Derived	3.3	20.7		6.7
	Magallanes (71,600 sq mi)	0.9	15.0		3.4
	Derived	2.5	41.3		9.4
FOREARC	So. American Forearc (500,000 sq mi)	2.9	4.0		3.6
	Derived	2.5	3.4		3.1
INTERIOR SAG	Karoo (85,000 sq mi)	NEGLIGIBLE			
	Derived	NEGLIGIBLE			
	Solimoes (116,000 sq mi)	0.08	4.0		0.7
	Derived	0.30	12.0		3.1
	Cooper (49,000 sq mi)	0.05	4.4	0.4	1.2
	Derived	0.5	44.0	4.0	12.0

FINAL ESTIMATE DELPHI CONSENSUS

Probability: 95 = 95% probability; ML = most likely; 5 = 5% probability

Province	Probability	BBO	TCFG	BBOE
RIFTED MARGIN	95	1	10	3
	ML	4	30	9
	5	25	150	50
INTERIOR RIFT	95	2	13	4
	ML	10	50	18
	5	50	300	100
BACKARC	95	1	6	2
	ML	4	20	7
	5	26	120	46
FOREARC	95	0.1	0.5	0.2
	ML	0.7	2.0	1.0
	5	3.3	10.0	5.0
INTERIOR SAG	95	0	1	0.2
	ML	0.1	4	0.8
	5	1.5	35	7.3
TOTAL MOST LIKELY		19	106	37
IF MINIMUM ECONOMIC REQUIREMENTS ARE GIANT-SIZE FIELDS (0.5 BBO):		6	32	11
IF MINIMUM ECONOMIC REQUIREMENTS ARE SUPERGIANT FIELDS (5.0 BBO):		0	0	0

the analogous Gondwana provinces are relatively well known. The total play area of the marginal rift basins of Gondwana, exclusive of the northern Tethyan zone, I estimate to be 1,255,000 mi^2 (3,250,000 km^2). I estimate the reserves to be 26.7 BBO, 91.6 TCFG, or 42.0 BBOE (derived from Petroconsultants and other sources); and the ultimate resources, including undiscovered recoverable petroleum, I judge conservatively, on the basis of my own and other U.S. Geological Survey estimates, to be 34.7 BBO, 147.8 TCFG, and 59.3 BBOE. An areal comparison of the Antarctic marginal rift provinces (Antarctica-Australia, Antarctica-India, Antarctica-Africa, and Antarctica-Falkland provinces), having an area of some 290,600 mi^2 (753,000 km^2), with the total play area of the rifted margin provinces of the other Gondwana continents, of some 1,255,000 mi^2 (3,250,000 km^2), indicate petroleum resources of 8.0 BBO, 34.2 TCFG, and 13.7 BBOE.

A problem with this analogy is that the areas of play, especially on the continental slopes, are not well established. A more reliable analogy might be made by comparing the area of the total rifted margins (rather than that of the supposed play areas), which I judge to generally include the shelf and to extend outwards to the COB. Even this area is not completely known, since the COB location has not been mapped in most regions. However, it is assumed that the COB is about at the base of the upper continental slope (the depth of which varies from about the 2,000-m to the 2,500-m isobath, but is deeper in Antarctica). The width of the rift zone, therefore, is taken to roughly extend from the shoreline to the 2,500-m isobath. On this basis, the rifted margins of the high-standing Gondwana platform areas, except Antarctica, have an area of 2,850,000 mi^2 (7,380,000 km^2) (excluding the largely wrenched Antarctica-India interface, and including the Bengal foreland). By comparison the margins of Antarctica have an area of 540,000 mi^2 (1,400,000 km^2). By areal analogy, therefore, to the petroleum resources of the Gondwana rifted margins areas, the Antarctic marginal rift provinces would contain 6.6 BBO, 28.0 TCFG, and 11.2 BBOE.

Given the uncertainty of the amount of area involved, an analogy between the Antarctic rifted continental margin provinces and those of the other Gondwana continents also may be made on the basis of the margins relative lengths. The length of the rifted margins of the Gondwana platform area is some 19,500 mi (31,200 km), while those of Antarctica are 4,500 mi (7,200 km), indicating by analogy petroleum resources of 8.0 BBO, 31.0 TCFG, and 13.6 BBO in the Antarctic marginal rift provinces.

Interior Rift Provinces

The rifted continental margins of Antarctica and other Gondwana continents were interior rifts from Late Jurassic to Early to Late Cretaceous before the continents separated. The interior rift zones of Antarctica, the Ross, Weddell, and Amery basins (fig. 2), presumably had identical Cretaceous synrift histories as did the Gondwana marginal rifts, only failing to achieve the final continental separation, so that rifting and an accompanying synrift environment apparently continued up into at least early Tertiary. It appears, therefore, that the more critical petroleum-accumulation events in both the marginal and interior rifts occurred in the synrift period when organic material was concentrated and preserved and traps formed. Later subsidence histories may have been somewhat different for the two types of rifts, but in general they are considered analogous. An areal analogy of the Antarctic interior rift provinces (456,000 mi^2 or 1,181,000 km^2) with marginal rifts of the Gondwana platform region (1,225,000 mi^2 or 3,173,000 km^2) can be made. Such an analogy indicates petroleum resources of 12.6 BBO, 53.9 TCFG, and 21.6 BBOE in the Antarctic interior rift provinces.

Given the uncertainty concerning the amount of areas involved in the above analogy, a simple comparison of the rift lengths of the other southern Gondwana continents (19,500 mi or 31,400 km) with the length of the Antarctic interior rifts (2,840 mi or 4,570 km) may provide a rough corroboration of the above estimate. However, a more relevant analogy on a length basis would be that of the interior rifts prior to breakup so that the comparison would be with the reunited marginal rifts (19,500/2 mi or 31,400/2 km) versus the Ross and Weddell interior rifts (2,840 mi or 4,570 km), indicating resources of 10.1 BBO, 43.0 TCFG, or 17.3 BBOE.

Another perhaps closer analogy exists between the Antarctic interior rifts and the Bass Strait, which is a zone of interior rifts between Australia and Tasmania, containing the Gippsland oil province (O, fig. 4). The Bass Strait synrift environment persisted up into the early Tertiary as appears to be the case in the Antarctic rifts (figs. 17 and 19). The Bass Strait has an area of some 100,000 mi^2 (270,000 km^2) and estimated reserves of 3.0 BBO, 7.8 TCFG, 0.8 BBNGL, or 5.1 BBOE (Shanmugam, 1985). Here, we estimate ultimate resources for Bass Strait of 3.5 BBO, 10.0 TCFG, 1.0 BBNGL, or 6.2 BBOE. Areal analogy of the Antarctic's interior rift provinces with the Bass Strait indicates resources of 16.0 BBO, 45.5 TCFG, 4.6 BBNGL, or 28.3 BBOE.

Backarc Provinces

The Larsen basin (117,000 mi^2 or 300,000 km^2) (figs. 2 and 22) and Byrd basin (80,000 mi^2 or 200,000 km^2) of West Antarctica (figs. 2 and 24) are basins within the convergent margin area of Antarctica, Pacific-wards of the Gondwanides (figs. 1, 2, 3, and 4). Because of their position inboard of the volcanic-magmatic arc of the Antarctic Peninsula and its Pacific-margin extension, the Larsen and Byrd provinces are here presumed to be simple backarc basins although they have a more complicated earlier geologic history as attested by the accumulation of accreted continental blocks (figs. 3 and 4). The provinces are approximately on trend with the major petroliferous basins of the analogous convergent margin area of accreted blocks of southern South America (fig. 4). The basinal areas of this South American convergent margin region (east of the Tertiary-rising

Andes) totals some 607,500 mi^2 (1,573,000 km^2) and has reserves of 7.2 BBO and 47.9 TCFG (Petroconsultants, 1989). The World Energy Resources Program geologists estimate that further discoveries in this maturely explored region of South America will result in ultimate resources of 10.2 BBO and 63.9 TCFG. By areal analogy the Antarctic backarc basins would have resources of 3.3 BBO and 20.7 TCFG. However, although the southern South American basins are in the Gondwana convergent area, their individual geologies vary considerably from those of a simple backarc basin. A more direct, but perhaps narrow, analogy would be with the nearest basin, the Magallanes backarc basin (71,6000 mi^2 or 185,000 km^2) (E, fig. 4), which, disregarding the later opening of the Scotia Sea (fig. 1) in mid-Tertiary, was on trend and relatively close. The Magallanes basin has reserves of 0.8 BBO and 14.2 TCFG, (Petroconsultants, 1989) which probably amount to 0.9 BBO and 15 TCFG of ultimate resources in this maturely explored province. By areal analogy, this would indicate resources of 2.5 BBO and 41.3 TCFG in the Antarctic backarc basins.

Forearc Provinces

The only available analogy to the Alexander and Amundsen forearc provinces, of some 424,600 mi^2 (1,100,000 km^2), is the entire forearc region Pacific-wards of the Andes. Assuming this Pacific forearc area extends from the shore to the base of the continental slope, an area of 500,000 mi^2 (1,300,000 km^2) is estimated. In this area, appreciable petroleum has only been found in the Talara region on the coast at the Peru-Ecuador border (R, fig. 4). As of 1989, reserves of some 1.8 BBO and 2.7 TCFG had been established in maturely developed fields (Petroconsultants, 1989). Probably ultimate resources would amount to 2.9 BBO and 4.0 TCFG. On this basis the ultimate resources of the Antarctic forearc basins would be 2.5 BBO, 3.4 TCFG, and 3.1 BBOE.

Interior Sag Provinces

There are a number of Gondwana interior sag basins which might serve as analogs for the Wilkes Land (100,0000 mi^2 or 270,000 km^2) and Aurora (390,000 mi^2 or 1,010,000 km^2) interior sag basins. The initially nearby and apparently geologically closest analogy is the Karoo basin (85,000 mi^2 or 200,000 km^2) of South Africa. The Karoo basin, however, has negligible resources, but two Gondwana interior sag basins which do have petroleum production and are somewhat analogous are the Cooper basin of Australia and the Solimoes basin of Brazil. The Cooper basin (49,000 mi^2 or 127,000 km^2) has reserves of 0.04 BBO, 3.5 TCFG, 0.3 BBNGL or 0.9 BBOE (Rudd and Sprigg, 1976) and estimated ultimate resources in this maturely explored basin of around 0.05 BBO, 4.4 TCFG, 0.4 BBNGL or 1.2 BBOE. The Cooper basin is deeper than the Karoo basin and probably the Antarctic interior sags, and is additionally anomalous to the Antarctic and other Gondwana interior sag basins in that the usually voluminous Jurassic dolerite intrusions and volcanics are absent. An undiscounted areal analogy with the Cooper basin suggests resources of 0.5 BBO, 44.0 TCFG, 4.0 BBNGL or 11

BBOE in the Antarctic interior rift basins. The second and more distant possibly analogue basin, Solimoes, is an interior, or, possibly peri-cratonic, sag of the Gondwana supercontinent, of 116,000 mi^2 or 300,000 km^2. This basin is the only producing of several large interior sags of Brazil. It has Beacon age-equivalent sediments, containing tillites and including a Devonian source section (which the Karoo and Cooper basins do not),. are predominantly marine or restricted marine in origin. The estimated reserves of the Solimoies basin are 0.037 BBO and 2.0 TCFG (Petroconsultants, 1989) with estimated ultimate resources of 0.08 BBO and 4.0 TCFG in this immaturely explored basin. By areal analogy this would indicate 0.3 BBO and 17.0 TCFG in the interior sags of Antarctica.

Because the little available evidence indicates that the Antarctic basins are probably shallow (fig. 29), I am inclined to equate them with the shallow, thermally immature Karoo basin and estimate the petroleum resources to be negligible.

There remains the possibility, however, for biogenic gas under an ice and permafrost cover.

FIELD-SIZE DISTRIBUTION

Because of the very hostile environment and unfavorable economics for Antarctic petroleum recovery, the size of potential fields is a key factor in assessing the recoverable petroleum resources of the area. Probably for some time into the future a discovered field must be at least of giant (0.5 BBO, international definition) size and possibly supergiant (5.0 BBO) size.

Figure 31 shows the field-size distribution in the rifted margins of the continental fragments of the Gondwana platform (Gondwana exclusive of the subsided, Tethyan-sediment-covered northern zone, fig. 3). There are some 933 oil fields, distributed rather evenly over all the Gondwana continental margins excepting the east coast of Africa, which has few or none.

The field-size distribution of the oil fields in the rifted continental margins of the Gondwana platform area, using Petroconsultants reserve figures, indicates that about 40 percent of the oil accumulation is concentrated in giant fields and 33 percent in fields of over one billion barrels. There are no supergiant fields. The 40 percent of the oil reserves that are in giant fields are in only seven accumulations, Marlim of Brazil, Bombay High of India, Albacora of Brazil, Kingfish of Australia, Halibut of Australia, Rabi-Kounga of Gabon, and Matar of India. These giant fields are distributed evenly over the analogous Gondwana platform area rift basins, excepting the east coast of Africa. Possibly significant is that two of the giant fields are in the Gippsland basin of the Bass Strait, Australia, the nearest and most closely analogous to the interior rift basins of Antarctica.

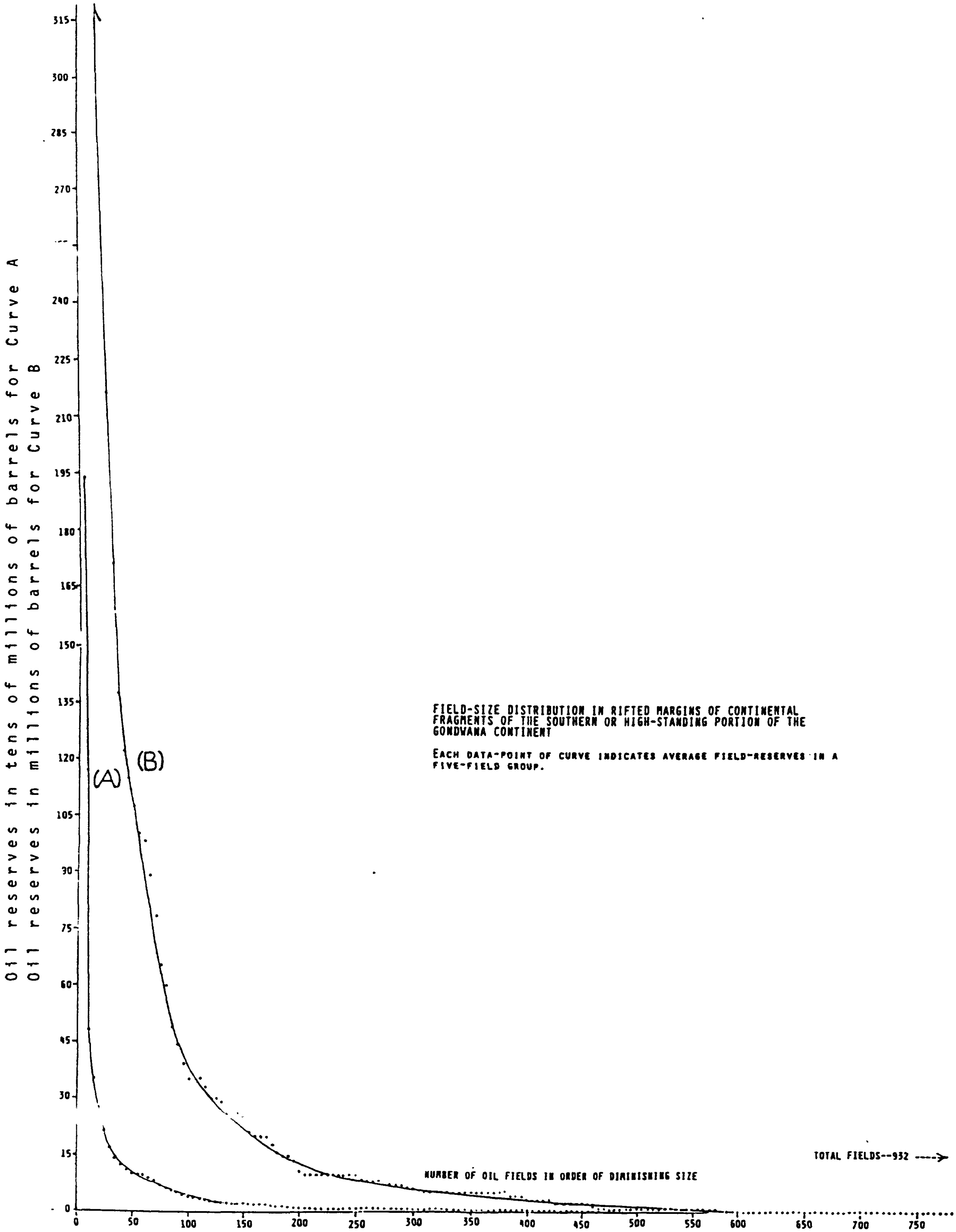

Figure 31.--Curve showing oil field-size distribution in the rifted margins of continental fragments of the southern, or high-standing portion of Gondwana, exclusive of the Niger Tertiary delta, showing the distribution curve for (B) millions and (A) tens of millions of barrels so as to present together both the very large and the many small fields. For presentation purposes each data point on the curve represents the average field reserves for a five-field group in a total of 932 fields. The indicated small fields after 570 are largely of no reserve data and assumed to be mainly noncommercial discoveries.

An areal analogy of the Antarctic rift province to those of the rifted margins of other Gondwana platform areas, from which the field-size distribution curve of figure 31 was derived, may be made. The analogy is admittedly tenuous for several reasons, but is comprehensive and the best analogy available. If such an analogy is assumed, it suggests the probable existence of four giant fields in the Antarctic rift basins, two of which may be over a billion barrels of oil, but no probability of a supergiant field.

Probably the most accessible prospective area of Antarctica is the relatively ice-free continental slopes. Since two of the seven Gondwana rift giant fields are on the continental slope, by analogy one such giant might be expected on the continental slope of Antarctica.

None of the oil fields of the convergent area of Gondwana, Pacificward of the Gondwanides, reach giant size suggesting that no giant field will be found in the convergent West Antarctica area.

CONCLUSIONS

The estimated ultimate petroleum resources of Antarctica, arrived at by the two discussed methods, play analysis and areal analogy, are in reasonable accord and served as a guide for the U.S. Geological Survey panel of petroleum geologists (The World Energy Resources Program) in arriving at a consensus. This consensus as to the petroleum resources of the main groups of provinces is summarized below and in table 1. It is emphasized that to avoid unpredictable feasibility factors in this hostile, virgin area, and to allow comparison of Antarctica resources with resources of other areas on comparable terms, these estimates are made on the presumption of ordinary recovery conditions.

Probability

Basin type	Oil (BBO)			Gas (TCFG)			Basin or geographic tie
	95%	ML	5%	95%	ML	5%	
Marginal rift	1	4	25	10	30	150	Australia, India, Africa, South America
Interior rift	2	10	50	13	50	300	Ross, Weddell, Amery
Backarc	1	4	26	6	20	120	Larsen, Byrd
Forearc	0.1	0.7	3.3	0.5	2	10	Alexander, Amundsen
Interior sag	0	0.1	1.5	1	4	35	Wilkes Land, Aurora

In this very unknown region, while the most likely probability (ML) estimates may have some degree of validity, the indicated ranges, 95 percent and 5 percent probability, are only informed guesses and the mean values of these ranges are of little meaning. Accordingly, I believe the best aggregate Antarctic resource estimate is made by totaling the most-likely values. This would indicate the petroleum resources of Antarctica to be 19 BBO and 106 TCFG if normal recovery conditions prevailed.

If giant-size (0.5 BBO) fields will eventually be required as a minimum size for commercial recovery, such fields would be limited to the rift basins. And if, as suggested, 40 percent of the rift-basin petroleum is in the fields of giant-size, the estimated petroleum resources of Antarctica are reduced to 6 BBO and 32 TCFG.

If supergiant-size fields will be required, the petroleum resources of Antarctica are probably nil.

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APPENDIX A - PLAY ANALYSIS SUMMARIES

Play analysis summaries for each province follow in the order they are discussed in the text. The estimates for each of the five principal geologic factors are given in ranges signifying the degree of certainty. These ranges include three values, a low number (95 percent probability that the quantity will exceed this value), a modal number (most likely quantity), and a high number (a 5 percent probability that the quantity will exceed this value). For conciseness, the rationale for arriving at only the most likely quantities is noted. The product of the most likely values for each of the five key factors may indicate, generally, the quantity of ordinarily recoverable oil and gas.

Abbreviations used:

O =	oil
G =	gas
OE =	oil equivalent
BO =	barrels of oil
BBO =	billion barrels of oil
MMBO =	million barrels of oil
MCFG =	thousand cubic feet of gas
MMCFG =	million cubic feet of gas
BCFG =	billion cubic feet of gas
TCFG =	trillion cubic feet of gas
BNGL =	barrels of natural gas liquids
BBNGL =	billion barrels of natural gas liquids
AF =	acre-foot
MMA =	million acres

Play Analysis Summary of Undiscovered Petroleum

Basin Antarctica-Australia Marginal Rift Antarctica   Play Cretaceous-Paleogene sandstones No. 1

Area of basin (mi^2) 554,000   Area of play (MMA) 71.0

Volume of basin (mi^3) 1,660,000   Play est. orig. reserves 0 BBO 0 TCFG

Estimate original reserves 0 BBO 0 TCFG

Tectonic classification of basin: Rifted continental margin

Definition and area of play: Synrift/postrift (Cretaceous and Paleogene) deltaic sandstones in drapes and traps. The play areas are the depocenters in the rifted margin which, by analogy to the Australian margin, is 20 percent. Province extends from shore to COB.

	MAJOR GEOLOGICAL/EXPLORATION FACTORS	PROBABILITY DISTRIBUTION 95%	MOST LIKELY	5%
A.	Untested trap area (MMA)	2.00	4.12	10.0
B.	Percent untested trap area productive (%)	3.0	4.5	12.0
C.	Average effective pay (feet)	50	150	250
D.	Percent oil versus gas in petroleum fill (%)	10	40	60
E.	Oil recovery (BBLS/AF)	100	240	350
F.	Gas recovery (MCF/AF)	700	1030	1200
G.	NGL recovery (BBLS/MMCFG)	11	50	100

Product of most likely probabilities: Oil 2.7 BB, Gas 17.0 TCF, NGL 0.9 BB, OE 6.4 BBOE

REMARKS

A. The amount and areas of traps are assumed to be analogous to the Bass basin where mapped structural traps make up 5.8 percent of the play area (4.12 MMA).

B. By analogy to the productive Gippsland and Bass basins, it is estimated that 15 percent of the closures will be productive. The area of fill is estimated to be 30 percent of the closure, giving a productive area of 4.5 percent of trap.

C. By analogy to the Australian margin (Halibut Field average 137 ft, Otway basin - estimated 200 ft, and Jerboa - 1 of the Great Australian Bight - 185 ft).

D. Nearest production, Gippsland basin, is 59 percent oil, generated from Upper Cretaceous synrift shales. The Lower Cretaceous synrift shales of this province, though similar, are deemed more gas prone from source studies in Otway basin and oil is deemed only two-thirds as prevalent in petroleum mix.

E. By analogy to Australian reservoirs, porosity - .2, water saturation - .3, and oil recovery - .3. The volume of oil recovered is about 240 BO/AF.

F. Assuming an average depth of 8,000 ft and a gas recovery of .9, the volume of gas recovered is about 1,030 MCFG/AF.

G. The NGL recovery of nearby Gippsland basin is very high, 97.7 BNGL/MMCFG from Upper Cretaceous-Lower Tertiary deltaic sediments. The NGL recovery from the more gas-prone Lower Cretaceous deltaic sediments is estimated to about half.

Play Analysis Summary of Undiscovered Petroleum

Basin Antarctica-India Marginal Rift   Antarctica   Play Cretaceous-Paleogene sandstones No. 2

Area of basin (mi^2) 490,000   Area of play (MMA) 62.7

Volume of basin (mi^3) 1,470,000   Play est. orig. reserves 0 BBO 0 TCFG

Estimate original reserves 0 BBO 0 TCFG

Tectonic classification of basin: Rifted continental margin

Definition and area of play: Synrift and postrift (presumed Cretaceous and Paleogene) deltaic sandstones in drapes and fault traps. Play areas-depocenters - by analogy to S. Australia is 20 percent of basin area. Margin is considered to be area between shore and COB, including Prydz Bay.

PROBABILITY DISTRIBUTION

	MAJOR GEOLOGICAL/EXPLORATION FACTORS	95%	MOST LIKELY	5%
A.	Untested trap area (MMA)	2.00	3.64	9.00
B.	Percent untested trap area productive (%)	3.0	4.5	12.0
C.	Average effective pay (feet)	50	150	250
D.	Percent oil versus gas in petroleum fill (%)	10	40	60
E.	Oil recovery (BBLS/AF)	100	240	350
F.	Gas recovery (MCF/AF)	700	1030	1200
G.	NGL recovery (BBLS/MMCFG)	11	50	100

Product of most likely probabilities: Oil 2.4 BB, Gas 15.2 TCF, NGL 0.8 BB, OE 5.7 BBOE

REMARKS

I. Factors A through G above are considered analogous to those of Antarctica-Australia rift margin yielding the above estimates.

II. An alternate assessment may be made by making analogies to resource estimates of the once adjoining (in Cretaceous) and well explored basinal areas of east coast Peninsula India and Sri Lanka:

	MMA	BBO	TCFG
Cauvery basin	19.3	0.18	1.2
Palar basin	2.6	.02	0.1
Godavari-Krishna basin	5.9	.37	1.2
	27.8	.57	2.5

(Analogies to related Indian Margin basins - Mahanadi-Bengal Foreland and North Assam are obscured by other geologic factors.)

Applying these estimates to the 62.7 MMA play area of this province, give resource estimates of 1.3 BBO, 5.6 TCFG, 0.3 BBNGL, amounting to 2.5 BBOE.

III. The geographically nearer (India in the Cretaceous) analogy appears more relevant; a weighted average between the two analogies would be:

1.7 BBO, 10.0 TCF, 0.5 BBC, and 3.9 BBOE

Play Analysis Summary of Undiscovered Petroleum

Basin Antarctica-Africa Marginal Rift   Antarctica   Play Cretaceous-Paleogene sandstones   No. 3

Area of basin (mi^2) 291,000   Area of play (MMA) 37.2

Volume of basin (mi^3) 870,000   Play est. orig. reserves 0 BBO 0 TCFG

Estimate original reserves 0 BBO 0 TCFG

Tectonic classification of basin: Rifted continental margin

Definition and area of play: Sandstones in Cretaceous to Paleogene fault traps and drapes of rifted continental margin. By analogy to S. Australian margin, 20 percent of rifted margin is deeper depocenters, i.e. play area.

	MAJOR GEOLOGICAL/EXPLORATION FACTORS	PROBABILITY DISTRIBUTION 95%	MOST LIKELY	5%
A.	Untested trap area (MMA)			
B.	Percent untested trap area productive (%)			
C.	Average effective pay (feet) — See remarks below			
D.	Percent oil versus gas in petroleum fill (%)			
E.	Oil recovery (BBLS/AF)			
F.	Gas recovery (MCF/AF)			
G.	NGL recovery (BBLS/MMCFG)			

Product of most likely probabilities: Oil 0.12 BB, Gas 2.9 TCF, NGL 0.1 BB, OE 0.7 BBOE

REMARKS

The most appropriate analogy is the Mozambique basin, which adjoined in Early Mesozoic. It has an area of 78.7 MMA and has estimated resources of .267 BBO and 6.66 TCFG. By direct areal analogy, the Antarctica-Africa Rift Province would have resources of .12 BBO and 2.9 TCFG.

(Assuming a wrenched margin at shelf edge, restricting the province to the shelf (81,000 mi^2 with 10.3 MMA basinal (play) area), but otherwise approximately analogous to the Antarctica-Australia Rift Province, the resources would be .39 BBO, 2.5 CFG, 0.1 BBNGL, amounting to 0.9 BBOE.)

Play Analysis Summary of Undiscovered Petroleum

Basin Antarctica-Falkland Marginal Rift Antarctica Play Drapes and fault traps No. 4
Area of basin (mi^2) 118,000 Area of play (MMA) 15.1
Volume of basin (mi^3) 36,000 Play est. orig. reserves 0 BBO 0 TCFG
Estimate original reserves 0 BBO 0 TCFG
Tectonic classification of basin: Rifted continental margin
Definition and area of play: Drapes and fault traps involving synrift and postrift sediments. Area of play is estimated, by analogy to Antarctica-Australia rift margin, to be about 20 percent of the continental margin area.

PROBABILITY DISTRIBUTION

	MAJOR GEOLOGICAL/EXPLORATION FACTORS		95%	MOST LIKELY	5%
A.	Untested trap area (MMA)		0.5	0.88	1.5
B.	Percent untested trap area productive (%)	(Resources probably	3.0	4.5	12.0
C.	Average effective pay (feet)	negligible. This	50	150	250
D.	Percent oil versus gas in petroleum fill (%)	play analysis on	10	40	60
E.	Oil recovery (BBLS/AF)	less-likely assump-	100	240	350
F.	Gas recovery (MCF/AF)	tion of rich synrift	700	1030	1200
G.	NGL recovery (BBLS/MMCFG)	source. See below.)	11	50	100

Product of probabilities: Oil 0.57 BB, Gas 3.67 TCF, NGL 0.18 BB, OE 1.36 BBOE
(on less-likely assumption
of rich synrift source)

REMARKS

The above play analysis is based on the less likely assumption that the synrift sediments are Late Jurassic to Early Cretaceous non-marine, organically rich sediments and the play in this, and all other respects, is analogous to the Antarctic-Australia marginal rift province. The results of ODP hole 692B, however, establish the age of indicated synrift strata to be at latest, Early Cretaceous and therefore probably largely Jurassic volcanics or sill-intruded Beacon Supergroup, in which case the resources of this hostile area are negligible, i.e., analogous to the Cooper basin or, optimistically, 0.03 BBO, 2.65 TCFG, and 0.2 BBNGL, or analogous to the Solinoes basin, 0.08 BBO and 4.0 TCFG.

Play Analysis Summary of Undiscovered Petroleum

Basin Ross Sea Interior Rift Antarctica Play Cretaceous-Paleogene sandstones No. 5
Area of basin (mi^2) 572,000 Area of play (MMA) 87.9
Volume of basin (mi^3) 990,000 Play est. orig. reserves 0 BBO 0 TCFG
Estimate original reserves 0 BBO 0 TCFG
Tectonic classification of basin: Interior rift
Definition and area of play: Sandstones in Cretaceous-Paleogene traps in the rifted Ross Sea, an area of some 572,000 mi^2 of which 24 percent is rift basins, i.e., play area.

PROBABILITY DISTRIBUTION

	MAJOR GEOLOGICAL/EXPLORATION FACTORS	95%	MOST LIKELY	5%
A.	Untested trap area (MMA)	2.0	5.1	10.0
B.	Percent untested trap area productive (%)	3.0	4.5	12.0
C.	Average effective pay (feet)	50	200	300
D.	Percent oil versus gas in petroleum fill (%)	10	45	60
E.	Oil recovery (BBLS/AF)	100	260	375
F.	Gas recovery (MCF/AF)	700	1100	1200
G.	NGL recovery (BBLS/MMCFG)	11	50	100

Product of most likely probabilities: Oil 5.4 BB, Gas 27.8 TCF, NGL 1.4 BB, OE 11.4 BBOE

REMARKS

A. By analogy to the Bass basin of the Bass Strait, it is assumed that the trap area is 5.8 percent of the play area.

B. Also by analogy to the same province, the percentage of trap area, which may be productive, is assumed to be around 4.5 percent.

C. Reservoirs are assumed to be somewhat thicker than those of the Antarctica-Australia Province (150 ft) since the quartz provenance of the Eocene-raised Transantarctic Mountains is nearby. I estimate an average of 200 ft.

D. The percent of oil is assumed analogous, but about three-fourths that of the unusually oily Gippsland production of 59 percent, i.e. 45 percent oil in petroleum mix.

E. Because of closer quartz provenance, the reservoirs are probably better than those of the Antarctica-Australia Rift Province (estimated at 240 BO/AF). I estimate 260 BO/AF.

F. Reservoirs somewhat better than the analogous Antarctica-Australia Province and at about the same depth.

G. Analogous to the Antarctica-Australia Province; half the yield of the unusually rich Gippsland gas yield (97.7 BNGL/MMCFG), i.e. 50 BBNGL/MMCFG.

Play Analysis Summary of Undiscovered Petroleum

Basin Weddell Sea Interior Rift   Antarctica   Play Cretaceous-Paleogene drape/fault traps No. 6
Area of basin (mi^2) 300,000   Area of play (MMA) 192.0
Volume of basin (mi^3) 2,000,000   Play est. orig. reserves 0 BBO 0 TCFG
Estimate original reserves 0 BBO 0 TCFG
Tectonic classification of basin: Interior rift
Definition and area of play: The play is presumed Cretaceous and Paleogene sands in fault trap and drape closures. The play is the rifted portion of the Weddell Sea and adjoining ice shelves, an area of some 300,000 mi^2.

	MAJOR GEOLOGICAL/EXPLORATION FACTORS	PROBABILITY DISTRIBUTION 95%	MOST LIKELY	5%
A.	Untested trap area (MMA)	2.00	11.14	15.0
B.	Percent untested trap area productive (%)	3.0	4.5	12.0
C.	Average effective pay (feet)	50	150	250
D.	Percent oil versus gas in petroleum fill (%)	10	34	50
E.	Oil recovery (BBLS/AF)	100	260	375
F.	Gas recovery (MCF/AF)	1000	1400	1600
G.	NGL recovery (BBLS/MMCFG)	11	50	100

Product of most likely probabilities: Oil 6.7 BB, Gas 69.5 TCF, NGL 3.5 BB, OE 21.8 BBOE

REMARKS

A. By analogy to the rift basins of the Bass basin and Ross Sea province, it is assumed that traps occupy 5.8 percent of the play area.

B. Also by analogy to the Bass basin and Ross Sea.

C. By analogy to the Antarctica-Australia and Ross Sea provinces except thinner being more distal to the presumed Transantarctic Mountain and provenance. Estimate three-fourths as thick as Ross Sea reservoirs.

D. In view of the thicker sedimentary cover, including thick, deep presumed Beacon sediments, more abundant gas is assumed (i.e., gas 66 percent, oil 34 percent), than in the analogous Ross Sea Province.

E. By analogy to the Ross Sea Province.

F. Gas reservoirs are assumed analogous to those of the Ross Sea Province but deeper, i.e., average 12,000 ft.

G. Analogous to the Antarctica-Australia Rift province, i.e., half that of the unusually rich Gippsland yields.

NOTE: Another analogy would assume that graben fills were equivalent in Ross and Weddell provinces and, therefore, the Weddell Sea resource would be analogous on an areal basis, i.e., 11.8 BBO, 60.7 TCFG, 3.1 BBC, 24.9 BOE.

Play Analysis Summary of Undiscovered Petroleum

Basin Amery Interior Rift Antarctica Play Cretaceous sands/drapes and fault traps No. 7

Area of basin (mi^2) 28,000 Area of play (MMA) 12.0

Volume of basin (mi^3) 70,000 Play est. orig. reserves 0 BBO 0 TCFG

Estimate original reserves 0 BBO 0 TCFG

Tectonic classification of basin: Interior rift

Definition and area of play: Cretaceous sandstones in drape or fault traps. Area confined to that under Amery ice shelf. Onshore Lambert graben considered too shallow; two-thirds basin considered deep enough for play (Prydz Bay considered part of marginal rift play).

PROBABILITY DISTRIBUTION

	MAJOR GEOLOGICAL/EXPLORATION FACTORS	95%	MOST LIKELY	5%
A.	Untested trap area (MMA)	.50	.70	1.00
B.	Percent untested trap area productive (%)	3.0	4.5	12.0
C.	Average effective pay (feet)	50	200	300
D.	Percent oil versus gas in petroleum fill (%)	10	45	60
E.	Oil recovery (BBLS/AF)	100	260	375
F.	Gas recovery (MCF/AF)	700	1100	1200
G.	NGL recovery (BBLS/MMCFG)	11	50	100

Product of most likely probabilities: Oil 0.74 BB, Gas 3.82 TCF, NGL .20 BB, OE 1.58 BBOE

REMARKS

From figure 22 it appears that about two-thirds of the rift basin is sufficiently deep (about 3 km) to generate petroleum; therefore, two-thirds of the basin or 12.0 MMA is considered play area.

Factors A through G are considered analogous to the rift grabens of the Ross Sea, factor A being 5.8 percent of 12.0 MMA.

Play Analysis Summary of Undiscovered Petroleum

Basin Larsen Antarctica Play Cretaceous-Paleogene sandstones No. 8

Area of basin (mi^2) 117,000 Area of play (MMA) 75.0

Volume of basin (mi^3) 364,000 Play est. orig. reserves 0 BBO 0 TCFG

Estimate original reserves 0 BBO 0 TCFG

Tectonic classification of basin: Backarc

Definition and area of play: Cretaceous-Paleogene sandstone in drapes and fault traps. The whole basin is considered the play area.

	MAJOR GEOLOGICAL/EXPLORATION FACTORS	PROBABILITY DISTRIBUTION 95%	MOST LIKELY	5%
A.	Untested trap area (MMA)	1.50	4.35	6.00
B.	Percent untested trap area productive (%)	3.0	4.0	12.0
C.	Average effective pay (feet)	75	100	200
D.	Percent oil versus gas in petroleum fill (%)	20	60	90
E.	Oil recovery (BBLS/AF)	100	161	400
F.	Gas recovery (MCF/AF)	500	729	1200
G.	NGL recovery (BBLS/MMCFG)	11	50	100

Product of most likely probabilities: Oil 1.7 BB, Gas 5.1 TCF, NGL 0.30 BB, OE 2.9 BBOE

REMARKS

A. Although the tectonics are generally those of a convergent margin, the overriding, trap-forming structure is perhaps that resulting from Tertiary extension. By analogy to the extensional traps of the 5.8 percent of the play area is trap (this compares with 5.5 percent estimated for the trap area of the classic backarc basins of Indonesia).

B. Somewhat analogous to backarc basins of Indonesia (5 percent trap area productive) but discounted for poorer reservoirs to about 4 percent.

C. Estimate effective pay of Indonesian backarc basins (200 ft) where sands come from foreland rather than volcanic arc side.

D. Assumed partly analogous to nearest production, Gippsland basin, 60 percent oil, involving about same section, and partly analogous to Indonesian backarc basins where oil averages 50 to 90 percent of petroleum mix. Assume 60 percent.

E. Since sediments mainly derived from volcanic arc side, reservoir sandstones are assumed relatively poor.

F. Assumed intermediate depth, poor reservoirs.

G. Assumed deltaic environment, half the NGL yields of the unusually rich Gippsland basin.

Play Analysis Summary of Undiscovered Petroleum

Basin Byrd Antarctica Play Cretaceous and Tertiary drapes and fault traps No. 9

Area of basin (mi^2) 80,000 Area of play (MMA) 51.2

Volume of basin (mi^3) 160,000 Play est. orig. reserves 0 BBO 0 TCFG

Estimate original reserves 0 BBO 0 TCFG

Tectonic classification of basin: Backarc

Definition and area of play: Basin area very loosely defined from reconnaissance magnetic and gravity data. On trend with Larsen backarc basin and has some play, i.e., Cretaceous and Tertiary sandstones in drape and fault traps.

		PROBABILITY DISTRIBUTION		
	MAJOR GEOLOGICAL/EXPLORATION FACTORS	95%	MOST LIKELY	5%
A.	Untested trap area (MMA)	.50	2.97	2.00
B.	Percent untested trap area productive (%)	3.0	4.0	12.0
C.	Average effective pay (feet)	75	100	200
D.	Percent oil versus gas in petroleum fill (%)	10	60	60
E.	Oil recovery (BBLS/AF)	100	161	375
F.	Gas recovery (MCF/AF)	700	729	1200
G.	NGL recovery (BBLS/MMCFG)	11	50	100

Product of most likely probabilities: Oil 1.15 BB, Gas 3.5 TCF, NGL 0.2 BB, OE 1.9 BBOE

REMARKS

A. By analogy to the on-trend Ross Sea Interior Rift, estimate of 5.8 percent of play area is trap.

B, C, D, E, F, G estimates same as those made for the on-trend Larsen backarc basin.

Play Analysis Summary of Undiscovered Petroleum

Basin Alexander Antarctica Play Cretaceous sandstones No. 10
Area of basin (mi^2) 190,600 Area of play (MMA) 122
Volume of basin (mi^3) ________ Play est. orig. reserves 0 BBO 0 TCFG
Estimate original reserves 0 BBO 0 TCFG
Tectonic classification of basin: Forearc (over subducted spreading ridge)
Definition and area of play: Cretaceous sandstones in drapes and fault traps (mainly Tertiary). Area includes western continental shelf of the Antarctic Peninsula and Bellingshauser Sea.

	MAJOR GEOLOGICAL/EXPLORATION FACTORS	PROBABILITY DISTRIBUTION 95%	MOST LIKELY	5%
A.	Untested trap area (MMA)	1.0	3.5	5.0
B.	Percent untested trap area productive (%)	1.0	2.2	4.5
C.	Average effective pay (feet)	35	50	150
D.	Percent oil versus gas in petroleum fill (%)	10	50	90
E.	Oil recovery (BBLS/AF)	100	150	300
F.	Gas recovery (MCF/AF)	500	645	1200
G.	NGL recovery (BBLS/MMCFG)	11	50	100

Product of most likely probabilities: Oil .29 BB, Gas 1.24 TCF, NGL 0.06 BB, OE 0.55 BBOE

REMARKS

A. Although forearc basin formed in plate convergence, last event was Tertiary extension which is assumed to be overriding, trap-former. By analogy to Larsen basin estimates, traps would make up 5.8 percent of play area but owing to presumably more severe forearc tectonics the viable trap area is judged to be only half, or 2.9 percent.

B. Estimate analogous to Gippsland basin involving equivalent age (Early Cretaceous) and facies deltaic strata. Usual estimated forearc thermal gradient (1°F/100 ft) would preclude petroleum generation, but presumed subduction of hot oceanic spreading ridge would cause some generation, perhaps half as productive as Gippsland or 2.2 percent.

C. Reservoir sands derived from an essentially island arc provenance would be sparse and only thin, perhaps 50-ft reservoirs may be expected.

D. Oil versus gas ratios somewhat less than estimates for backarc.

E. Oil recovery deemed relatively low (assumed porosity - 12.5 percent) on basis of volcanic arc provenance for reservoirs.

F. Gas recovery low because of assumed low reservoir quality. Intermediate depth assumed.

G. Deltaic environment; half the yield of the nearby analogous, but unusually high condensate-yielding Gippsland basin.

Play Analysis Summary of Undiscovered Petroleum

Basin Amundsen Antarctica Play Traps of Cretaceous-Tertiary Reservoirs No. 11

Area of basin (mi^2) 234,000 Area of play (MMA) 150.0

Volume of basin (mi^3) 350,000 Play est. orig. reserves 0 BBO 0 TCFG

Estimate original reserves 0 BBO 0 TCFG

Tectonic classification of basin: Wrenched and rifted forearc margin

Definition and area of play: Cretaceous-Tertiary sandstones involved in drapes, fault traps, and perhaps, wrench folds.

		PROBABILITY DISTRIBUTION		
	MAJOR GEOLOGICAL/EXPLORATION FACTORS	95%	MOST LIKELY	5%
A.	Untested trap area (MMA)	0.50	4.35	6.50
B.	Percent untested trap area productive (%)	1.0	2.2	4.5
C.	Average effective pay (feet)	35	50	150
D.	Percent oil versus gas in petroleum fill (%)	10	50	60
E.	Oil recovery (BBLS/AF)	100	150	300
F.	Gas recovery (MCF/AF)	500	645	1200
G.	NGL recovery (BBLS/MMCFG)	11	50	100

Product of most likely probabilities: Oil 0.36 BB, Gas 1.54 TCF, NGL .08 BB, OE 0.62 BBOE

REMARKS

A. Margin is considered rather tectonized with both wrench and rift faulting; the number and area of intact, viable closures are, therefore, assumed limited to half that of the backarc Larsen basin, i.e. 2.9 percent.

B. Outcrops indicate a provenance of accreted melange and volcanic arc material, so reservoirs are poor. Accordingly, the percent of trap area productive is assumed to be much less, probably half that of the rift basins, i.e. 2.2 percent.

C. Given the volcanic provenance, reservoirs would be thin, perhaps averaging 50 ft in combined pay thickness.

D. Assumed analogous to the Alexander forearc basin.

E. Given the volcanic provenance, low-porosity reservoirs are assumed.

F. Low-porosity reservoirs; intermediate depth assumed.

G. Half the condensate yield of the analogous but unusually high condensate-yielding Gippsland basin.

Play Analysis Summary of Undiscovered Petroleum

Basin Wilkes Land Antarctica Play Beacon strata in drapes/fault traps No. 12

Area of basin (mi^2) 100,000 Area of play (MMA) 64.0

Volume of basin (mi^3) 100,000 Play est. orig. reserves 0 BBO 0 TCFG

Estimate original reserves 0 BBO 0 TCFG

Tectonic classification of basin: Interior sag

Definition and area of play: Low amplitude drapes and fault traps involving Beacon Supergroup or younger sediments in a shallow or shelfal basin. Area and depth of basin/play based on poor evidence. Play covers entire basin.

MAJOR GEOLOGICAL/EXPLORATION FACTORS		PROBABILITY DISTRIBUTION 95%	MOST LIKELY	5%
A. Untested trap area (MMA)				
B. Percent untested trap area productive (%)				
C. Average effective pay (feet)				
D. Percent oil versus gas in petroleum fill (%)	(Resources negligible,			
E. Oil recovery (BBLS/AF)	see below)			
F. Gas recovery (MCF/AF)				
G. NGL recovery (BBLS/MMCFG)				

Product of most likely probabilities: Oil N BB, Gas N TCF, NGL N BB, OE N BBOE

REMARKS

Basin is deemed, on the basis of weak evidence, to be shallow, less than 5,000 ft. This, with the presumed low thermal gradient, indicates the sediments to be immature and petroleum resources, therefore, negligible. The likely fill is the Beacon Supergroup. If, in the less likely case, the basin is deeper than indicated, i.e. 15,000 ft, the basal beds would have reached maturity and the basin condition would be somewhat similar to that of the Cooper basin (49,000 mi^2, 0.05 BBO, 4.4 TCFG, 0.4 BBNGL, 1.2 BBOE). By analogy to that basin, the resources would be 0.10 BBO, 8.8 TCFG, 0.8 BBNGL, amounting to 2.4 BBOE. Areal analogy to the Solimoes basin of Brazil (116,000 mi^2, ultimate resources of 0.08 BBO, 4.0 TCFG, or 0.7 BBOE) indicates resources of 0.07 BBO, 3.4 TCFG or 0.64 BBOE, insignicant amounts when disseminated through this vast hostile area.

The formation of biogenic gas combined with permafrost and ice seals could result in fairly large gas deposits.

Play Analysis Summary of Undiscovered Petroleum

Basin Aurora Antarctica Play Beacon strata in drapes/fault traps No. 13

Area of basin (mi^2) 390,000 Area of play (MMA) 250.0

Volume of basin (mi^3) 390,000 Play est. orig. reserves 0 BBO 0 TCFG

Estimate original reserves 0 BBO 0 TCFG

Tectonic classification of basin: Interior sag

Definition and area of play: Low amplitude drapes and fault traps involving Beacon and possibly younger strata in a shallow or shelfal basin. Area and depth of basin/play based on poor evidence. Play covers whole basin.

MAJOR GEOLOGICAL/EXPLORATION FACTORS		PROBABILITY DISTRIBUTION 95%	MOST LIKELY	5%
A. Untested trap area (MMA)				
B. Percent untested trap area productive (%)				
C. Average effective pay (feet)				
D. Percent oil versus gas in petroleum fill (%)	(Resources negligible,			
E. Oil recovery (BBLS/AF)	see below)			
F. Gas recovery (MCF/AF)				
G. NGL recovery (BBLS/MMCFG)				

Product of most likely probabilities: Oil N BB, Gas N TCF, NGL N BB, OE N BBOE

REMARKS

Basin is deemed shallow, less than 5,000 ft and with a low thermal gradient so that the sediments would be immature and the basin resources negligible. The basin fill is probably Beacon Supergroup or younger. If the sediments are deeper than the weak evidence indicates, and thermal maturity is reached, the basin appears somewhat similar to the Cooper basin. By this analogy, the resources would be 0.40 BBO, 35 TCFG, 3.2 BBNGL, amounting to 9.6 BBOE. Areal analogy to the Solimoes basin of Brazil (116,000 mi^2, ultimate resources of 0.08 BBO, 4.0 TCFG or 0.7 BBOE) indicates resources of 0.27 BBO, 13.5 TCFG or 2.52 BBOE, insignificant amounts when disseminated through in this vast and hostile area.

The formation of biogenic gas combined with permafrost and ice seals could result in fairly large gas reserves.