GEOLOGICAL SURVEY CIRCULAR 909

Petroleum and Mineral Resources of Antarctica

Work done in cooperation with the National Science Foundation

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By John C. Behrendt, *Editor*

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CONTENTS

	Page
Introduction	1
Are there petroleum resources in Antarctica?, by John C. Behrendt	3
Mineral occurrences of Antarctica, by Peter D. Rowley, Paul L. Williams, and Douglas E. Pride	25
The Dufek Intrusion of Antarctica and a survey of its minor metals and possible resources, by Arthur B. Ford	51

ILLUSTRATIONS

			Page
FIGURE	1.	Index map of Antarctica	4
	2.	Cartoon of "ring of oil"	5
	3–9.	Maps showing:	
		3. Worldwide distribution of giant petroleum fields	5
		4. Southernmost giant oil fields on a continental reconstruction	6
		5. Magnetic anomalies over the Ross Ice Shelf and Transantarctic Mountains	8
		6. Contours of depth to magnetic basement in area of figure 5	10
		7. Contours of bedrock elevation of area shown in figures 5 and 6	11
		8. Contours of magnetic intensity in the Ross Sea	12
		9. Ship (*Polarsirkel*) tracks in the Weddell Sea along which multichannel seismic reflection data were collected	13
	10.	Seismic-record section across the Crary Trough	14
	11–18.	Maps showing:	
		11. Ship (*Explora*) tracks in the Weddell Sea along which multichannel seismic reflection data were collected	14
		12. Examples of reflection profiles in the Weddell Sea	15
		13. Ship tracks in the Weddell Sea along which 12-channel seismic reflection data were collected by U.S.S.R	16
		14. Ship (*Hakurei-Maru*) tracks in Weddell Sea along which 24-channel seismic, gravity, and magnetic data were collected	17
		15. Ship (*Explora*) tracks in Ross Sea where multichannel seismic reflection data were collected for BGR and IFP	18
		16. Ship (*Explora*) tracks over continental shelf of East Antarctica along which 48-channel seismic reflection data were collected	19
		17. Ship (*Hakurei-Maru*) tracks in the Bellingshausen Sea along which 12-channel seismic, gravity, and magnetic data were collected	20
		18. Cruise track of *Glomar Challenger* DSDP leg 28 in the Ross Sea	21
	19.	Composite stratigraphic section from DSDP sites in the Ross Sea	22

Page

FIGURES 20–22. Maps showing:
20. Localities of mineral occurrences in Antarctica 28
21. Localities of mineral occurrences in Antarctic Peninsula 30
22. Location of Dufek intrusion in Antarctica 52
23. Section showing rock-stratigraphic nomenclature of Dufek intrusion and generalized range of minerals 56
24. Photograph of summit of Aughenbaugh Peak 57
25. Photograph of cross section of anorthosite-filled channel, southern Forrestal Range 59
26–28. Charts showing:
26. Chemical variation in Dufek intrusion 61
27. Possible comparison between lower parts of the Bushveld Complex and the Dufek intrusion . 63
28. Correlation of analyzed elements in 22 cumulates of the Dufek intrusion 66

TABLES

Page

TABLE 1. Comparison of areas of selected mafic stratiform intrusions 53
2. Chemical analyses of little-differentiated rocks inferred to represent original magmas of selected mafic stratiform intrusions 62
3. Spearman rank correlation coefficients for chemical constituents with stratigraphic height and mineral content in 22 analyzed cumlates of the Dufek intrusion 65
4. Summary of minor-element content of typical rocks from the layered sequence of the Dufek intrusion . 65

Petroleum and Mineral Resources of Antarctica

By John C. Behrendt, *Editor*

INTRODUCTION

No known petroleum or mineral resources occur in Antarctica. The data on these subjects have been collected, mainly since the IGY (International Geophysical Year), 1957–58, as a part of other research carried out by geologists and geophysicists from a number of countries. Specific resource-related studies have not been made. Wright and Williams (1974) summarized what was known of Antarctic mineral resources a decade ago.

The U.S. Geological Survey has been actively pursuing various investigations in Antarctica since 1947. In the course of this work and that of our colleagues elsewhere in the United States and in other countries, much information relevant to petroleum and mineral resources has been obtained. Since 1976, modern state-of-the-art multichannel seismic reflection and aeromagnetic surveys by several countries over the continental margin of Antarctica have indicated thick sedimentary basins. However, no offshore drilling beneath the continental shelf has taken place since the DSDP (Deep Sea Drilling Project) holes in the Ross Sea in 1973. Geologic field investigations begun at the turn of the twentieth century have been intensified in the past two decades; most rock outcrops have been visited and samples collected. Technology to exploit resources, particularly in the Arctic, has been developing at a rapid rate, and much of it could be applied to Antarctica.

As a result of the petroleum price increases of the past decade, the attention of a number of countries has turned to Antarctica, but under the policy of "voluntary restraint" adopted by the Antarctic Treaty nations, no active petroleum or mineral exploration is taking place. The Antarctic treaty countries are in the process of negotiating an Antarctic mineral resources regime that is anticipated to be completed within the next several years. Therefore it seemed timely to us to readdress the question of petroleum and mineral resources. These reports review and summarize the available information. The first report summarizes the information relevant to petroleum resources. Although uneconomic at present, petroleum is generally considered more likely to be exploited (if supergiant fields were ever found) in the next few decades than hard minerals. The second report reviews the reported occurrences of minerals in Antarctica and discusses their significance. The final report discusses the Dufek layered mafic intrusion, second only to the Bushveld Complex in size in the world; the Dufek intrusion might be considered as a potential target for mineral exploration.

ACKNOWLEDGMENTS

We thank our colleagues in the U.S. Geological Survey, in the United States Antarctic Research Program, and from a number of other countries active in Antarctic Research for ideas, material, and helpful discussion. The National Science Foundation has provided funds and logistic support for field work over the years for the authors.

REFERENCE CITED

Wright, N. A., and Williams, P. L., 1974, Mineral resources of Antarctica, U.S. Geological Survey Circular 705, 29 p.

Are There Petroleum Resources In Antarctica?

By John C. Behrendt

No known petroleum resources occur in Antarctica (fig. 1). Nonetheless, because of current concern about world supplies of oil and gas, geologists, geophysicists, economists, lawyers, and statesmen from a number of countries have turned their attention to Antarctica. The Antarctic Treaty nations are working on the problems of establishing a mineral resources regime. Exploitation of any metallic minerals that could be mined economically would be many years in the future (Rowley and others, in press; Rowley and others, this volume), even if deposits were to be found that might be economic to recover in other parts of the world. The only mineral commodity with the possibility of exploitation within the next two or three decades is petroleum. Most of Antarctica is covered by a moving ice sheet about 3 km thick. The only areas accessible to available or soon-to-be-developed oil exploitation technology are the continental margin, possibly including the areas beneath ice shelves. Several authors (Wright and Williams, 1974; Zumberge, 1979a, b; Holdgate and Tinker, 1979; Dugger, 1978; Splettstoesser, 1977; Group of Experts, 1977; Rivera, 1977; Ivanhoe, 1980; Cameron, 1981; Quigg, 1983; Behrendt, in press) have addressed the possibility of the occurrence of petroleum resources on the Antarctic continental margin from various perspectives (geologic, environmental, economic, and legal); I will be referring to their work as well as my own in this report.

In a study of world oil resources, Nehring (1978) discussed the occurrence of giant fields (0.5 billion bbl or about 70 million tons of recoverable oil) and supergiant fields (5 billion bbl or about 700+ million tons of recoverable oil; Meyerhoff (1976) used the figure 10 billion bbl or 1.4 billion metric tons for supergiant fields). Nehring (1978) estimated that a total of four to ten supergiants containing 30–100 billion tons remain to be discovered in the world. It is probable that nothing smaller than giant, and more probably supergiant, fields would be economic in the harsh Antarctic environment, particularly considering the world petroleum "glut" as this is written in 1983. Nehring (1978) concluded that "...the rate at which the ultimate resource will become available depends primarily on the development of technology for offshore Arctic [Antarctica was not discussed] and deep-water exploration and production, the production policies of the OPEC countries, and the existence of the necessary economic incentives to producers and refineries." The cartoon presentation of the "ring of oil" (fig. 2) from Nehring (1978) shows the concentration of nearly 85 percent of the world's known petroleum resources on a reconstruction of Gondwanaland, from which one would infer that it is unlikely that Antarctica as a whole would be promising for petroleum. Possibly the "ring of oil" is only a reflection of the areas of the world where the most intense exploration has so far taken place. Meyerhoff (1976) published a map (fig. 3) showing the locations of giant and supergiant oil fields of the world; these have a significant concentration in the Northern Hemisphere.

I plotted the southernmost of the giant oil fields from figure 3 on the continental reconstruction published by Craddock (1969) as shown in figure

4, which suggests that the areas with the most potential for petroleum resources are the Ross, Amundsen, Bellingshausen, and Weddell Seas' parts of the West Antarctic continental margin. However, the validity of any conclusion drawn from a Gondwanaland reconstruction is largely restricted to the consideration of rocks that predate the Gondwanaland fragmentation. After fragmentation, the various fragments have distinct geologic histories. Given this, the age of the various oil fields on figure 4 becomes crucial. R. J. Tingey (written commun., 1982) made the following comment. "The Australian examples (in fig. 4) range from small gas fields in western Australia in pre-break-up Triassic strata, to intracontinental Permian strata in central Australia, to oil bearing strata of break-up (i.e. Eocene) age in the Gippsland basin. In the South American San Jorge basin, the petroleum-bearing rocks are the Late Cretaceous Chubut Group which post-date the Africa-South America separation and thus bear no relation to the underlying (and older) orogen that allegedly once continued right across Gondwanaland. Similarly the Gippsland oil fields of Australia are not related to the much older Tasman orogen on which they are plotted; both the San Jorge and Gippsland rocks appear to be related not to trans-Gondwanaland orogens but rather to the processes

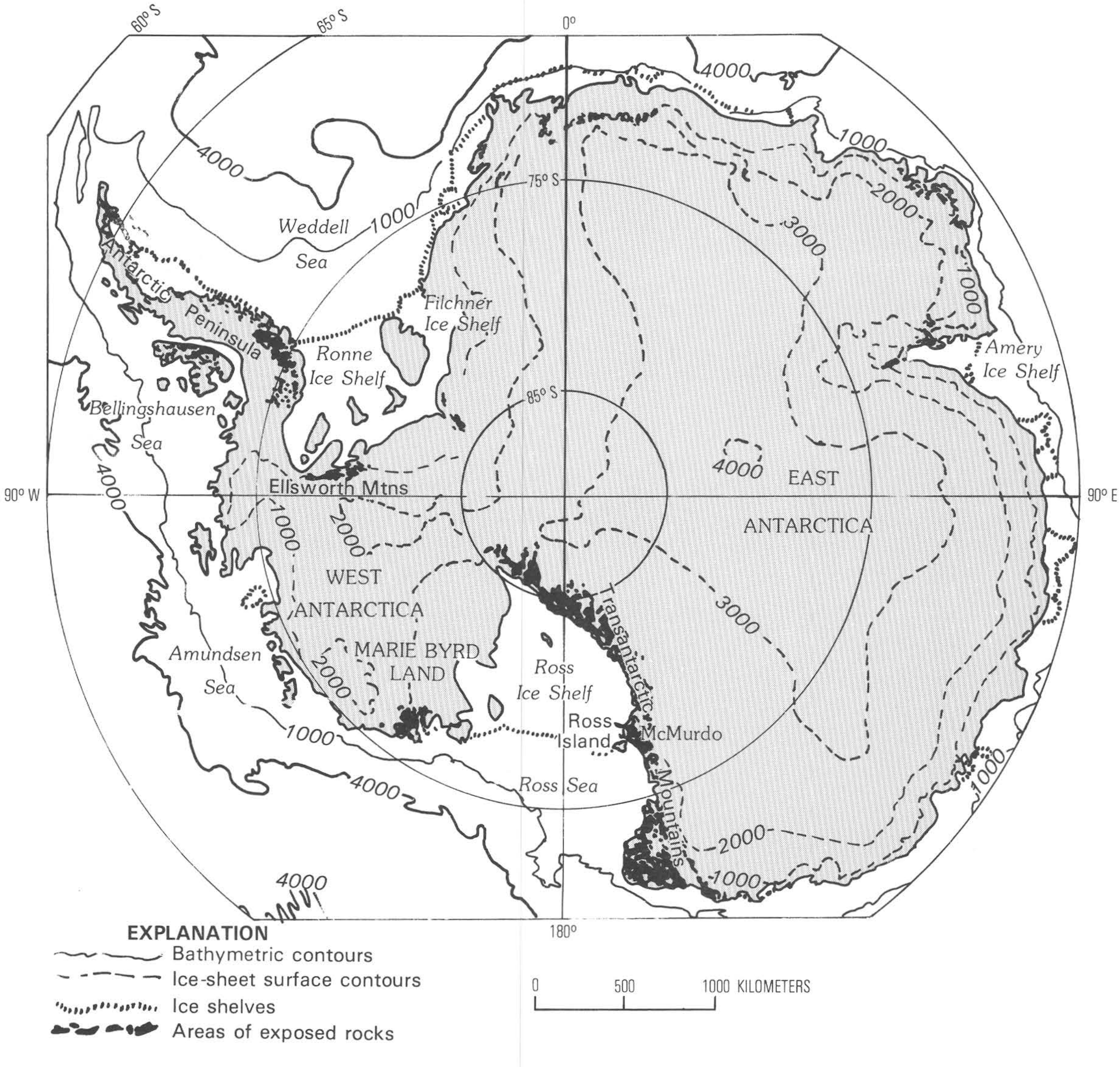

FIGURE 1.—Index map of Antarctica showing major geographic features discussed in text, including the continental margin. Bathymetric contour interval 3000 meters; ice-sheet surface contour interval 1000 meters.

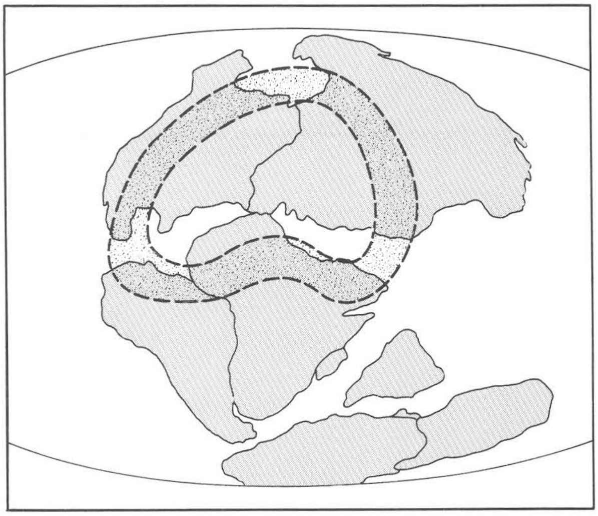

FIGURE 2.—Cartoon of "ring of oil" showing concentration of nearly 85 percent of known petroleum resources of the world on a continental reconstruction about 170 m.y. B.P. (From Nehring, 1978.)

of Gondwanaland orogens break-up."

Consideration of the known geology of Antarctica and inferences from sparse geophysical work suggest the presence of significant thicknesses of sedimentary rock in the areas throughout West Antarctica and several areas in East Antarctica (fig. 1). The Amery Ice Shelf area of East Antarctica might be considered, on the basis of the large indentation in the continent suggesting a possible failed rift, analogous to the petroleum-rich Benue Trough area of West Africa. In this report I review the available geophysical data and discuss the results of drilling on the continental margin by the DSDP (Deep Sea Drilling Project). I also briefly discuss the environmental hazards associated with future Antarctic petroleum exploration and exploitation.

ACKNOWLEDGMENTS

I thank P. D. Rowley and K. A. Kvenvolden for helpful discussions. A. B. Ford, C. M. Masters, and G. L. Dolton and R. J. Tingey (Australian Bureau of Mineral Resources) critically reviewed the manuscript. The material covered in this report is essentially the same as that in Behrendt (in press).

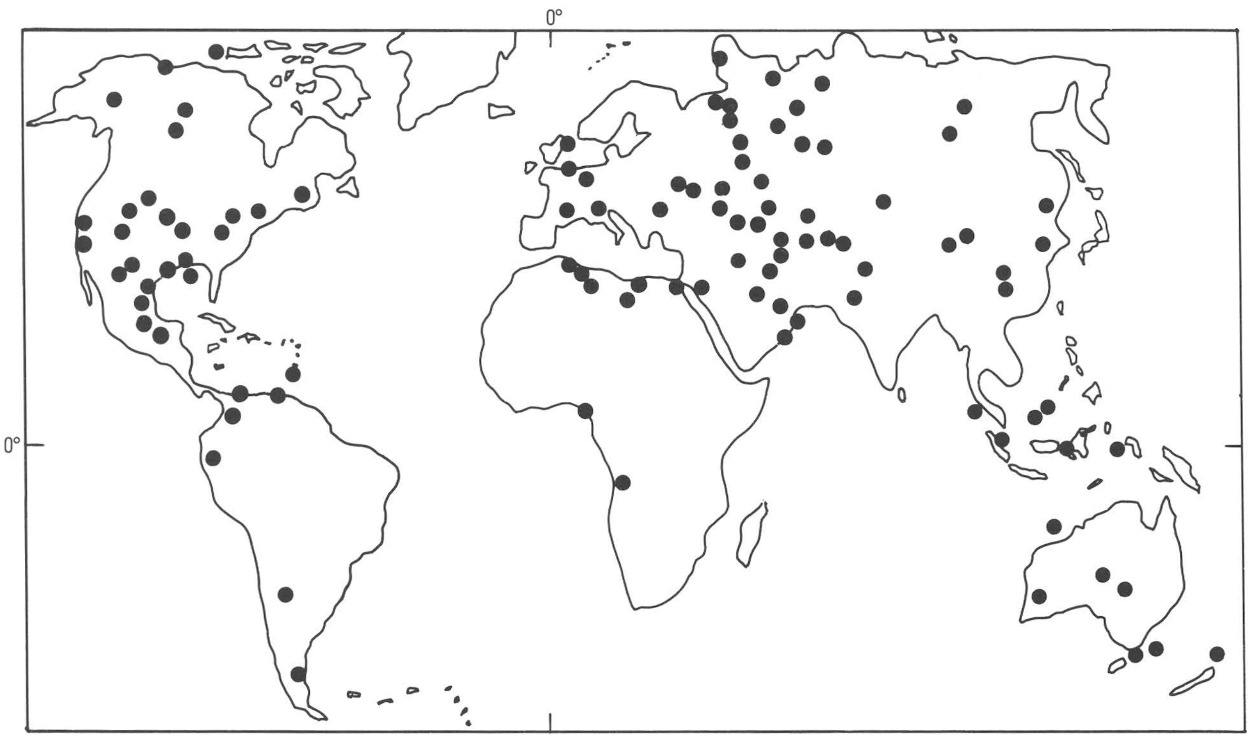

FIGURE 3.—Worldwide distribution of giant petroleum fields (solid dot). (Modified from Meyerhoff, 1976.)

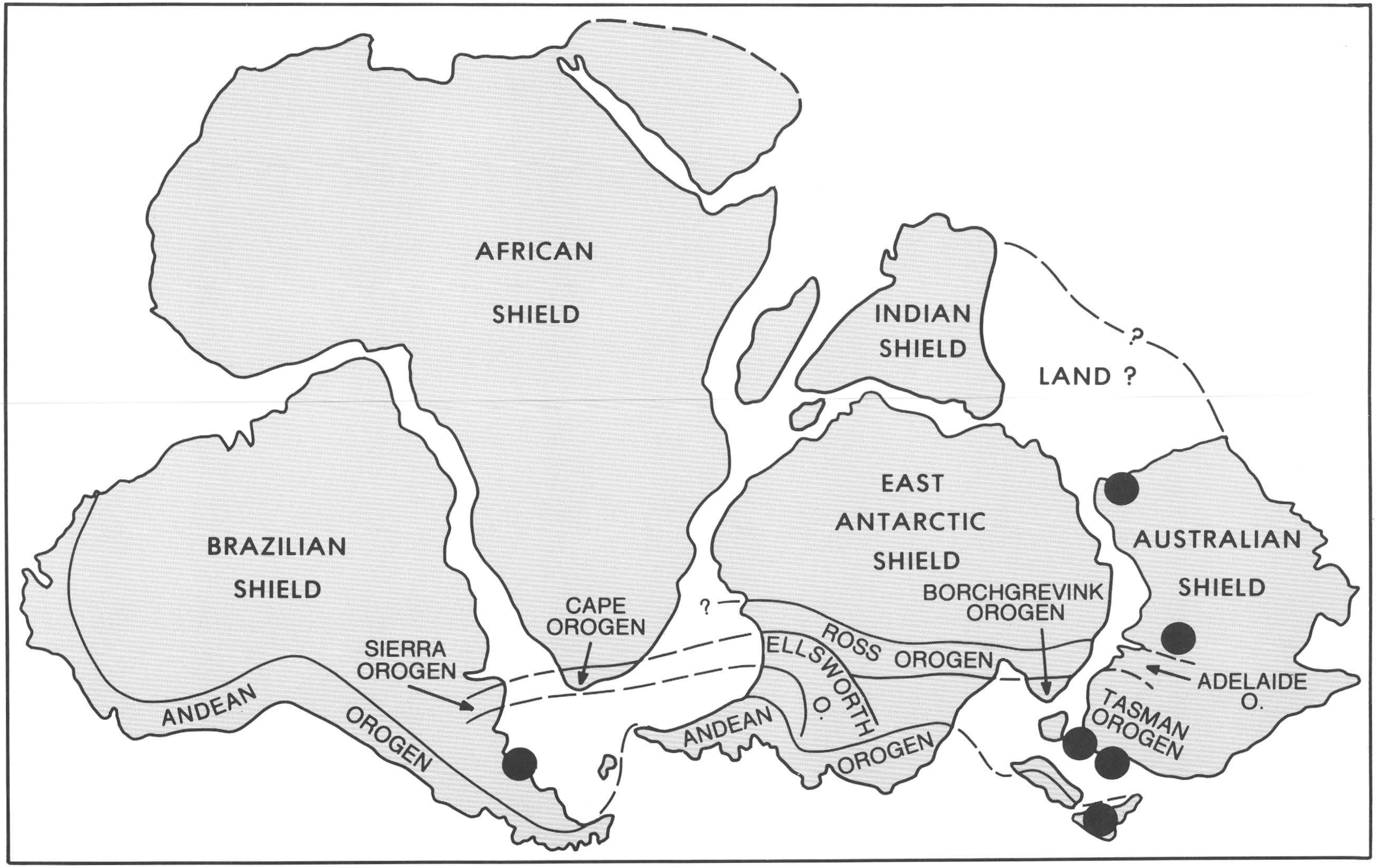

FIGURE 4.—Southernmost giant oil fields (solid dot) from figure 3 on a continental reconstruction. Dashed lines and queries indicate uncertainty. (Modified from Craddock, 1969; oil fields from Meyerhoff, 1976.)

SUMMARY OF GEOLOGY

Rowley and others (in press) summarized the regional geology of Antarctica, and I am using material from their text here. Antarctica (fig. 1) is generally divided into two parts, geologically and topographically. The semicircular area (fig. 1) lying mainly in the Eastern Hemisphere is known as East Antarctica. There the ice sheet is mostly more than 3 km high and bedrock is near or below sea level in places. Subglacial mountain ranges exist with as much as 4 km of local relief. The rocks of East Antarctica are rarely exposed except at the coast and along the Transantarctic Mountains marking the boundary with West Antarctica. East Antarctica, where outcrops exist, is mainly a craton consisting of Precambrian crystalline metamorphic complexes welded together in late Precambrian or early Paleozoic time. These older rocks, deformed and folded in early Paleozoic time, are overlain unconformably by the generally flat lying Beacon Supergroup sedimentary sequence that ranges from Devonian and possibly Silurian to Early Jurassic in age. The Beacon rocks are particularly well exposed in the Transantarctic Mountains.

West Antarctica, lying only in the Western Hemisphere, is much lower in elevation, and in many areas the bedrock is more than 1 km below sea level (Bentley, 1964). West Antarctica is faulted and fragmented and may consist of several microplates, as discussed by Dalziel and Elliot (1982) and Behrendt (1964a). These microplates include the 5-km-high Ellsworth Mountains (mainly upper Precambrian and Paleozoic sedimentary rocks folded in Mesozoic time) and the Antarctic Peninsula (consisting largely of upper Mesozoic and Tertiary stocks and batholiths intruding Mesozoic sedimentary and volcanic sequences). Sedimentary rocks are locally abundant in Marie Byrd Land. Tertiary and Quaternary volcanic rocks crop out in Marie Byrd Land and in the McMurdo area.

All of the known geology on land is based on samples from highly competent outcrops projecting through the ice as mountain ranges and isolated nunataks. Therefore, sampling is biased and the Cretaceous and Cenozoic basins, containing unmetamorphosed sedimentary rocks whose presence would be expected by analogy to other continents, are not exposed but probably occur beneath the ice sheet and continental margin. These basins are the places likely to contain petroleum, but only geophysical methods and drilling can determine their presence and resource potential.

GEOPHYSICAL STUDIES

Some geophysical work was carried out in Antarctica during the 1930's (Poulter, 1937) and 1940's, but the 1950's saw the beginning of systematic reconnaissance seismic-reflection and -refraction, gravity, land-magnetic, and aeromagnetic studies. The early seismic reflection work on the oversnow traverses (Robin, 1958; Kapitza, 1960; Bentley, 1964; Thiel and Behrendt, 1959; Behrendt, 1962; Crary and Robinson, 1962) was primarily directed at measuring ice thickness, with few sub-ice reflection results reported. No modern multichannel seismic reflection data have been collected on the grounded ice sheet or floating ice shelves of Antarctica. The seismic refraction results from the oversnow traverses were biased towards the higher velocities because the seismic velocity of ice is about 3.9 km/s, precluding direct observation of lower velocity sedimentary rocks in basins beneath the ice.

The gravity measurements made along oversnow traverses are of severely limited quality because of poor elevation control (Bentley, 1964). Most gravity data on the ice sheet are not particularly useful geologically because ice thickness is known only at widely spaced intervals where seismic reflection measurements were made. Modern radio echo ice-sounding techniques allow quick measurements of ice thickness but, except in a few local surveys, such as England and others (1979), gravity measurements are no longer being made on long oversnow traverses.

Radio echo ice-sounding from the air (Drewry, 1975) has allowed continuous measurements of bedrock topography over large areas of Antarctica, but only recently (Behrendt and others, 1980; Jankowski and others, 1983) have simultaneous aeromagnetic measurements been made, allowing subglacial geologic interpretations. Aeromagnetic data without radio echo ice-thickness measurements have been obtained on a reconnaissance basis mostly on widely spaced profiles throughout large areas of Antarctica. In West Antarctica, Behrendt and Wold (1963) and Behrendt (1964b) reported substantial (>5 km) thicknesses of nonmagnetic presumably sedimentary rocks west of the Ellsworth Mountains. Jankowski and Drewry (1981) also indicated several-kilometer-thick sedimentary rocks in this area on the basis of

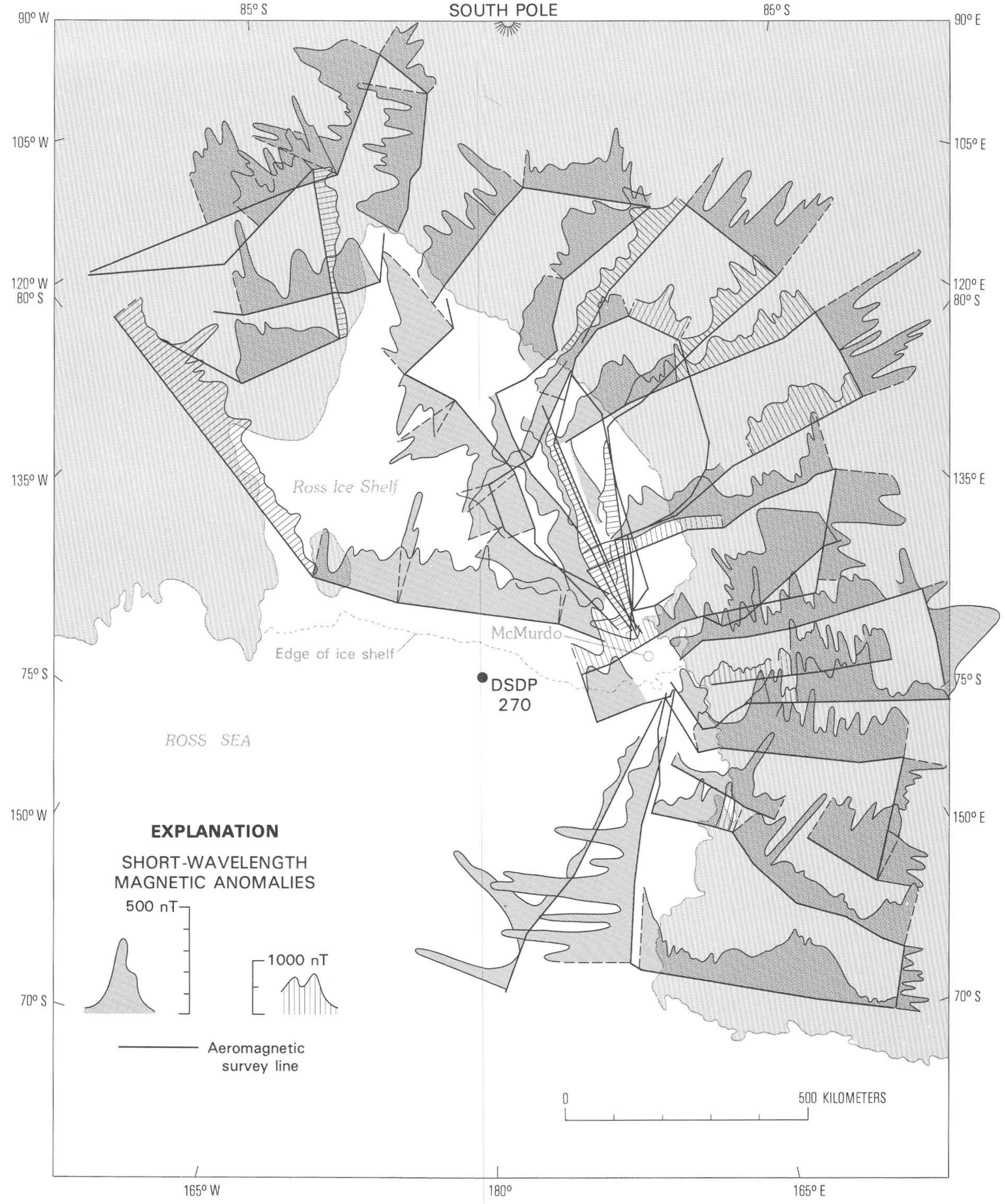

FIGURE 5.—Magnetic anomalies along aeromagnetic track lines flown in 1963–64 over the Ross Ice Shelf and adjacent parts of the Transantarctic Mountains. Turns on flight lines are indicated by dashed lines on magnetic profiles. Drillhole is indicated at DSDP 270.

aeromagnetic and radio echo ice-sounding. Behrendt and others (1974) reported thick but undetermined amounts of sedimentary rock between the Pensacola and Ellsworth Mountains on the basis of unusually smooth magnetic profiles.

In the early 1960's, widely spaced aeromagnetic profiles were collected across the entire length of the Transantarctic Mountains (Behrendt, 1964b; Behrendt and Bentley, 1968). Figure 5 shows the locations of these profiles between longs 120° W. and 135° E. in the Ross Ice Shelf area. I reinterpreted the data shown in figure 5 using the method of Vacquier and others (1951) to obtain rough estimates of elevation of magnetic basement as shown in figure 6. For comparison, figure 7 shows the generalized bedrock elevation of the same area. Beneath the Ross Ice Shelf and the grounded ice sheet west of the Transantarctic Mountains, large areas of rock inferred to be sedimentary have thicknesses of 4–8 km or greater.

The R/V *Eltanin* collected magnetic profiles (Hayes and Davey, 1975) over the Ross Sea continental shelf (fig. 8) along with single-channel seismic reflection profiles, but Hayes and Davey did not attempt to calculate depth estimates because temporal variations in the magnetic field relative to the slow ship speed made it difficult to separate temporal from spatial anomalies. The anomalies I determined by the aeromagnetic method are not as sensitive to distortion by temporal variation because of much higher aircraft speeds. Nevertheless, the 200-nT-contour magnetic anomaly map (fig. 8) published by Hayes and Davey (1975) is not inconsistent with several kilometers of sedimentary rock beneath the continental shelf as suggested in figure 6 for areas beneath the Ross Ice Shelf.

In the past 5 years, geophysicists from the U.S.S.R. have collected substantial aeromagnetic data in the Filchner and Ronne Ice shelf areas south of the Weddell Sea (Masolov, 1980). His data suggest a 12–15 km thickness of sedimentary rock beneath the continental shelf in that area (Masolov, 1980). The BAS (British Antarctic Survey) has also begun a program of aeromagnetic survey flights over the Ronne Ice Shelf, results of which are consistent with thicknesses of 14 or 15 km of sedimentary rock (G. Renner, personal commun., 1981). Thus, it appears that the area beneath the Ronne Ice Shelf and the continental margin bordering the Weddell Sea to the north may be underlain by a thick section of sedimentary rock.

The results from magnetic surveys in West Antarctica discussed previously suggest that several kilometers of sedimentary rock occur beneath the ice sheet and continental shelves. By analogy to sedimentary basins in other continents and the known geology of West Antarctica, we might expect Cretaceous and Tertiary rocks to constitute a substantial part of the unexposed sedimentary section. Because several kilometers of Paleozoic and older sedimentary rock are exposed in the Ellsworth Mountains, sedimentary rocks of this age may also underlie the Ronne Ice Shelf (fig. 1). Bibby (1966) reported that Cretaceous sandstone crops out at the north end of the Antarctic Peninsula and that a few outcrops of sedimentary rocks of Tertiary age are also found there. Rocks of Early Cretaceous age do occur beneath the narrow continental shelf of East Antarctica at about long 147° W. (Domack and others, 1980). Near long 95° E. there is evidence of Early to Late Permian, Late Jurassic to mid-Cretaceous, and Late Cretaceous to early Tertiary age sediments (Truswell, 1982). There are indications of Early Cretaceous, and Late Cretaceous to early Tertiary sequences on the continental shelf and slope near longs 130° E.–135° E. and about long 145° E. (Truswell, 1982). Truswell (1982) pointed out that the sequence near long 95° E. (Shackleton Ice Shelf area) probably has faced the Indian Ocean since Mesozoic time, whereas the other two Cretaceous sequences occur at points conjugate to the Great Australian Bight Basin and Otway Basin in Australia. Precambrian, Paleozoic, and early Mesozoic sedimentary rocks crop out in the mountains throughout West Antarctica and along the Transantarctic Mountains, but these rocks are mostly metamorphosed, or fractured and intruded by dikes and sills. The most promising areas for petroleum resources in a frontier region like Antarctica would seem to be those with younger (that is, Cretaceous and Tertiary age) rocks.

Since 1976, ships from Norway (Haugland and others, 1983; Fossum and others, 1982), the Federal Republic of Germany (Hinz, 1982), and the U.S.S.R. (G. E. Grikurov, written commun., 1982) have collected multichannel seismic reflection profiles over the continental margin in the Weddell Sea area. In 1976–77, the NARE (Norwegian Antarctic Research Expedition) acquired 16-channel data along tracks shown in figure 9 (Fossum and others, 1982). The profile across the Crary Trough (fig. 10; southernmost profile in fig. 9), which extends beneath the Filchner Ice Shelf

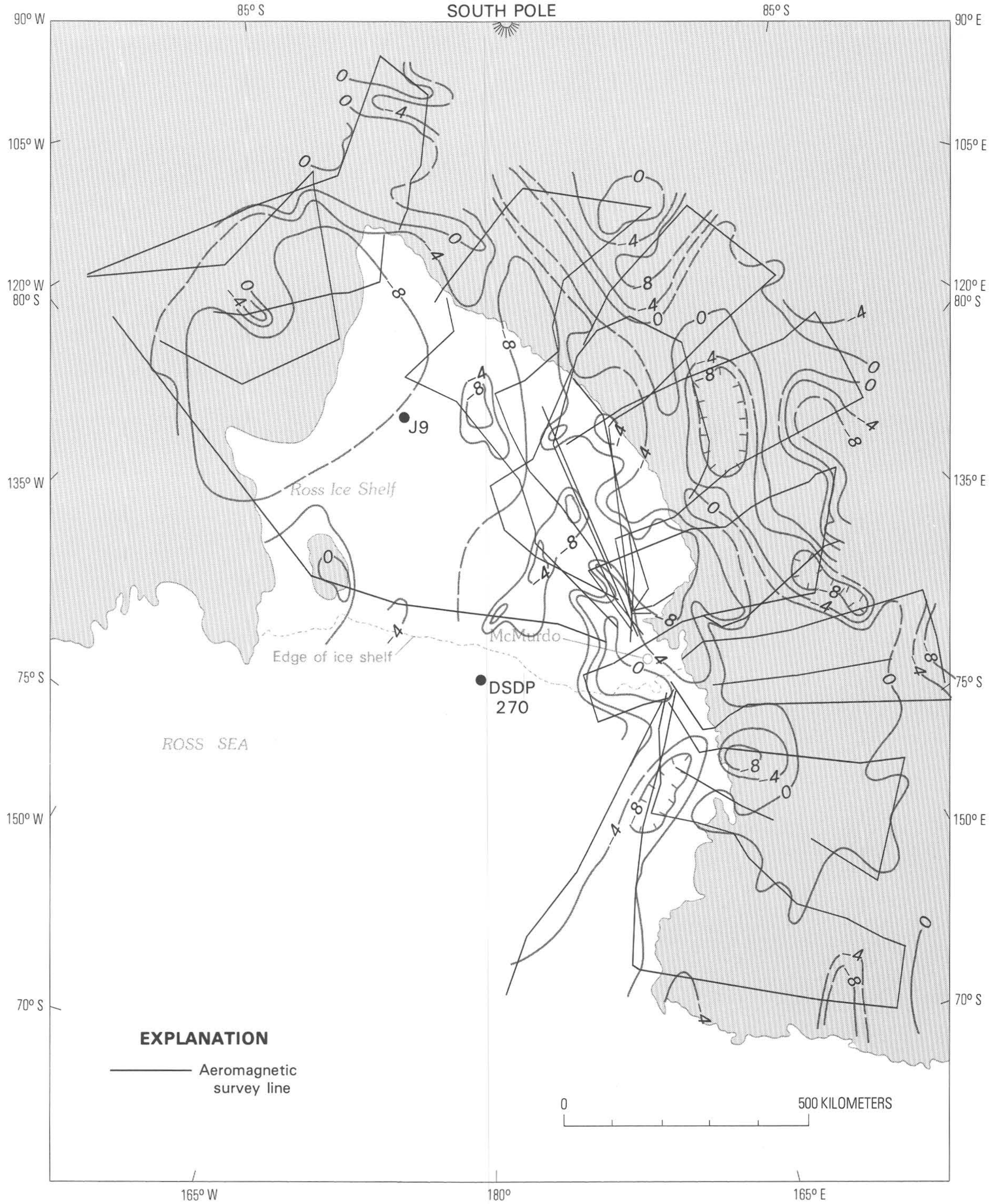

FIGURE 6.—Contour map showing estimated depth to magnetic basement on the basis of magnetic profiles shown in figure 5. Drill holes are indicated at DSDP 270 and J9. Contour interval 4 km; dashed where least certain. Hachures indicate closed "low".

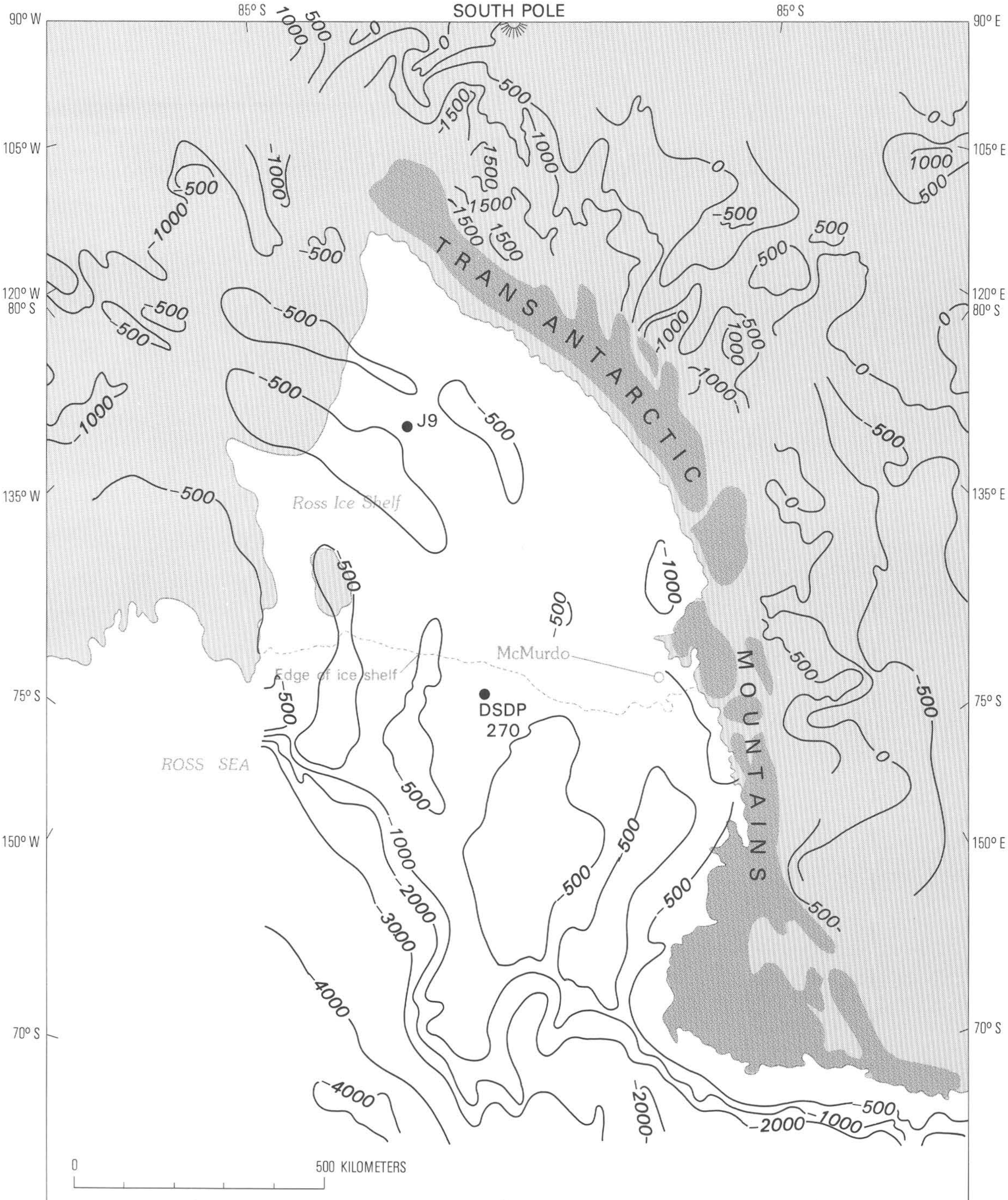

FIGURE 7.—Bedrock elevations of area shown in figures 5 and 6. Contours were generalized from Drewry (1975), Clough and Hansen (1979), and Bentley and Jezek (1981). Drill holes are indicated at DSDP 270 and J9. Contours indicated in meters.

(Haugland and others 1983, and Yngve Kristofferson, written commun., 1983). The west-dipping reflections are consistent with the thick section of sedimentary rock inferred from aeromagnetic data (Masolov, 1982) in the western Weddell Sea continental shelf and Ronne Ice Shelf area discussed in the preceding. Additional profiles were collected by NARE in 1978–79 (Haugland and others, 1983) in the same area.

In 1978, the BGR (Federal Institute for Geosciences and Natural Resources) of the Federal Republic of Germany collected 5854 km of 48-channel data over the continental shelf between longs 25° W. and 20° E., as shown in figure 11 (Hinz, 1982). Hinz reported the "Explora wedge" of seaward-dipping relectors having seismic velocities >4.5 km/s to be overlain by sediments as much as 3–5.2 km thick having velocities of 1.6–3.6 km/s. These lower velocities seem reasonable for Tertiary or possibly Late Cretaceous age rocks. Hinz (1982) interpreted the >4.5-km/s, seaward-dipping reflectors as evidence of volcanic layers rather than

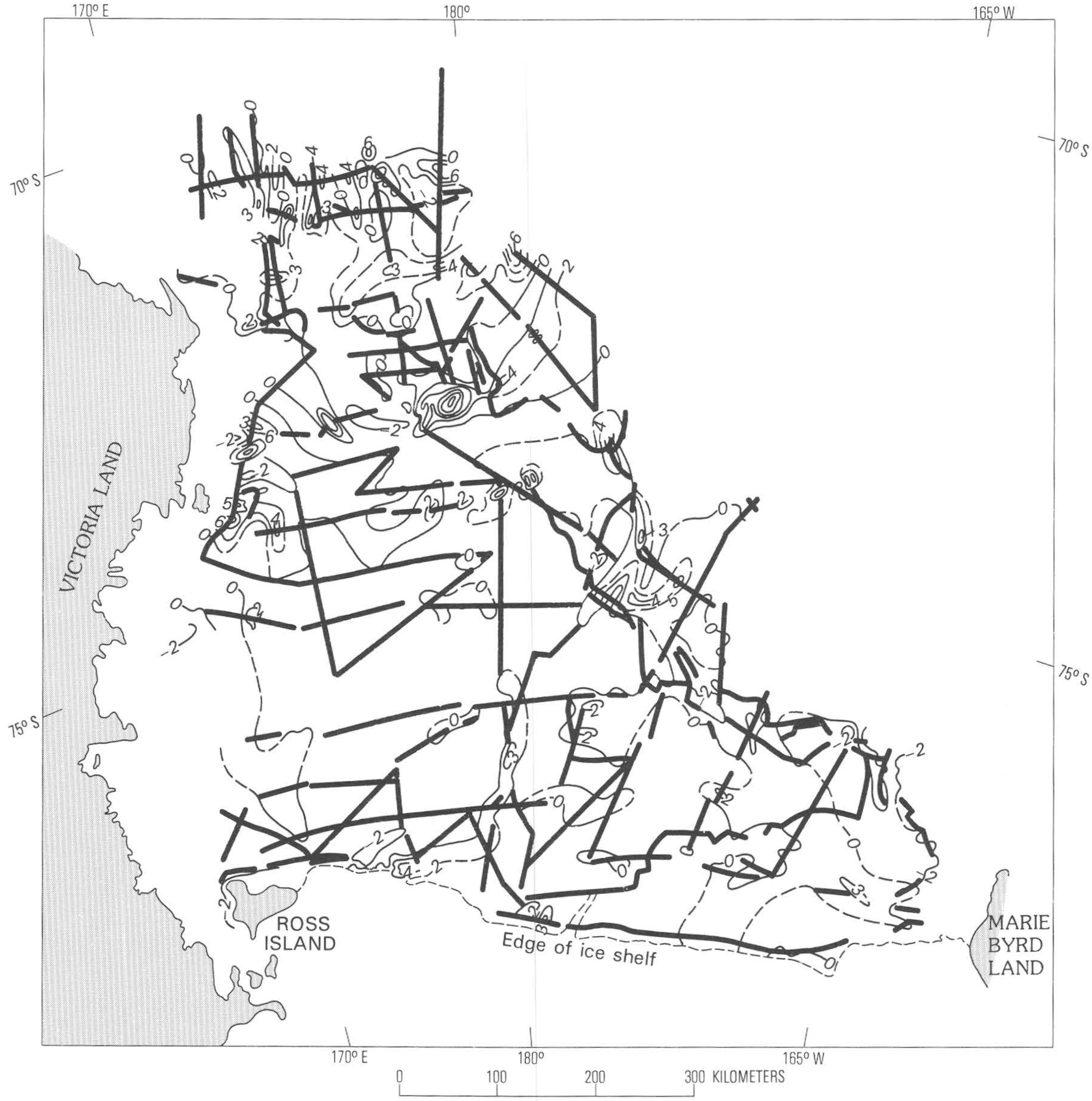

FIGURE 8.—Contour map of magnetic intensity along R/V *Eltanin* cruise tracks (heavy line) in the Ross Sea. Contours indicate multiples of 200 nT. Dashed lines indicate uncertainty. (From Hayes and Davey, 1975.)

sedimentary rock, and therefore inferred a low petroleum potential for the continental margin in this area. Figure 12 shows examples of profiles from Hinz's (1982) report. Neither the 1976 NARE or the 1978 BGR expeditions penetrated the heavy pack ice of the Weddell Sea north of the Ronne Ice Shelf where the magnetic data referred to on page 9 suggested a 12–15 km depth to magnetic basement. The U.S.S.R. collected 12-channel seismic reflection data (G. E. Gikurov, written commun., 1982) partly over this area along the tracks shown in figure 13 between longs 15° W. and 60° W. from 1980 to 1982, but no results are available.

In 1981–82, the R/V *Hakurei-Maru* from the JNOC (Japan National Oil Corporation) collected 24-channel reflection profiles in the southern Weddell Sea along the tracks shown in figure 14

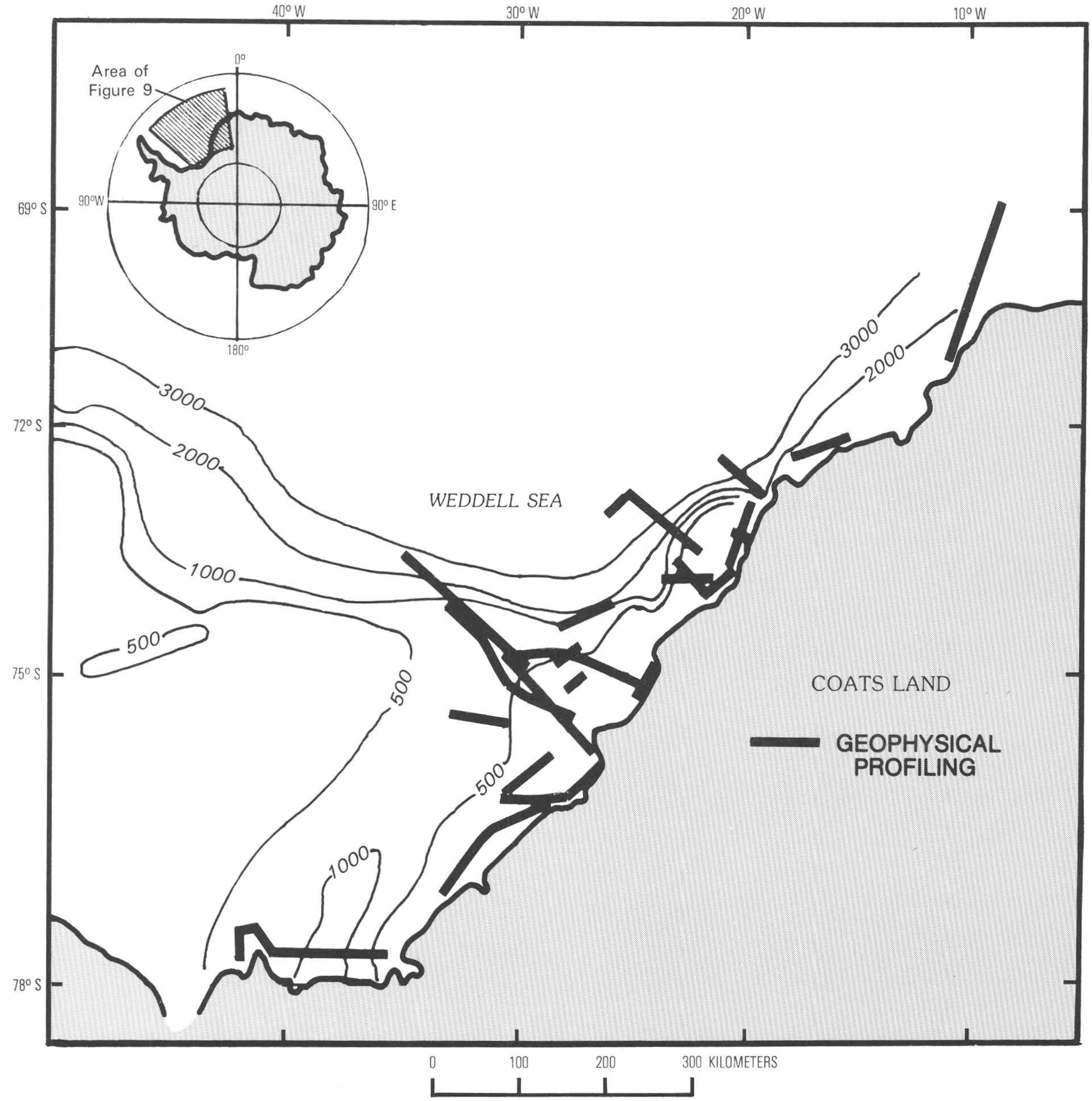

FIGURE 9.—Ship (*Polarsirkel*) tracks (heavy line) over the Weddell Sea continental margin along which multichannel seismic and other geophysical data were collected in 1976–77 by NARE. Bathymetric contours indicated in meters. (Modified from Fossum and others, 1982.)

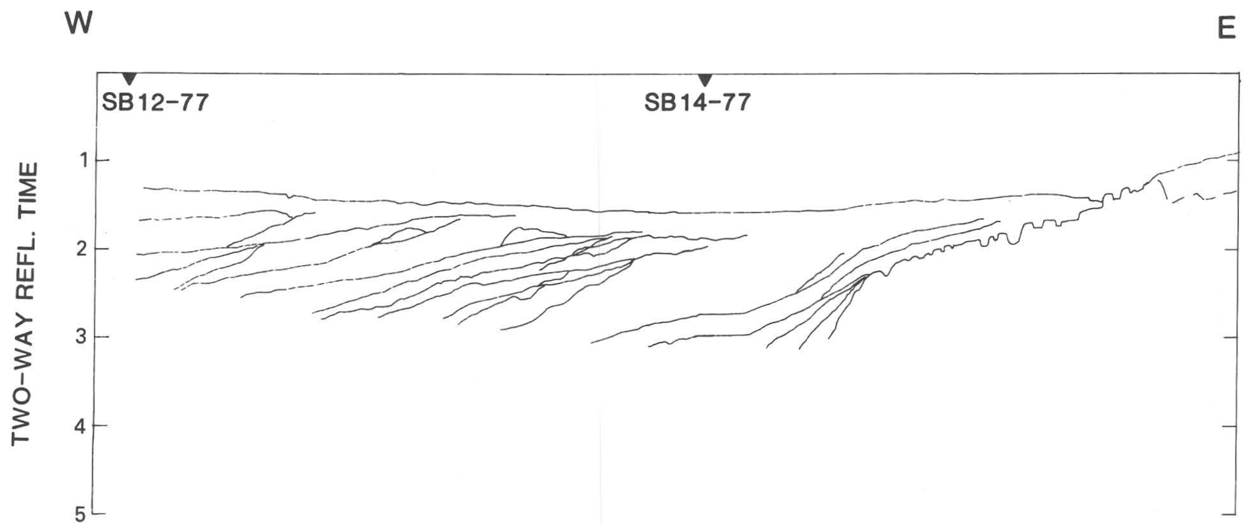

FIGURE 10.—Seismic-record section across the Crary Trough (southernmost profile in fig. 9). From Haugland and others (1983). Kindly furnished by Yngve Kristoffersen. SB, sonobuoy location. Length of profile, 150 km. Reflection time in seconds.

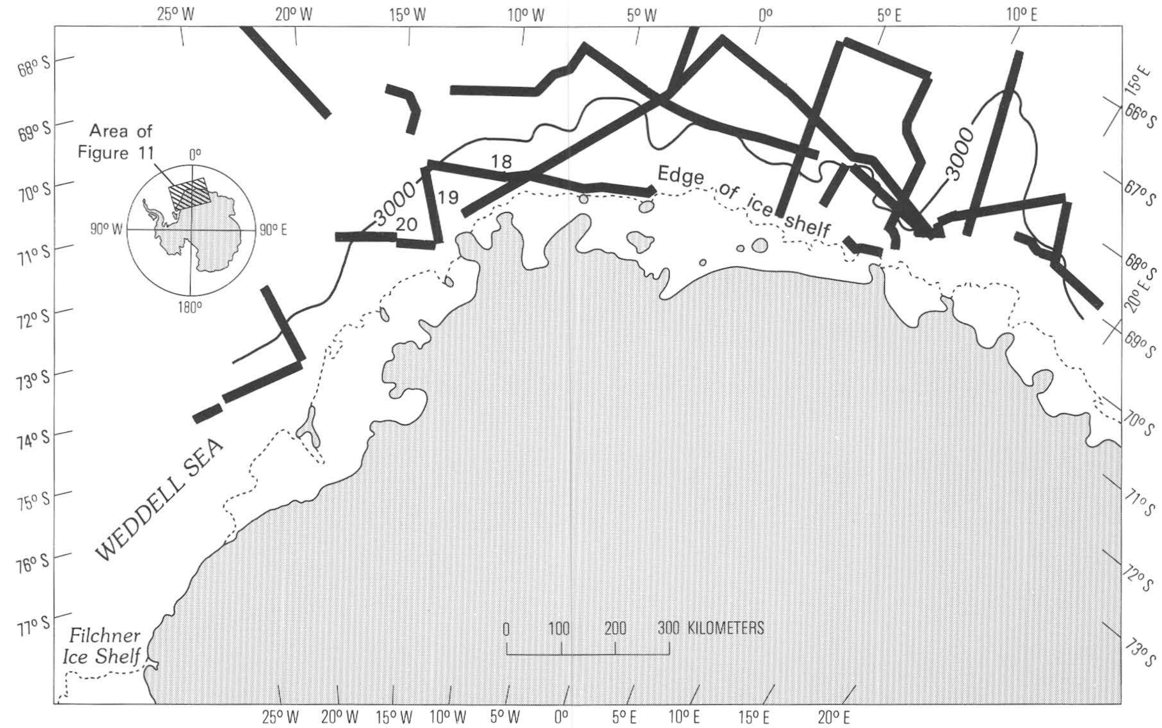

FIGURE 11.—Ship (*Explora*) tracks (heavy line) over the Weddell Sea continental margin along which multichannel seismic and other geophysical data were collected by the BGR in 1978. Bathymetric contour in meters. (Modified from Hinz, 1982.)

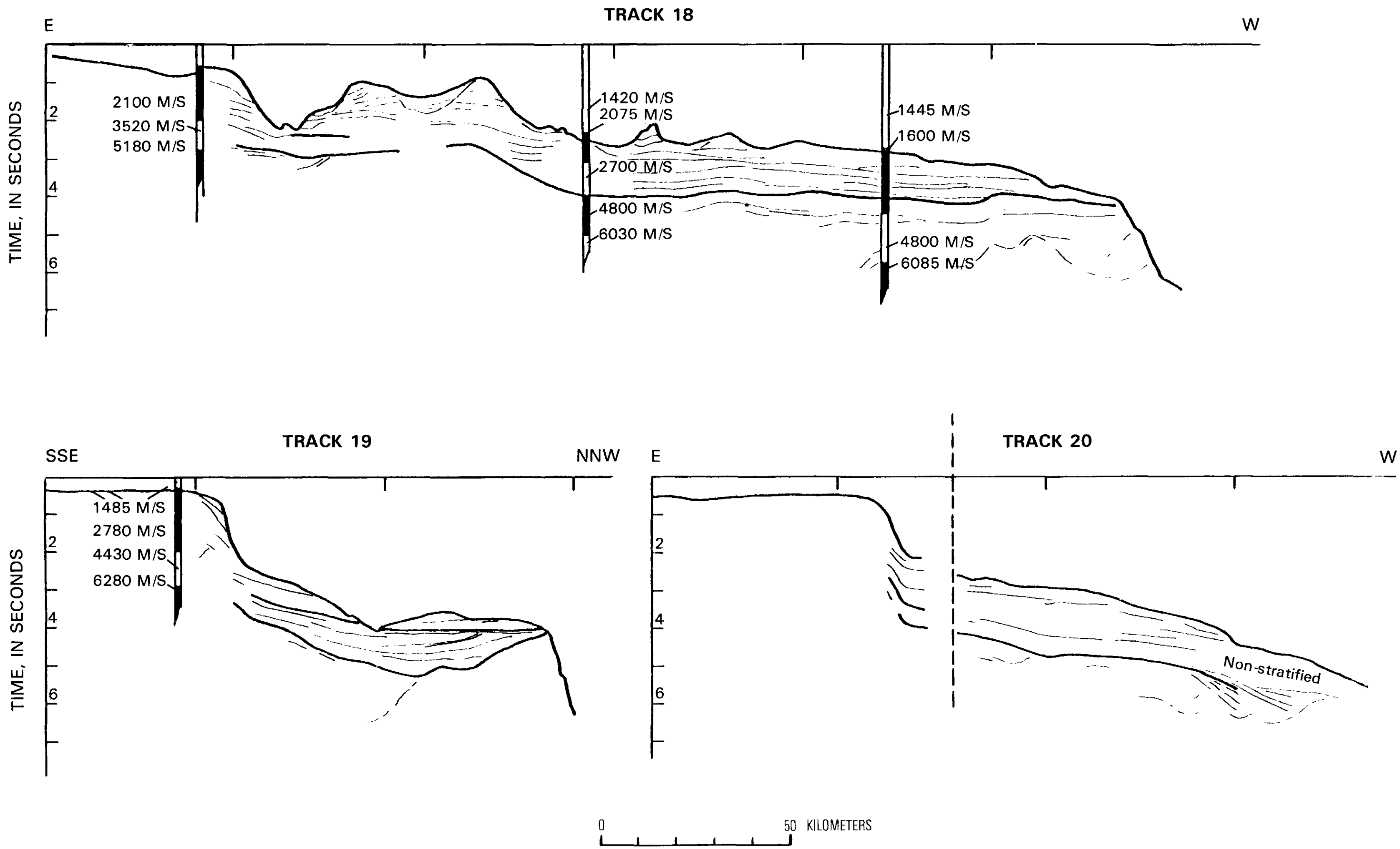

FIGURE 12.—Three examples of interpreted profiles from seismic reflection data along tracks of figure 11. Vertical lines are locations where velocities were determined by sonobuoys. Vertical dashed line indicates jogin track. (Modified from Hinz, 1982.)

(Okuda and others, 1983), which is the same area as that of the BGR data shown in figure 11. Their preliminary interpretation indicates about a 1.0–s time thickness of sedimentary rock on the continental slope near long 5° W., which would be equal to 1.5 km for an assumed velocity of 3 km/s.

In 1980, the BGR acquired 6745 km of 48-channel data over the Ross Sea continental shelf (fig. 15) (Fritsch, 1980). These data cover the same general area as the *Eltanin* cruise track (along which single-channel data were obtained) shown in figure 8. Fritsch (1980) reported that two discontinuities were found in the eastern part of the Ross Sea continental shelf, which he could correlate with upper Miocene-lower Pliocene and middle Miocene-upper Miocene contacts recognized in the DSDP core holes. He reported a structural high along about the 180° meridian, which divides the Ross Sea into two geologic provinces. His data processing is not completed and a maximum sedimentary rock thickness is not available, but at least several kilometers are suggested. In 1981–82 the IFP (Institut Francais du Petrol), also using the same ship *Explora*, collected about 1500 km of 48-channel data in the Ross Sea area; the ship tracks are shown in figure 15 (J. Wannesson, written commun., 1982). No results from this work are available. Davey and others (1982) reported sedimentary basins in the Ross Sea on the basis of data from seismic refraction and variable angle reflection measurements using sonobuoys in 1980–81. These results indicate three major basins with sedimentary rock thickness exceeding 4 km in the central trough basin along about the 175° E. meridian west of the ridge reported by Fritsch (1980). In 1983, the JNOC ship *Hakurei-Maru* also col-

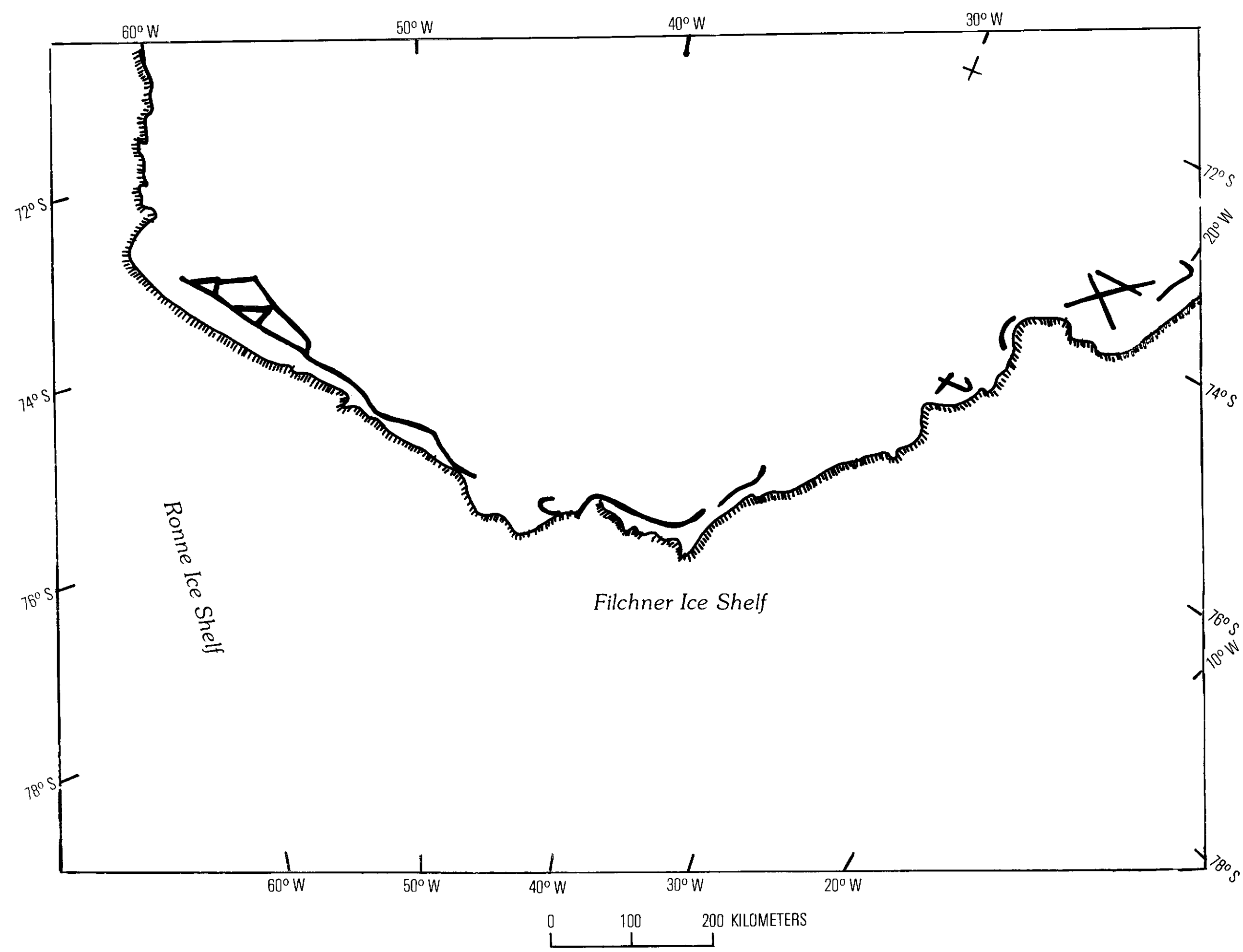

FIGURE 13.—Ship tracks (heavy line) in the Weddell Sea along which 12-channel seismic reflection data were collected by U.S.S.R. from 1980 to 1982 (G. E. Grikurov, written commun., 1982).

lected multichannel reflection profiles in the Ross Sea area, but no results are known.

In the 1981–82 season, *Explora* collected 48-channel relection data for IFP along the approximately 3000 km of tracks shown in figure 16 between longs 135° E. and 155° E. over the East Antarctic continental margin (J. Wannesson, written commun., 1982) near Adélie Land. No results are available yet.

The JNOC ship *Hakurei-Maru* collected more than 3280 km of 12-channel (3-fold) reflection data in the Bellingshausen Sea area in 1981 (Kimura, 1982) along the tracks shown in figure 17. Kimura (1982) reported that maximum sedimentary rock thickness (about 3 s or about 3–3.5 km) is greatest in the site of a paleo-trench lower-slope complex and decreases both seaward and landward.

The BMR (Australian Bureau of Mineral Resources) collected about 5000 km of 6-channel reflection data on closely spaced tracks over the continental margin in the area offshore of the Amery Ice Shelf (fig. 1) during 1981–1982 between longs 55° E. and 80° E. (R. J. Tingey, oral commun., 1982). No results of this work are available. The BMR survey should provide interesting information on this area in East Antarctica, which is the most favorable for petroleum resources.

DRILLING STUDIES

The *Glomar Challenger* drilled a series of holes on Leg 28 of the DSDP from December 22 to February 16, 1973 (fig. 18) in the Antarctic area (Shipboard Scientific Party, 1975). Of these, Sites 270, 271, 272, and 273 were drilled beneath the continental shelf at the thinnest part of the sedimentary wedge and are relevant to the evaluation for petroleum resources. The most significant results of this work are summarized in the initial reports (Shipboard Scientific Party, 1975). Results from these four holes (fig. 19) showed a Paleozoic continental basement overlain by a section of early Oligocene to late Miocene, Pliocene, and Pleistocene rocks.

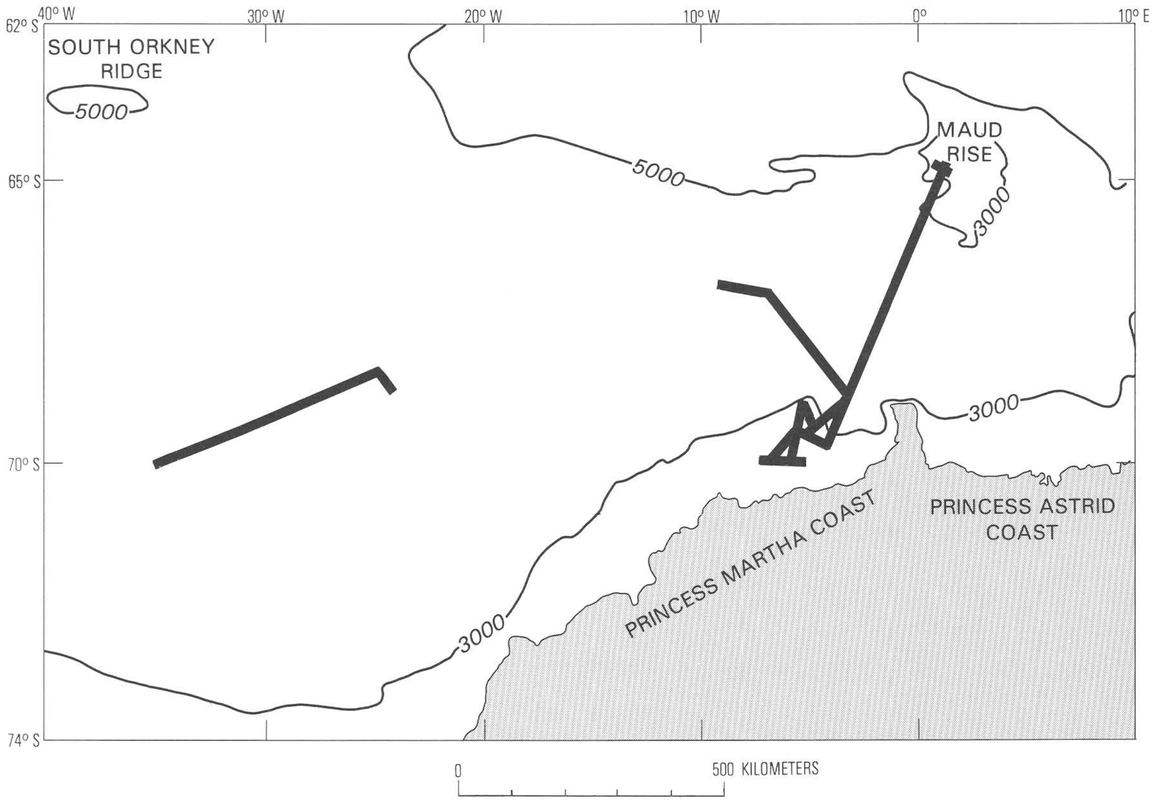

FIGURE 14.—Ship (*Hakurei-Maru*) tracks (heavy line) in the Weddell Sea along which 24-channel seismic, gravity, and magnetic data were collected by Japan in 1981–82. The 3000- and 5000-m bathymetric contours are indicated. (Modified from Okuda and others, 1983.)

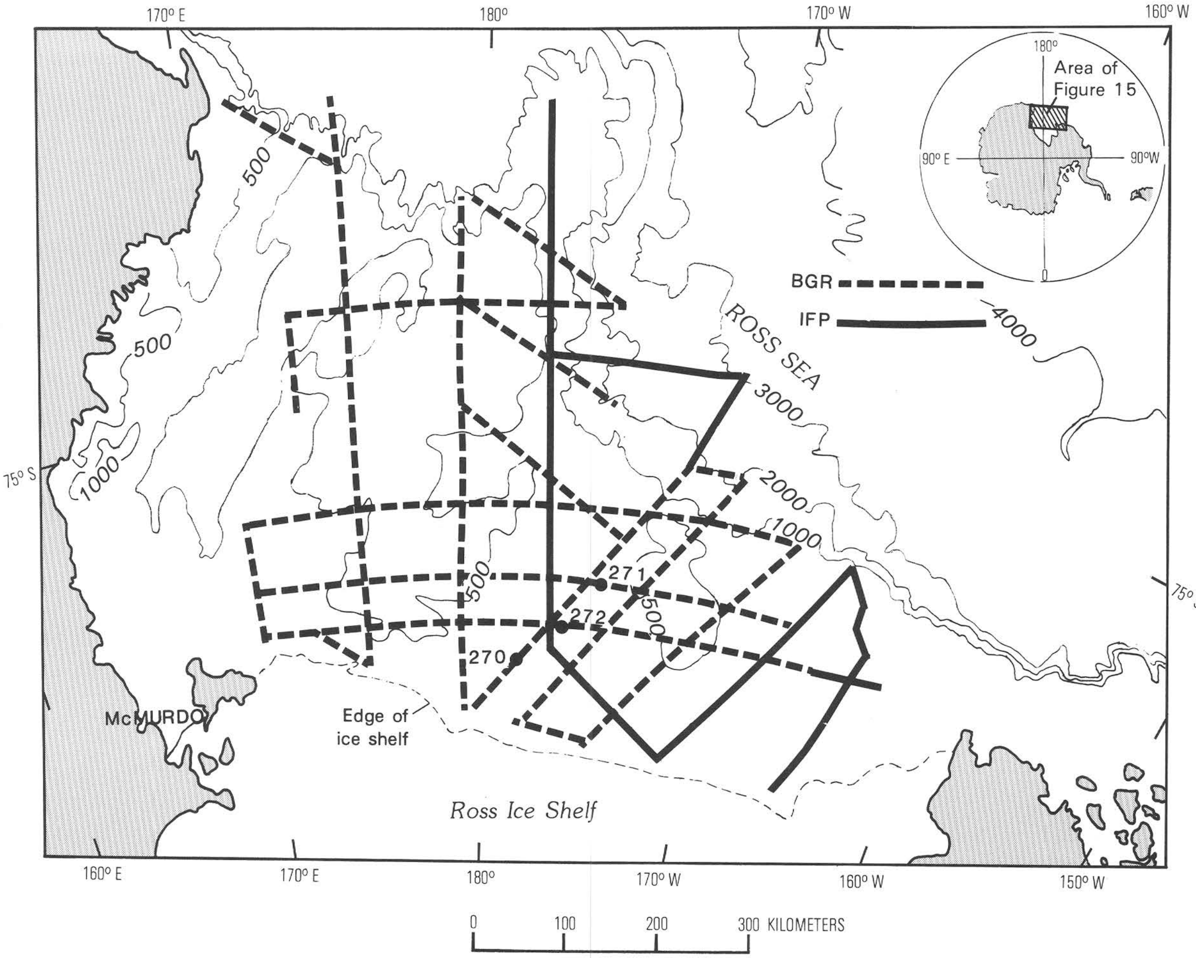

FIGURE 15.—Ship (*Explora*) tracks (heavy line) over the continental shelf in the Ross Sea area along which 48-channel and other geophysical data were collected in 1980 by the BGR (from Fritsch, 1980) and in 1981–82 by the IFP (J. Wannesson, written commun. 1982). DSDP holes 270, 271, and 272 are indicated from Hayes and Frakes (1975). Bathymetric contours indicated in meters.

Although small amounts of methane and ethane were reported in parts of the dominantly nonmarine Miocene sedimentary rock (Shipboard Scientific Party, 1975), the authors considered it premature to attach any economic significance to the hydrocarbons. McIver (1975) also analyzed samples from the cores of Sites 271, 272, and 273. He reported significantly higher amounts of ethane and heavier homologs in these samples than from others collected in the DSDP. He suggested this as evidence of local organic diagenesis. These provocative results must be considered cautiously until further drilling takes place.

Leg 35 of DSDP in the Antarctic area did not drill on the continental shelf or slope, and thus does not have a direct bearing on the petroleum resource question. However, leg 35 provides a great deal of data on the Paleogene and Neogene climate in Antarctica (Shipboard Scientific Party, 1976).

DISCUSSION

Various reconstructions of Gondwanaland have been published, and the position of Antarctica is basically similar in all. For the purpose of this report, that of Craddock (1969) shown in figure 4 is most useful. The tectonic relationships of West Antarctica are complex subsequent to rifting (Dalziel and Elliot, 1982), which was probably initiated in Jurassic time, as suggested by the ages from 163–179 m.y. of the Ferrar Dolerite and correlative intrusions found along the Transantarctic

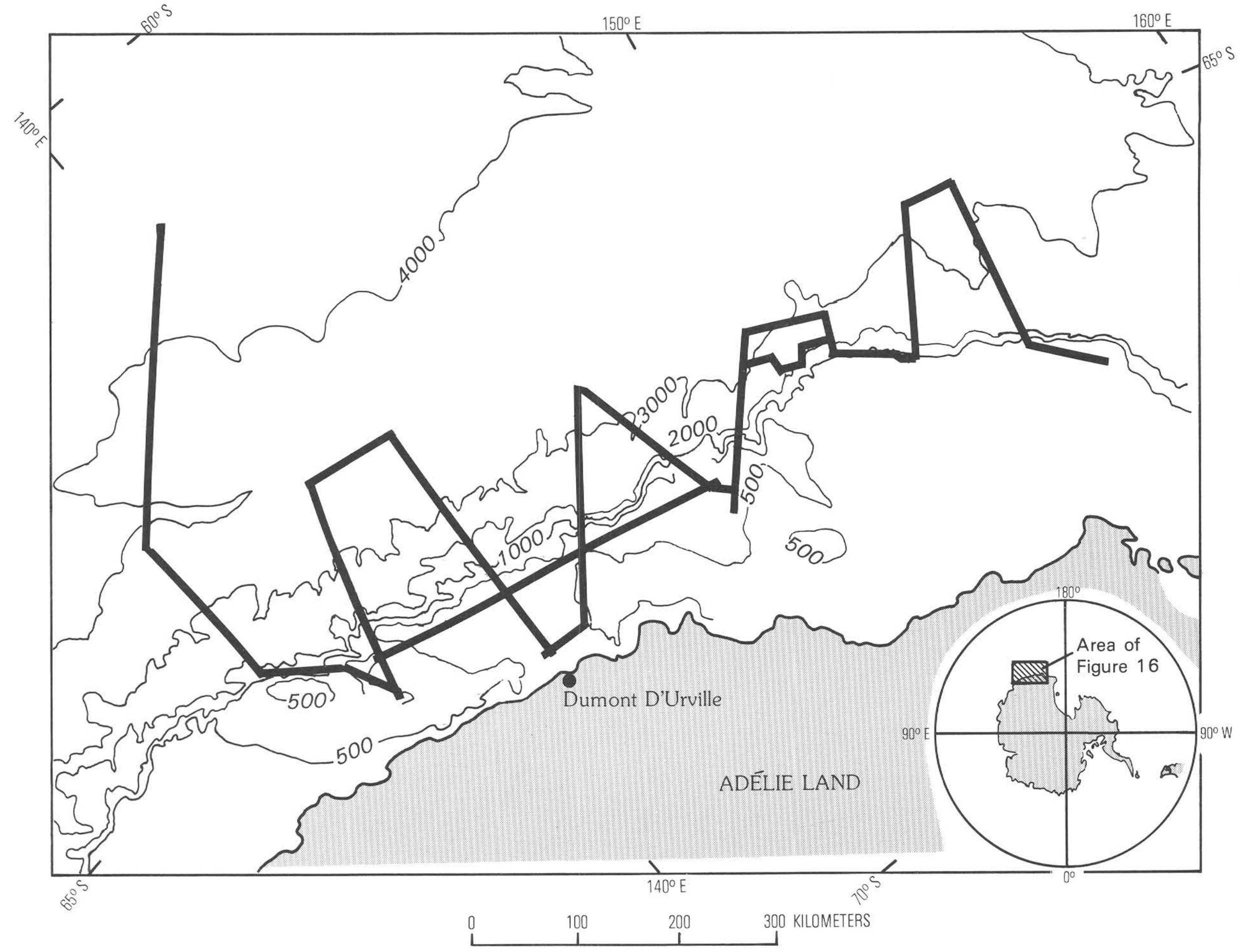

FIGURE 16.—Ship (*Explora*) tracks (heavy line) over the continental shelf of East Antarctica along which IFP collected 48-channel seismic reflection data in 1981–82. Bathymetric contours indicated in meters. (From J. Wannesson, written commun., 1982.)

Mountains (Grindley, 1963; Elliot, 1970; Ford and Kistler, 1980). The limited geophysical data discussed in this report and general geologic considerations suggest that the continental shelves of the Ross, Bellingshausen, Amundsen, and Weddell Seas, including areas covered by ice shelves and large areas of the Byrd subglacial basin (fig. 1), contain sections of Cretaceous and Tertiary sedimentary rock several kilometers thick. Large areas beneath the ice sheet in East Antarctica such as the Wilkes subglacial basin (fig. 1) are also probably underlain by several kilometers of sedimentary rocks of similar ages, as suggested by the magnetic depth estimates in figure 6. The Antarctic continental shelf east of about long 90° E. can be expected to have parallels with Australia's southern margin in breakup (late Mesozoic) and early Cenozoic sequences. Distinct differences are probable between Antarctica and Australia, particularly in strata deposited after the Oligocene/Miocene onset of Antarctic glaciation, by which time Australia and Antarctica were widely separated. West of long 90° E., the Antarctic continental shelf could be expected in pre-breakup strata to have similarities to the Indian and West Australian continental margins.

Data are insufficient to predict which of the areas along the West Antarctic continental margin might be the most likely for petroleum resources. Wright and Williams (1974) suggested that the Ross Sea continental shelf may contain more oil and gas than the Weddell Sea shelf because of the Ross Sea shelf's affinities with the Gippsland Basin of Australia, which in 1974 had proved reserves of 345 million tons (about 2.5 billion bbl) of oil and 220 billion m^3 of gas. Cameron (1981) pointed out that the Gippsland Basin is not part of the southern Australian marginal rift and therefore has no direct analog on the Antarctic margin. On the other hand, the probable greater thickness of sedimentary rock beneath the Weddell Sea shelf might make this area the most promising location for petroleum deposits in Antarctica (despite small amounts of oil and gas produced to date from the adjacent margins in South America and Africa in the Gondwanaland reconstruction). Little or no information is available on the Bellingshausen and Amundsen Sea's shelves to allow speculation of their petroleum resources potential relative to the Ross and Weddell Sea's shelves.

The specific questions relating to presence or absence of source rocks, organic material, reservoir rocks, seals, and structures favorable for hydrocarbon accumulation in West Antarctica cannot be answered now. No data are available on past geothermal gradients that might answer the question of whether there is sufficient maturation for genesis of petroleum. The presence of Tertiary and Quaternary volcanic activity beneath the Ross Sea shelf as suggested by the magnetic anomalies of figure 5 is well known in various areas of West Antarctica, and suggests that the regional heat flow in at least these areas is probably high. Further research drill holes such as those proposed for the "deceased" Ocean Margin Drilling Program (Davies and Hay, 1981) are needed to answer the general questions relating to petroleum geology. These will need to be preceded by much more geophysical data collection, such as the profile shown in figure 10 (Joint Oceanographic Institutions, 1981), to correctly site the drill holes.

ENVIRONMENTAL HAZARDS

Antarctica has the most severe environment on Earth in which to carry out petroleum exploration or exploitation. Were exploration and exploitation to occur, much research would be required into the types of hazards that might be encountered and the types of ecosystems that might be disturbed. Various groups (such as Group of Experts, 1977; Zumberge, 1979b; and Holdgate and Tinker, 1979) have attempted to deal with potential environmental problems and to suggest research

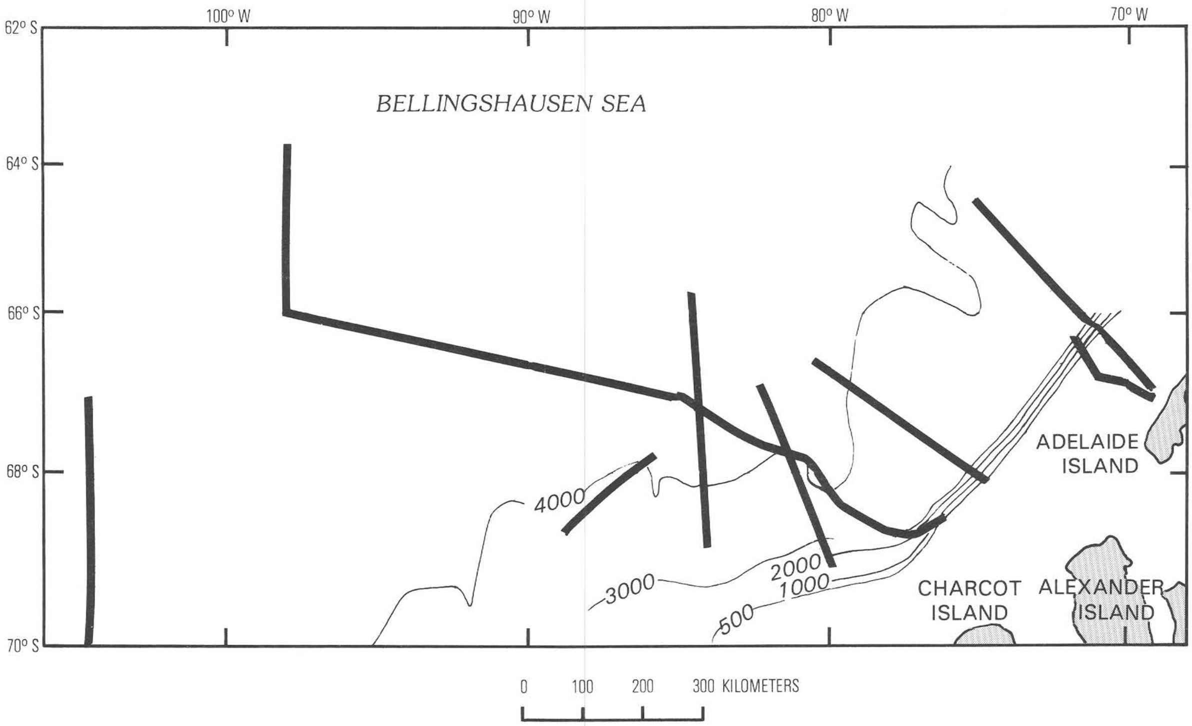

FIGURE 17.—Ship (*Hakurei-Maru*) tracks (heavy line) in the Bellingshausen Sea along which 12-channel seismic, gravity, and magnetic data were collected by Japan in 1980–81. Bathymetric contours indicated in meters. (From Kimura, 1982.)

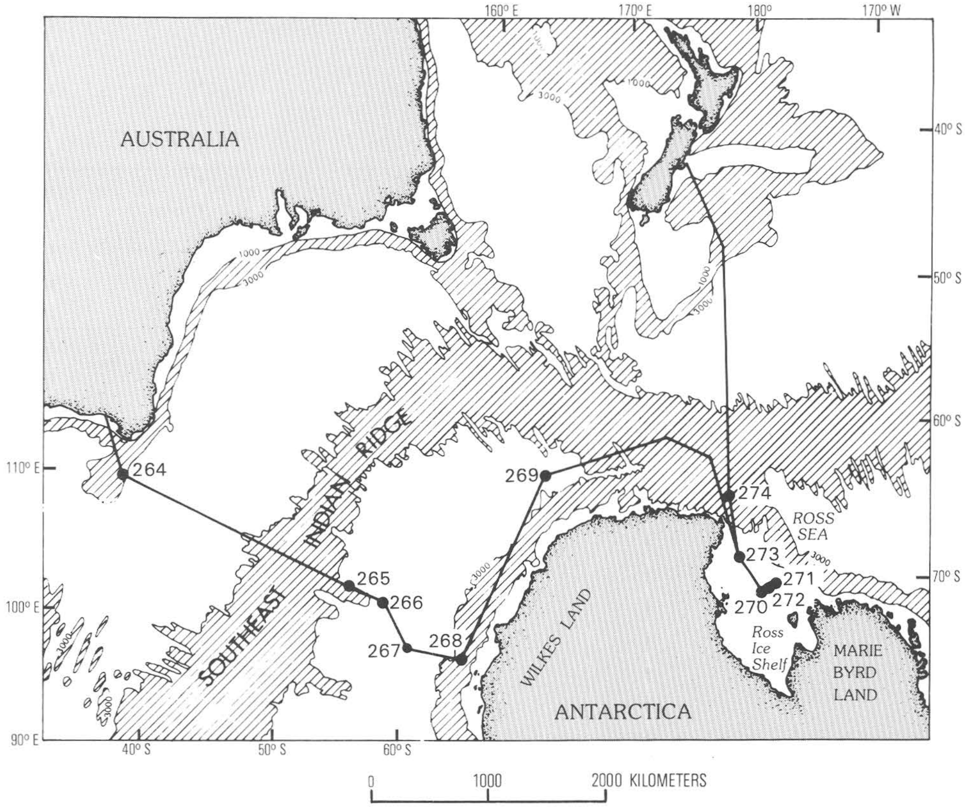

FIGURE 18.—Cruise track (heavy line) of *Glomar Challenger* DSDP leg 28, and locations of core holes in the Ross Sea. (From Hayes and Frakes, 1975.)

areas. Generally, these reports have concentrated on climatological, oceanographic, and glaciologic hazards and the fragile Antarctic ecosystems that might be affected, yet have largely ignored the geologic hazards that could actually lead to blowouts and oil spills.

Considering the expense incurred in Antarctic research, ships conducting the marine geophysical surveys for geologic framework studies should also collect as much data relative to environmental hazards as possible. Subsequently, as specific regions are delineated as possibly high in hydrocarbon potential, systematic programs of research into environmental hazards should be undertaken. For example, the Ross Sea area is attractive for future exploitation in that the area is largely free of ice in the austral summer, and geophysical data suggest a reasonably thick section of sedimentary rock. Therefore, it is generally considered the most probable area for early exploration. However, further research might exclude the entire area, or large parts of it, on the basis of results from geophysical surveys and research drill holes, long before other exploration leading to exploitation would have started.

Some of the specific studies needed from a physical-sciences standpoint (as opposed to the biological studies also necessary) are: the occurrence and frequency of icebergs, pack-ice conditions, weather, physical oceanography (relative to currents that might move icebergs or oil spills, or transport sediment along the sea bottom), sea-bed stability, evidence of iceberg scour, possible presence of permafrost or clathrate (Kvenvolden and McMenamin, 1980), and areas of slumping on steeper slopes. The Antarctic continental shelf is at a depth of about 500 m, or deeper than that of the other continents; this would have a strong bearing on the difficulty of exploratory or production drilling, subsea completion of oil wells, or risk from icebergs to subsea installations. A hole drilled through the Ross Ice Shelf (J9) (Clough and Hansen, 1979) demonstrated the feasibility of rapidly and repeatedly drilling large-diameter holes through moving ice shelves. The technology probably could be developed to keep such a hole open along a track as an ice shelf moved at a meter or so per day. The risks are obvious and one wonders at the difficulty of containing a blowout on the sea bottom beneath an ice shelf 250 m thick.

SUMMARY

Although no petroleum resources are known in Antarctica and the petroleum industry is not particularly interested at present (Ivanhoe, 1980), economic and political considerations may change the industry's interest in the next few years, and exploration and exploitation are possible within one or two decades. A number of countries are actively carrying out multichannel seismic reflection surveys of the Antarctic continental margin, as noted in this report, which are obviously focused on petroleum resource studies. Technology development will probably occur at a more rapid rate than research, exploration, and legal developments (Holdgate and Tinker, 1979; Dugger, 1978). The only types of potentially economically exploitable petroleum resources in Antarctica would be giant or supergiant fields—and probably only four to ten supergiants remain to be discovered in the world. In this report I have attempted to discuss some of the available information on potential petroleum resources in Antarctica, which can be summarized as follows.

1. West Antarctica is probably the most promising area of Antarctica for petroleum because it likely contains large areas of unmetamorphosed sedimentary rock of post-rift age. East Antarctica probably contains a number of subglacial sedimentary basins particularly adjacent to high mountain ranges and within the probable failed rift in the Amery Ice Shelf area.

2. Because of the moving grounded ice sheet several kilometers thick that covers most of Antarctica, the only practical areas for possible exploitation, were petroleum to exist, are the continental margins (possibly including the parts covered by ice shelves). The most probable areas for petroleum resources are those bordering the Ross, Amundsen, Bellingshausen, and Weddell Seas in West Antarctica, and the Amery Ice Shelf in East

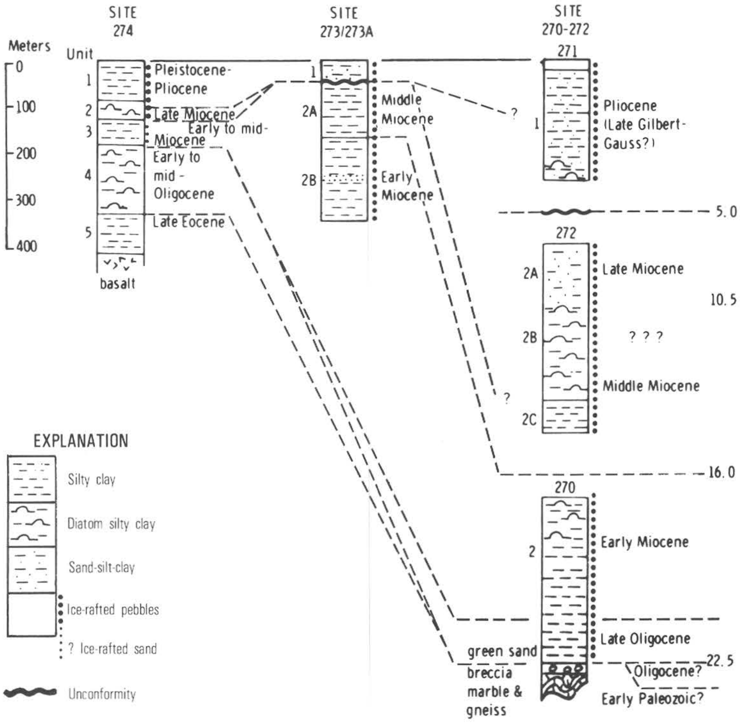

FIGURE 19.—Composite stratigraphic sections from DSDP sites 274, 273/273A, and 270–272 in the Ross Sea. Age in millions of years indicated at right. (From Hayes and Frakes, 1975.)

Antarctica.

3. The sparse geophysical data suggest that a >8-km-thick section of sedimentary rock occurs beneath the Ross Sea continental shelf and a 14- to 15-km-thick section beneath the Weddell Sea continental shelf. The Bellingshausen Basin probably contains >3 km of sedimentary rock. No information is available on sedimentary rock thickness beneath the continental shelves bordering the Amundsen Sea and Amery Ice Shelf area at this time.

4. DSDP holes on the Ross Sea continental shelf indicate the presence of rocks from Oligocene to Pleistocene in age. Sedimentary rocks of Cretaceous or possibly Jurassic age might be present in the deepest parts of the section indicated by seismic reflection data and depths estimated from aeromagnetic data. Jurassic, Cretaceous, and Tertiary sedimentary rocks are probably present beneath the continental shelf and adjacent glacierized areas of East Antarctica on the basis of the analysis of a number of samples by several investigators.

5. No direct information is available on the petroleum geology beneath Antarctic continental shelves, with the possible exception of the provocative and equivocal shows of gas reported in core holes beneath the Ross Sea continental shelf.

6. If future geophysical and geologic (deep-drilling) research were to indicate certain areas as being worthy of exploration, programs of environmental research would be necessary to study possible meteorological, glaciological, oceanographic, and geologic hazards that might be encountered which would adversely affect future exploration or exploitation. Concomitant biological research programs into the fragile ecosystems that might be affected by possible blowouts or oil spills would also be required.

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Mineral Occurrences of Antarctica

By Peter D. Rowley, Paul L. Williams, and Douglas E. Pride[1]

Interest in the exploration and mining of metallic and nonmetallic minerals in Antarctica has increased steadily during the late 1970's and early 1980's as world demands for mineral resources have risen. A major reason for the interest has been numerous comparisons of parts of Antarctica with mineral-rich belts on Gondwana continents that formerly were connected with Antarctica; such comparisons have revealed many similarities. Numerous reports have summarized the mineral occurrences of Antarctica, including the following: Fermor (1951), Fairbridge (1952), Kosack (1955), Schnellmann (1955), Anonymous (1956), Chalmers (1957), Potter (1969), Runnels (1970), Smith (1972), Wright and Williams (1974), Ericksen (1976), Piper (1976), Quartino and Rinaldi (1976), Schofield (1976), Splettstoesser (1976), Wade (1976), Anonymous (1977), Cheeseright (1977), Elliot (1977), Ferrán (1977), Law (1977), Mitchell (1977), Scientific Committee on Antarctic Research (1977), Dugger (1978), Turner (1978), Zegarelli (1978), Anonymous (1979), Kanehira (1979), Lovering and Prescott (1979), Rowley and Williams (1979), Zumberge (1979a, b), Ivanhoe (1980), Mitchell and Tinker (1980), Auburn (1982), Rowley and Pride (1982), Shapley (1982), Quigg (1983), Splettstoesser (1983), and Rowley (1983). Of these, the most comprehensive summary of mineral occurrences was that of Wright and Williams (1974). Kameveva and Grikurov (1983) and Rowley, Ford, and others (1983) tentatively defined the metallogenic provinces of Antarctica. This report summarizes the known occurrences of metallic and nonmetallic minerals on land in Antarctica and attempts to describe them within an overall framework of ore genesis. A similar report (Rowley and others, in press) is included in a volume, edited by J. F. Splettstoesser, that also discusses other types of mineral resources and the environmental implications of their development. Resources such as sand and gravel, manganese nodules on the ocean floor, icebergs for fresh water, and geothermal energy are discussed in some of the reports listed above. Oil and natural gas resources, which may be the first mineral resources to be exploited in Antarctica, are discussed by Behrendt (1983; this volume; in press).

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CONSTRAINTS TO MINERAL DEVELOPMENT

Largely ignored in the increased interest in Antarctic mineral resources are the physical and political constraints to development of an "ore body" in Antarctica. Weather forecasting is not highly developed in Antarctica. Mean land temperatures are much lower than those of any other large area of the Earth's surface, and winds generally are higher in velocity and more constant than elsewhere. The continent is far removed from potential markets and the surrounding waters are stormy and filled with pack ice and icebergs for most of the year. Port facilities and harbors where ports could be built are rare, and even if port facilities were constructed, few would be usable for more than 2 months per year. Icebreakers would be required for assistance during most ship trans portation. Land travel to the interior in most places is impaired by poorly accessible coastlines and by glaciers that are most strongly crevassed where they drop down the last pitch to the shoreline. Thus much of the transportation, especially from the interior of Antarctica, probably would have to be by aircraft. Because of the low temperatures and darkness, however, air transportation during most of the winter "night" would be dangerous at best.

Because of these many constraints, a study of the economics of hypothetical mining ventures (Elliot, 1977) found that it would cost about three times as much to recover hypothetical platinum from the Dufek intrusion (Ford and others, 1983; Ford, this volume; in press) as it would cost to recover an equal amount of platinum from a comparable orebody in the United States. The costs would be considerably higher for commodities such as iron and copper that have lower unit prices and thus larger transportation costs. Drastic increases in metal prices would be necessary to offset the economic liabilities of mineral development in Antarctica. Lacking such incentives, it is unlikely that private firms would invest in Antarctic mining ventures in the foreseeable future unless costs ceased to be a factor, perhaps as a result of war, collapse of the free market system, loss or potential loss of a supplier of some strategic metal, or some other disaster. Barring such calamities, projected world reserves indicate at least 50 years supply (Brobst and Pratt, 1973) elsewhere in the world for commodities identified in Antarctica.

Geologic constraints offer additional reasons to be cautious about the likelihood for development of mineral resources on land. Purely scientific investigations have dominated the geologic work in Antarctica; to date (1983) almost no detailed studies have been designed to explore for and characterize mineral deposits. Few chemical analyses of rock samples or unconsolidated sediment have been published. The nature and types of mineralized and altered rocks, including general geochemical patterns, are unknown for virtually the entire continent. No mineral occurrences have been explored by drilling techniques. In addition, the number of mineral deposits likely to be found in Antarctica is low because nearly 98 percent of the continent is covered by ice. (For an analysis of discovery probabilities, see Wright and Williams, 1974.) Furthermore, most of the exposed areas have been so little studied that they remain among the least geologically and geophysically explored parts of the world. Some large areas of rock exposures have never been visited, and most others are known by reconnaissance geologic mapping only. The logistics of transportation and supply commonly dominate decisions on where to go in the field; areas that deserve detailed study might not be accessible or may have to be studied hastily. Altered and mineralized rocks commonly are softer and subject to more rapid erosion than adjacent rocks, and thus are more likely to be in lowlands, now covered by ice. Furthermore, ice levels over most parts of Antarctica were much higher in Pleistocene and late Tertiary time, so most exposed bedrock has been deeply scoured by ice. Because ice has covered Antarctica during much of Cenozoic time, little surface drainage by running water has occurred there, and thus few alluvial sediments have been deposited. Therefore, prospecting by inspecting and analyzing alluvial sediments for upstream bedrock mineral deposits can rarely be used, and placer-type mineral deposits are not likely on the continent. Similarly, groundwater movement has been absent or restricted during most of Cenozoic time, and supergene enrichment deposits either never formed or have been removed by glacial erosion. Ore minerals will have to be recognized by their primary minerals and their alteration products.

The mineral deposits most likely to be exploited in Antarctica probably would be large-tonnage, low-grade types (for example, iron, copper, and coal). Therefore large volumes of ore would have to be exported or, more likely, milled or concentrated in Antarctica. The technology to mine on land in polar areas exists (Potter, 1969; Hall, 1975; Splettstoesser, 1976; Dugger, 1978; Zumberge, 1979a, b; Auburn, 1982), but the climate in Antarctica is much more severe than that encountered in any past or present mining venture. In addition, mining and milling activities require large energy supplies; the availability of adequate energy sources has not been studied in detail. Similarly, the effects of exploitation, construction, or mining on the environment are poorly known but are probably important obstacles to development.

Political problems offer additional formidable constraints to any exploitation of possible ore deposits in Antarctica. Antarctica is an international continent governed by the Antarctic Treaty. There are no provisions in the Antarctic Treaty that concern the recovery of minerals on the land areas or from the continental shelves (Scientific Committee on Antarctic Research, 1977; Alexander, 1978; Anonymous, 1979; Lovering and Prescott, 1979; Zumberge, 1979a, b; Mitchell and Tinker, 1980; Auburn, 1982; Quigg, 1983). International agreements concerning the exploitation of mineral resources may be reached in the near future, but until such time, we cannot speculate on what regulations or restrictions any such agreements might entail. It is unlikely that any private or government enterprise would be willing to commit large sums of money for exploration or development prior to establishment of international agreements on mineral rights and mineral exploitation.

Because of the numerous constraints to discovery and development of mineral deposits in Antarctica, it is unlikely that any such deposit will be economically developed for many years. Despite this conclusion, however, adequate knowledge of the mineral resource potential of Antarctica must be actively sought so that proper decisions can be made about the possible presence, distribution, and future use of these resources.

REGIONAL SETTING

For purposes of this report, a brief review of the regional geology of Antarctica—taken from Ford (1964), Dalziel and Elliot (1972), Craddock (1972, 1982), Rowley (1983), and others—is given here. Antarctica may be divided into two parts, East Antarctica and West Antarctica (fig. 20, inset), on the basis of differences in geology and topography. The rocks of East Antarctica are rarely exposed except along the coast and in the Transantarctic Mountains. East Antarctica is mostly a shield consisting largely of Archean "nuclei" craton blocks and surrounding belts of deformed Proterozoic rocks, all welded together in Proterozoic and perhaps early Paleozoic time during probable plate-tectonic processes. The shield of East Antarctica contains numerous mineral occurrences of many types, as do comparable shield rocks of most Gondwana continents formerly adjacent to East Antarctica. Deposits in Precambrian shields of these other continents include iron-formation and perhaps bedded manganese in Australia, India, and Africa; conglomeratic placer gold-uranium deposits of South Africa; chromite, nickel-copper, platinum, and magnetite-vanadium deposits of the stratiform Bushveld intrusion of Africa; copper-cobalt deposits of Zambia and Zaire; nickel deposits in intrusions in Australia; gold deposits in mafic volcanic rocks in Australia; lead-zinc-copper-silver deposits of Mount Isa and Broken Hill, Australia; and diamond-bearing kimberlite pipes (Cretaceous) of South Africa (Wright and Williams, 1974; Rowley, Ford, and others, 1983). Similar deposits might be expected in Antarctica.

The Transantarctic Mountains (Ross belt) are in large part underlain by Proterozoic and lower Paleozoic sedimentary, metamorphic, and igneous rocks that were folded and intruded during probable collisional plate-tectonic processes during Late Proterozoic and early Paleozoic deformation and magmatism. The igneous rocks and deformed rocks of East Antarctica are unconformably overlain locally by generally flat lying middle Paleozoic through lower Mesozoic sedimentary and igneous rocks of the Beacon Supergroup and Ferrar Group. These flat-lying rocks are especially widespread in the Transantarctic Mountains and locally may conceal mineral resources in the underlying rocks. In contrast to the East Antarctic shield, few mineral occurrences have been found in the Transantarctic Mountains. The Dufek Massif (Ford and others, 1983; Ford, this volume; in press) is one of the few areas in the Transantarctic Mountains that contains potentially important metal occurrences (iron and copper, and perhaps cobalt, chromium, and other metals). Suggestions as to what additional deposits might be present may be attained by looking at the Tasman fold belt of eastern and central Australia, which is geologically similar to the Transantarctic Mountains. In particular, the Adelaide part of the Tasman belt in central Australia may be correlative with some parts of the Transantarctic Mountains; the Adelaide area contains numerous deposits of copper and subordinate gold, lead, zinc, silver,

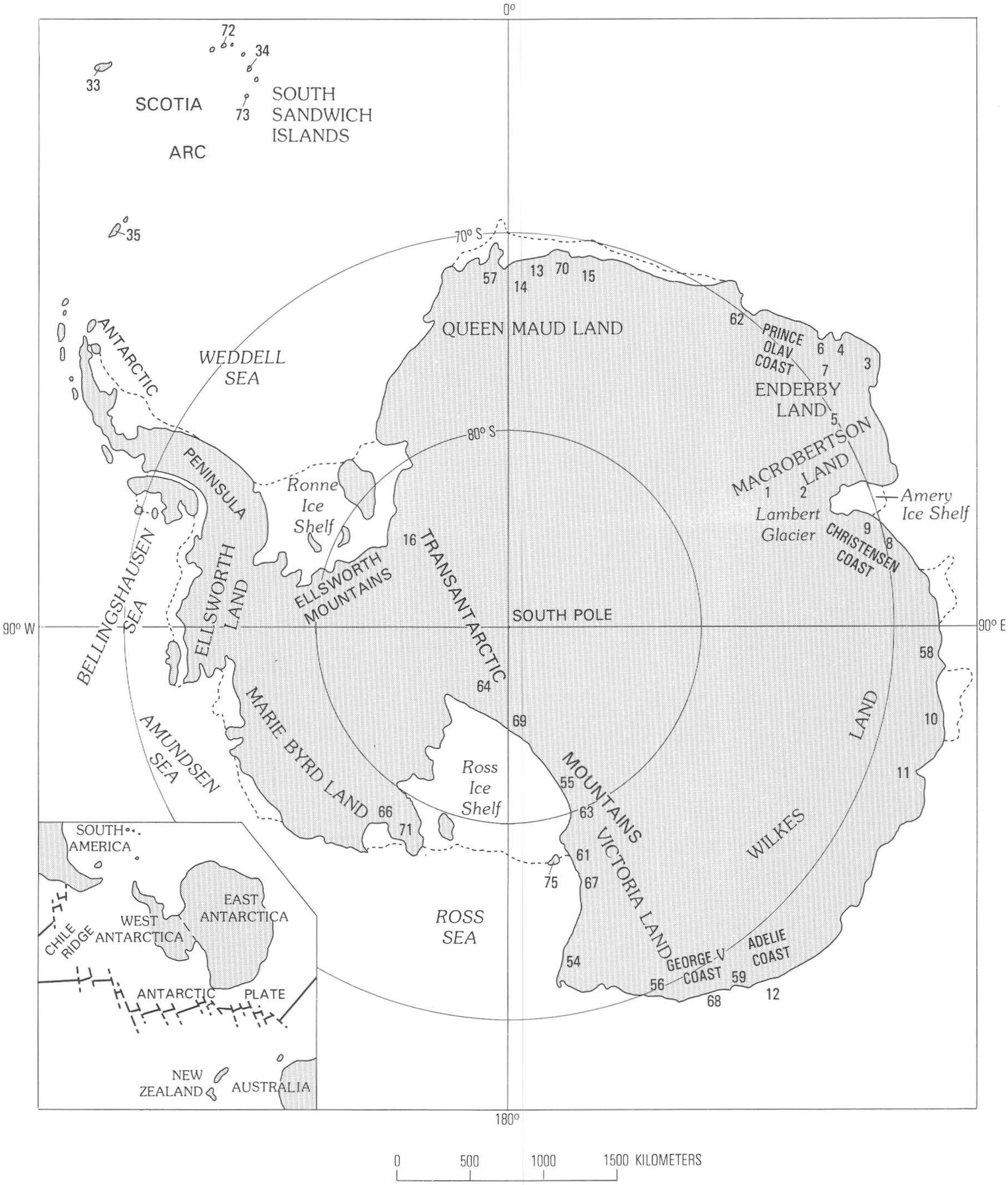

FIGURE 20.—Map of Antarctica showing numbered localities of mineral occurrences discussed in the text. Dotted lines show boundaries of ice shelves. Inset shows relationship of Antarctica to other continental and oceanic plates, as well as spreading ridges (solid lines) and transform faults (dashed lines) in the ocean basins.

barium, manganese, antimony, and other metals mostly in rocks of Late Proterozoic and early Paleozoic age. The more eastern parts of the Tasman belt, which geologically resemble the Victoria Land part of the Ross belt, contain gold, copper, silver, arsenic, lead, zinc, molybdenum, bismuth, tin, tungsten, antimony, and other metals related to lower Paleozoic volcanic rocks and lower to upper Paleozoic granitic intrusions (Wright and Williams, 1974; Rowley, Ford, and others, 1983).

West Antarctica is much lower topographically than East Antarctica and consists mostly of Mesozoic and Cenozoic rocks. West Antarctica may be composed of several small lithospheric plates that have moved independently of each other. The Andean belt, characterized by calc-alkaline igneous rocks formed during subduction of Pacific oceanic lithosphere beneath mostly continental lithosphere, has been superimposed on the Pacific margin of these small plates. Two of the small plates are the Ellsworth Mountains area and the Antarctic Peninsula, which exhibit, respectively, the lowest and highest potential for metallic mineral discoveries on the continent. The Ellsworth Mountains consist of Paleozoic clastic rocks that were folded in early Mesozoic time; the range contains no known mineral deposits.

The Andean belt is best developed in the Antarctic Peninsula. The peninsula consists in large part of stocks and batholiths of Early Jurassic through Tertiary age that form several magmatic arcs. Most arcs developed on continental lithosphere (Pankhurst, 1982) during subduction of oceanic lithosphere. The peninsula, which is more ice free than most other parts of the continent, is considered to be a particularly favorable geologic environment for copper, molybdenum, lead, zinc, tin, tungsten, and other mineral deposits because it has a geologic and plate-tectonic setting that is similar to the Andean belt of South America, one of the world's major mineral belts. But more recently, Wright and Williams (1974), Ericksen (1976), and Rowley and Pride (1982) pointed out that the southern Andes are not nearly as rich in mineral deposits as are the Andes farther north. A significant geologic break between the northern and southern Andes occurs where the Chile Ridge is subducted beneath South America. The late Cenozoic igneous evolution has been markedly different north and south of this intersect of the Chile Ridge with the continent. To the north, a trench and a rapidly moving Benioff zone still are active, whereas to the south, subduction generally has been slower and the oceanic plate has moved at an acute angle with respect to the continent (Herron and Tucholke, 1976; DeLong and Fox, 1977). Subduction under West Antarctica ceased at different times in different places: it halted first in Late Cretaceous time in Marie Byrd Land and western Ellsworth Land (LeMasurier and Wade, 1976), where no mineral deposits are known, and at various times during the Tertiary in various parts of the Antarctic Peninsula and southern South America (Herron and Tucholke, 1976). Thus the geologic history of the southern Andes and the Antarctic Peninsula is complex compared to that of the northern and central Andes. Hawkes (1981, 1982) has even speculated that the occurrence of some sulfide mineral deposits in the peninsula has been partly controlled by onshore extensions of oceanic transform fracture zones. In addition to the differences mentioned, southern South America and the Antarctic Peninsula may have undergone deeper erosion than the Andes farther north. These concepts indicate that the earlier predictions of numerous rich mineral deposits in the Antarctic Peninsula were premature (Rowley and Pride, 1982). Nonetheless, the peninsula appears to have the highest probability in Antarctica for containing an economic base-metal deposit (Wright and Williams, 1974).

MINERAL OCCURRENCES AND DEPOSITS

Mineral occurrences are abundant throughout much of Antarctica, but most of them are only small masses of metallic or nonmetallic minerals. They will be described by commodity and by groups of genetically related commodities. Their locations are shown on figures 20 and 21. Where necessary, isotopic ages given below have been corrected according to the new decay constants supplied by Steiger and Jäger (1977).

IRON

Iron probably is the commodity forming the potentially largest deposits in Antarctica. Its distribution suggests the presence of an iron metallogenic province in East Antarctica (Rowley, Ford, and others, 1983). The most extensive deposits are of banded iron-formation (jaspilite) that define an iron-formation subprovince extending from Enderby Land through Wilkes Land (fig. 20). The iron-formation is similar in lithology, geochemistry, and age to Superior- and perhaps Algoma-type deposits (Gross, 1965) in numerous other Precambrian terranes in the world; Gole and Klein (1981) noted that most deposits elsewhere in the world have an age range of 2.0 to 1.8 b.y. (billion years). An iron-oxide vein subprovince in

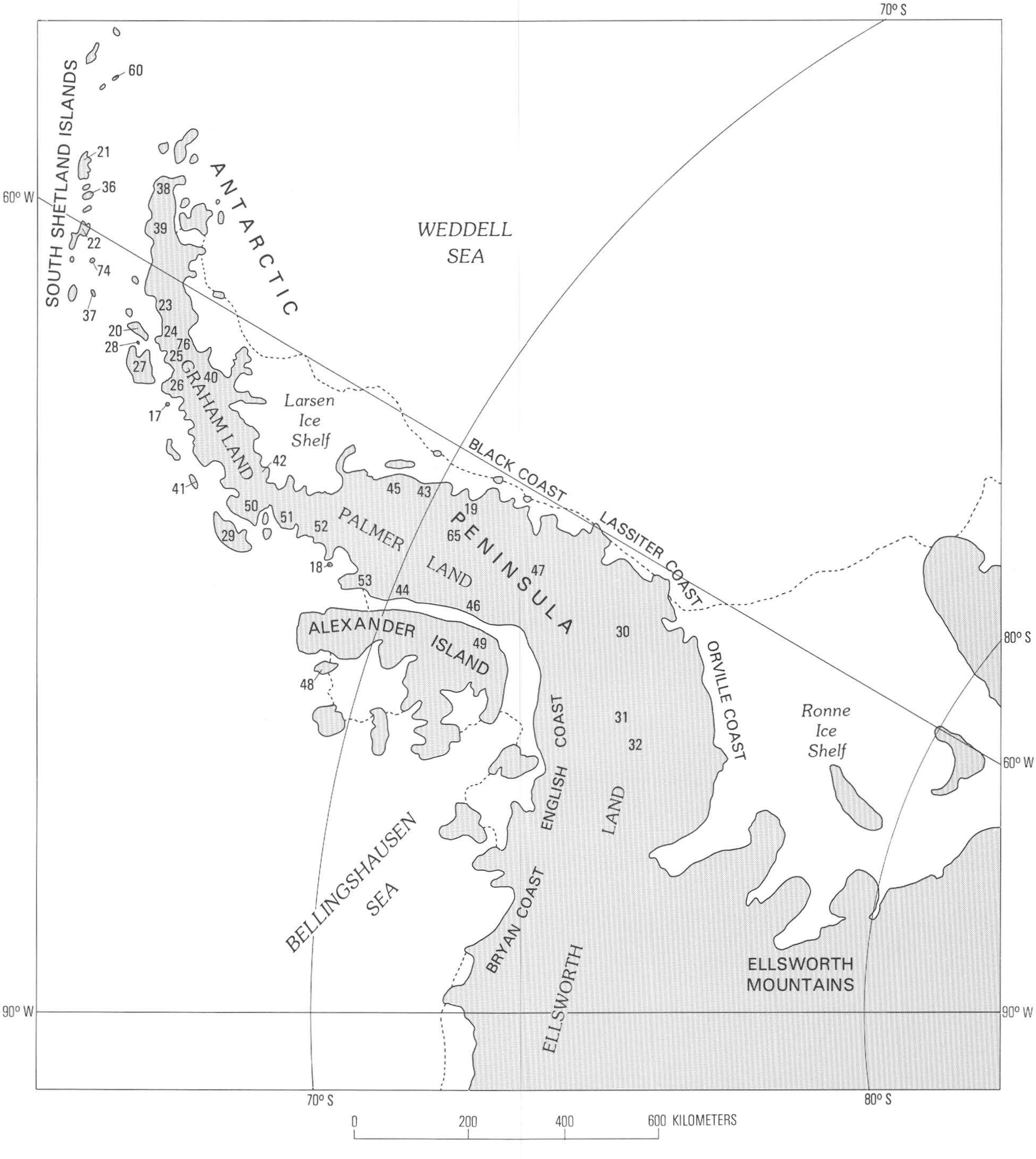

FIGURE 21.—Map of the Antarctic Peninsula showing numbered localities of mineral occurrences discussed in the text. In the vicinity of the Ronne Ice Shelf, the map follows the modifications suggested by Swithinbank and others (1076). Dotted lines show boundaries of ice shelves.

Queen Maud Land (Rowley, Ford, and others, 1983) contains veins of magnetite and possibly related sulfide minerals that may have been remobilized by hydrothermal processes acting on older iron source terranes. Australian and Soviet workers have studied Antarctic iron deposits in greatest detail; Tingey (in press) summarized the geology and history of discovery of the various iron occurrences and concluded that none are likely to be economically developed.

The largest known deposits of iron-formation in Antarctica are in the Prince Charles Mountains (localities 1 and 2, fig. 20), MacRobertson Land (Grew, 1982, fig. 57.2; Ravich and others, 1982; Tingey, 1982a, b, in press). The largest deposits occur on Mount Ruker (locality 1, fig. 20) Here, beds of banded iron-formation as thick as 70 m alternate with slate, siltstone, quartzite, chlorite schist, andesitic volcanic rocks or metagabbro(?), and talc-carbonate rocks (Ravich and others, 1982; Tingey, in press). The main sequence contains laminated-type iron-formation and is nearly 400 m thick. It is overlain and underlain by sequences, each more than 300 m thick, in which banded iron-formation is less abundant than other rock types (Ravich and others, 1982). These and overlying sequences have been subjected to greenschist metamorphism and are tightly folded. The age of the banded iron-formation is not known but probably is Early Proterozoic (that is, 2.5 to 1.6 b.y. old) or Late Archean on the basis of Rb-Sr (rubidium-strontium) ages that partly bracket the rocks (Tingey, 1982a, b, in press); the deposits may be part of an Archean craton block in the southern Prince Charles Mountains (Tingey, 1982a).

Beds of banded iron-formation consist of 0.1- to 2-cm-thick, crinkled, alternating laminae of quartzite and dark-gray and purplish-black opaque minerals (Ravich and others, 1982) of the Superior type (Tingey, in press). Magnetite is more abundant than hematite in the opaque fraction, and ilmenite locally replaces both (Ravich and others, 1982). Chemical analyses show that silica ranges from 36 to 61 percent, and total iron from 25 to 46 percent (average of 34 percent; Ravich and others, 1982; Tingey, in press). Fe_2O_3 content exceeds FeO; this ratio is the opposite of that in most other large deposits of banded iron-formation (Gole and Klein, 1981). Tingey (in press) noted that the average content of P_2O_5 is 0.17 percent, resulting in ore that is detrimental to steelmaking. Two aeromagnetic anomalies, each 5 to 10 km wide and with positive amplitudes of 600 to 3,000 gammas, extend west from Mount Ruker for 120 and 180 km under glacial ice (Hofmann, 1982, fig. 58.1; Ravich and others, 1982). These anomalies almost certainly indicate additional iron deposits. Intensely faulted beds of banded iron-formation were noted by Ravich and others (1982) at Mount Stinear (locality 2, fig. 20), northeast of Mount Ruker, and nearby positive aeromagnetic anomalies under glacial ice further suggest additional iron-bearing rocks there. Tingey (1982b, in press), however, found only low-grade iron-bearing rocks at Mount Stinear, the rocks of which have Archean ages based on Rb-Sr determinations.

Iron occurrences are abundant in Enderby Land (fig. 20), although none has been described in detail. For example, a zone of aluminous schist, in which magnetite forms as much as 30 percent of the volume of the rock, occurs over an area nearly 150 km long (Ravich and Kamenev, 1975). Ravich and others (1965) reported that the crystalline basement complex of Enderby Land also contains magnetite that cements clasts of garnet and pyroxene gneiss in breccia zones 10 to 50 m wide and more than 100 m long. Most magnetite, which forms 30 to 40 percent of the volume of the breccia zones, apparently originated from solutions that migrated along faults, perhaps during Archean migmatization (Ravich and others, 1965). Magnetite schist and gneiss also occur in other parts of Enderby Land (Ravich and others, 1965). Most iron occurrences are in the Napier Complex, an Archean craton block, but some are in the adjacent Rayner Complex of Early Proterozoic age (Sheraton and others, 1980; James and Tingey, 1983; Tingey, in press). In 1977, Australian geologists reported the discovery of the largest deposit of banded iron-formation in Enderby Land, at Newman Nunataks (locality 3, fig. 20); the deposit is 750 m long, 150 m wide, and 20 m thick and has an average iron content of 34 percent (Lovering and Prescott, 1979). The deposit is lithologically similar to, but much smaller than, the one at Mount Ruker (Tingey, in press). It is in high-grade metamorphic rocks of the Napier Complex and is considered to be at least 3.1 b.y. old (Tingey, in press). Magnetite-rich rocks also occur at nearby Mount Mueller (locality 4, fig. 20), at Mount Cook (locality 5, fig. 20), in the Amundsen Bay area (locality 6, fig. 20), and in other parts of Enderby Land (Crohn, 1959; Trail and others, 1967; Trail and McLeod, 1969a; Lovering and Prescott, 1979). Aeromagnetic anomalies were discovered near Knuckey Peaks (locality 7, fig. 20; Lovering and Prescott, 1979).

Glacial boulders of banded iron-formation have been found along the coastline of East Antarctica between longs 78° E. and 93° E. (Ravich and others, 1965; Tingey, in press). For example, in the Vestfold Hills (locality 8, fig. 20) of the Ingrid Christensen Coast, banded iron-formation of greenschist facies occurs as boulders as large as 2 m (Ravich and others, 1982). Average iron content of the boulders, based on sparse chemical analyses, is 21 percent (Ravich and others, 1982; Tingey, in press). These boulders of banded iron-formation are lithologically different from iron-formation of the Prince Charles Mountains; probably they were glacially transported from one or more, presently ice-covered, iron deposits upstream (Ravich and others, 1982). The location of possible sources is suggested by the presence of positive magnetic anomalies that extend beneath the ice in a 120-km-long east-trending belt to the south of the Vestfold Hills; the anomalies are 10 to 40 km long and 2 to 4 km wide and have positive amplitudes ranging from 800 to 5,900 gammas (Ravich and others, 1982). Bedrock exposures in the Vestfold Hills also contain unspecified volumes of banded iron-formation within an Archean craton block (Oliver and others, 1982; Collerson, 1983). Magnetite deposits also are present as veins and in garnet-quartz-feldspar gneiss in the Larsemann Hills (locality 9, fig. 20; Trail and McLeod, 1969b), west of the Vestfold Hills. The gneiss complex presumably belongs to the same Archean block (Collerson, 1983); plutonic rocks that intrude it in the Vestfold Hills have yielded consistent Rb-Sr whole-rock and K-Ar (potassium-argon) ages ranging from 1.5 to 1.0 b.y. old (Grindley and McDougall, 1969).

Farther east, in Wilkes Land, magnetite schist and gneiss occur in the Bunger Hills (locality 10, fig. 20). Plutonic rocks, which extend over an area from longs 90° to 130° E. and which have been dated by K-Ar, Pb-U (lead-uranium), and Pb-Th (lead-thorium) methods at 1.4 to 0.9 b.y. old (Grindley and McDougall, 1969), apparently cut the iron-bearing rocks. Still farther east, small lenses of limonite-stained magnetite-rich rocks, including banded iron-formation, have been found within high-grade Precambrian rocks near Casey Station, an Australian base (locality 11, fig. 20; Lovering and Prescott, 1979; Lovering and Plimer, 1983). Morainal boulders of banded iron-formation and magnetite schist have been noted by Kleeman (1940) and Mawson (1940) from Cape Denison, Adélie Land (locality 12, fig. 20).

The iron-oxide vein subprovince of Queen Maud Land contains numerous iron occurrences whose origins are poorly known. The age of the oldest rocks in Queen Maud Land is not definitely known, but it may be mostly Middle Proterozoic (James and Tingey, 1983). Paleozoic metamorphic, sedimentary, volcanic, and plutonic rocks of Late Proterozoic to early Mesozoic age also are present in Queen Maud Land (Grindley and McDougall, 1969; Neethling, 1972; Van Autenboer and Loy, 1972; James and Tingey, 1983). Metal occurrences in the subprovince include garnet-magnetite veins 0.5 to 5 m wide in a 50-m-wide fracture zone in a Precambrian basement complex in the "Mount Hedden" area of central Queen Maud Land (apparently in the Gjelsvik Mountains, locality 13, fig. 20; Ravich and Solov'ev, 1969). Magnetite schist and gneiss occur elsewhere in Queen Maud Land (Ravich and others, 1965). Secondary copper stains and a minor magnetite-quartz vein were noted in similar rocks in the nearby Sverdrup Mountains (locality 14, fig. 20) of Queen Maud Land (Van Autenboer and Loy, 1972). Breccia zones containing abundant magnetite and minor disseminated chalcopyrite are related to mafic intrusions in Queen Maud Land. For example, garnet-magnetite veins and pyroxene-magnetite veins occur in gneissic country rocks at the contacts of charnockite intrusions in the Humboldt Mountains (locality 15, fig. 20) of central Queen Maud Land (Ravich and others, 1965). Most charnockite plutons may be Late Proterozoic but some probably are early Paleozoic (Ravich and others, 1965; Ravich and Solov'ev, 1969). Individual veins are 0.2 to 0.5 m thick and occur in large stockworks reported to be "tens of meters" in diameter (Ravich and others, 1965); magnetite content within the stockworks ranges from 30 to 40 percent by volume. Magnetite adjacent to Upper Permian to Triassic syenitic intrusions occurs in the Paulsen Mountains and Gburek Peaks (both lying between the Sverdrup Mountains and Gjelsvik Mountains, Queen Maud Land); the deposits in the Gburek Peaks consist of biotite and titanomagnetite in lenticular bodies as much as 3 m wide and 15 m long within an 80-m-wide contact zone (Ravich and others, 1965; Ravich and Solov'ev, 1969). The many ages of iron occurrences and related mineralized rocks suggest remobilization, by plutons, of iron and other metals from Archean or Proterozoic iron-formation source terranes. Ravich and Solov'ev (1969) also reported magnetite "placer" boulders as heavy as 5 kg at two localities in central Queen Maud Land.

Iron occurrences are also abundant outside the East Antarctic shield. Magmatic-type iron is found in the stratiform gabbroic Dufek intrusion (Middle Jurassic) of the northern Pensacola Mountains (locality 16, fig. 20), Transantarctic Mountains. The intrusion contains seams of cumulus iron-titanium oxides as thick as 2 m; the seams have fairly high titanium and vanadium contents (Himmelberg and Ford, 1977). Scattered minor occurrences of copper and iron sulfides, and derivative minerals, also occur in the Dufek intrusion (Ford, 1970, 1976; Ford, Schmidt, and Boyd, 1978; Ford, Schmidt, and others, 1978; Ford, this volume). Layered bodies such as this commonly contain large volumes of cobalt, chromium, nickel, vanadium, copper, and iron, plus significant amounts of platinum-group minerals. Ford (this volume), in a detailed discussion of economic possibilities for the Dufek intrusion, considers it possible that economically important deposits occur in the lower part of this 9-km-thick body, but only the top of the intrusion is exposed. Magnetite layers may occur in other stratiform intrusions of the Ferrar Group in the Transantarctic Mountains (for example, Hamilton, 1964).

Magmatic iron is associated with other stratiform intrusions in Antarctica, especially in the Antarctic Peninsula, where they help define an iron subprovince within the Andean metallogenic province (Rowley, Ford, and others, 1983). Late-stage magmatic magnetite layers are reported by Fraser (1964) and Elliot (1964) within a stratiform gabbro body of Andean age in the Anagram Islands of the Argentine Islands (locality 17, fig. 21), southern Antarctic Peninsula. The gabbro is part of a batholith complex that includes silicic phases that have K-Ar ages (Rex, 1976) of 58–55 m.y. (million years). Other minerals found within the gabbro include limonite, talc, serpentine, and "copper minerals." Disseminated pyrite and small concentrations of pyrite, magnetite, molybdenite, hematite, and quartz veins, as well as potassic and propylitic altered rocks, occur elsewhere in the islands; all these features suggest porphyry mineralization in the area (Hawkes and Littlefair, 1981). No metallic minerals in the Argentine Islands are known to be of economic importance (D. H. Elliot, oral commun., 1977). A stratiform gabbro body of Andean age has been described by Adie (1955) and Nichols (1955) in the Terra Firma Islands (locality 18, fig. 21). Here, magnetite and limonite occur in a prominent cumulus layer about 6 m thick near the base of the intrusion. Cumulus layers of magnetite and chromite(?) were noted by Singleton (1980a) in the basal part of an Andean layered gabbro intrusion in the central Black Coast (locality 19, fig. 21).

Magmatic iron also occurs in Pleistocene lava flows of andesite and olivine basalt mapped throughout Brabant Island (locality 20, fig. 21; Alarcón and others, 1976; Alarcón, 1977; Vieira and others, 1982), Antarctic Peninsula. The lava flows apparently are lithologically similar to magnetite-bearing flows at El Laco, northern Chile (Park, 1961). The principal minerals in the flows on Brabant Island are magnetite and subordinate hematite and martite. Hematite and limonite locally have migrated into adjacent Upper Cretaceous to Miocene (British Antarctic Survey, 1979) sedimentary rocks (Vieira and others, 1982).

COPPER

Occurrences of disseminated copper, molybdenum, and related metals are common in the Antarctic Peninsula, but most are deeply eroded or poorly known, and none appear to be economically recoverable (Rowley and Pride, 1982). Secondary copper minerals, especially those called malachite by many authors, are abundant in the Antarctic Peninsula and to a lesser extent in other parts of Antarctica; X-ray studies show that most of these minerals are complex dry-climate copper sulfates and chlorides (Vennum, 1980; Vennum and Nishi, 1981). The most promising copper occurrences in Antarctica are on islands west of the mainland Antarctic Peninsula and are associated with the youngest (Tertiary) trondhjemitic plutons of the Andean intrusive suite (Rowley and Pride, 1982). These include possible porphyry deposits, most of which occur in plutonic rocks of hypidiomorphic-granular (granitoid) texture and appear to have been either emplaced at deeper levels or eroded to deeper levels; such deposits are of the "plutonic porphyry" type (Sutherland Brown, 1969, 1976; Sutherland Brown and others, 1971; Cox and others, 1981). Polymetallic vein deposits, some of which may be peripheral to porphyry mineral systems, also are common in the Antarctic Peninsula. The copper occurrences in the Pacific margin of West Antarctica define a copper subprovince within the Andean metallogenic province (Rowley, Ford, and others, 1983). Geologic maps by the British Antarctic Survey (1979, 1981, 1982) show the general geology and many of the localities containing metallic minerals and isotopic ages.

Pyrite deposits, quartz replacement bodies, and hydrothermally altered rocks of considerable volume are scattered throughout King George Island (locality 21, fig. 21), an 80 km by 30 km island within the South Shetland Islands (Hawkes, 1961; Barton, 1965). King George Island consists mostly of Upper Cretaceous(?) to Pleistocene volcanic rocks (British Antarctic Survey, 1979; Davies, 1982) that are intruded by small Tertiary quartz diorite to granodiorite plutons, one of which has K-Ar ages of 53–46 m.y. (British Antarctic Survey, 1979; Watts, 1982). According to Hawkes (1961) and Barton (1965), the plutons may represent cupolas of a large batholith that underlies the central part of the island. Quartz veins containing abundant pyrite and subordinate secondary hematite and limonite were first described by Ferguson (1921) and Tyrrell (1921). Some veins are large, including one in the central part of the island that is more than 2 km long and as much as 155 m wide (Ferguson, 1921), one in the northeast that is 1.5 km long and as much as 30 m wide (Ferguson, 1921), and one in the southwest that is more than 2 km long and as much as 0.3 km wide (Barton, 1965).

In a reappraisal of the deposits on King George Island, Littlefair (1978) concluded that the "veins" noted by earlier workers are replacement bodies formed by hydrothermal fluids that moved along fractures in country rocks. Cox and others (1980) also recently studied the deposits on Keller and Barton Peninsulas and concluded that plutonism, alteration, and mineralization were controlled by northeast- and northwest-striking faults and joints.

Broad areas of hydrothermally altered rocks (propylitic, argillic, phyllic, and potassic grades) on King George Island have been studied by numerous workers (Tyrrell, 1921; Hawkes, 1961; Barton, 1965; Grikurov and Polyakov, 1971a, b; Littlefair, 1978; Davies, 1982), although according to Cox and others (1980), alteration may not be as widespread as previously reported. Numerous alteration minerals, including chlorite, epidote, calcite, quartz, sericite, and clays, have been noted on the island (Littlefair, 1978; Cox and others, 1980; C. A. Cox, oral commun., 1981). In addition, Littlefair (1978) reported a mineral assemblage that includes chalcopyrite, bornite, pyrrhotite, marcasite, alunite, natroalunite, jarosite, native sulfur, fluorite, gypsum, barite, diaspore, and ankerite. Cox and others (1980) also noted the presence of magnetite and molybdenite(?) in rocks from Barton Peninsula. Chemical analyses of pyrite from King George Island (Littlefair, 1978) reveal anomalously high copper (100–2,200 ppm [parts per million]) and cobalt (5–230 ppm) contents. The copper content in samples of diorite from Keller and Barton Peninsulas also appears anomalously high (C. A. Cox, written commun., 1981), averaging 144 ppm (3 samples) and 187 ppm (20 samples), respectively. The alteration and mineralization on King George Island apparently is related genetically to plutonism (Hawkes, 1961; Barton, 1965; Littlefair, 1978; Cox and others, 1980). According to Littlefair (1978), the altered rocks may represent low-temperature epithermal-solfataric alteration of the type that characterizes an area above hot springs with magmatic sources, as at Yellowstone National Park, U.S.A. The presence of pyrrhotite and perhaps molybdenite in rocks from Barton Peninsula (Littlefair, 1978; Cox and others, 1980) suggests that at least some high-temperature mineralization and alteration occurred on the island. Littlefair (1978) and Hawkes (1982) speculated that a porphyry-type mineral deposit may be present at depth on King George Island. According to C. A. Cox (oral commun., 1981), however, the evidence for porphyry-type mineralization on the island is not compelling.

Two copper occurrences have been reported from south-central Livingston Island (locality 22, fig. 21) of the South Shetland Islands. Both occur adjacent to tonalite and trondhjemite Andean plutons. One is apparently a polymetallic base-metal vein deposit near and in a small altered tonalite pluton in the Johnsons Dock area of Hurd Peninsula (Hobbs, 1968; Caminos and others, 1973; del Valle and others, 1974; Cox and others, 1980; Pride and others, 1981). The pluton has a K-Ar age of 53 m.y. (British Antarctic Survey, 1979). Mineralized rocks occur scattered throughout an area 1.5 km long and 10 m wide within clastic sedimentary rocks of the Miers Bluff Formation (upper Paleozoic? or lower Mesozoic). Within the mineralized area, veins of quartz and calcite contain pyrite, chalcopyrite, covellite, bornite, tetrahedrite, tennantite, galena, sphalerite, chalcocite, malachite(?), azurite, linarite, antlerite, cerussite, witherite, hematite, and limonite. Altered rocks next to the veins contain albite, sericite, epidote, clinozoisite, chlorite, and calcite. One sphalerite vein is about 50 cm thick (Cox and others, 1980). Fieldwork by D. E. Pride suggests that the volume of mineralized rock, especially of galena, increases northward toward Johnsons Dock.

The second mineral occurrence on Livingston Island is in the northeastern part of the False Bay area, and may represent a deeply eroded copper-molybdenum porphyry deposit. Here, a pluton with Rb-Sr mineral ages averaging 39 m.y. (Dalziel and others, 1973) is intensely altered to sericite, chlorite, epidote, and quartz (Hobbs, 1968). J. E. Curl (oral commun., 1974) found boulders, deposited by glaciers draining the pluton, that contain molybdenite veins and stains of secondary copper minerals. The field studies in the False Bay area by D. E. Pride revealed the presence of glacially derived boulders containing several plutonic phases, especially gray granodiorite. These rocks contain pyrite, chalcopyrite, molybdenite, sphalerite, quartz, and secondary copper minerals but appear unaltered except for the presence of epidote (Pride and others, 1981).

Several areas of poorly known but widespread mineralized rocks in the Danco and northern Graham Coasts have been described by Alarcón and others (1976), Alarcón (1977), and Vieira and others (1982), and are shown on the map by the British Antarctic Survey (1979). The Spring Point region of the northern Danco Coast (locality 23, fig. 21), for example, contains veins and areas of disseminated pyrite, scattered subordinate chalcopyrite and copper oxides, and weakly altered rocks. The rocks consist primarily of calc-alkaline volcanic rocks of the Antarctic Peninsula Volcanic Group (Lower Jurassic to Lower Cretaceous) and silicic, locally porphyritic Andean plutons.

The Wilhelmina Bay region of the central Danco Coast (locality 24, fig. 21) contains several areas of polymetallic base-metal veins and accompanying disseminated pyrite, chalcopyrite, and limonite, and subordinate copper oxides, sphalerite, galena, marcasite, and silver-bearing minerals. The rocks are made up of hydrothermally altered (quartz and chlorite primarily) clastic sedimentary rocks of the Trinity Peninsula Formation (upper Paleozoic? and Triassic) and volcanic rocks of the Antarctic Peninsula Volcanic Group (British Antarctic Survey, 1979) that occur near silicic Andean plutons. Pride and others (1981) found float boulders that contain veins of pyrite, galena, sphalerite, and chalcopyrite along the shore of the Bahia Frei-Recess Cove area east of Wilhelmina Bay; the veins range in thickness from 1 to about 10 cm. Vieira and others (1982) suggested that the best exploration targets for a mineral deposit in the Wilhelmina Bay region are limonite covers.

The Paradise Harbor region of the southern Danco Coast (locality 25, fig. 21) contains scattered areas of disseminated and vein-type pyrite and subordinate chalcopyrite and copper oxides within hydrothermally altered rocks containing chlorite, quartz, clay, epidote, K-feldspar (potassium-feldspar), and calcite. The altered and mineralized rocks occur within volcanic rocks of the Antarctic Peninsula Volcanic Group near silicic Andean plutons (Ferguson, 1921; Vieira and others, 1982). One of the plutons has a K-Ar age of 96 m.y. (West, 1974; British Antarctic Survey, 1979).

The LeMaire Channel region (locality 26, fig. 21) of northeastern Graham Coast contains scattered minor disseminated and vein-type pyrite, chalcopyrite, and pyrrhotite, as well as hydrothermally altered rocks, all of which suggest hydrothermal copper vein mineralization (Vieira and others, 1982). The altered and mineralized rocks largely occur within volcanic rocks of the Antarctic Peninsula Volcanic Group that are adjacent to Andean plutons (British Antarctic Survey, 1981). One of the plutons has a Rb-Sr whole-rock age of 93 m.y. (British Antarctic Survey, 1981; Pankhurst, 1982).

Vein- and perhaps porphyry-type alteration and mineralization occurred on Anvers Island (locality 27, fig. 21). The altered and mineralized rocks are either within a large, deeply altered, composite Tertiary batholith that forms most of the island and smaller adjacent islands, or in the Antarctic Peninsula Volcanic Group marginal to the batholith. The batholith is primarily silicic to intermediate in composition and of medium-grained hypidiomorphic-granular texture; trondhjemite is a prominent rock type (Hooper, 1962). The batholith has K-Ar ages of 54–45 m.y. (Scott, 1965; Rex, 1976; British Antarctic Survey, 1979) and

Rb-Sr whole-rock and K-Ar ages of 34–20 m.y. (British Antarctic Survey, 1979; Gledhill and others, 1982). Mineralization related to emplacement of the batholith is widespread, but to date only small volumes of chalcopyrite, pyrite, and subordinate bornite, magnetite, molybdenite, and secondary copper minerals have been found in quartz veins and in disseminated form (Ferguson, 1921; Thomas, 1921; Hooper, 1962; Anderson, 1965; Potter, 1969; Alarcón and others, 1976; Alarcón, 1977; Cox and others, 1980; Vieira and others, 1982; C. C. Plummer, written commun., 1977; W. J. Zinsmeister, oral commun., 1977). These small deposits, summarized by Rowley and Pride (1982), occur in several places on Anvers Island and nearby Wiencke Island, Doumer Island, the Wauwermans Islands, and Isle Casabianca. C. C. Plummer (written commun., 1977), W. J. Zinsmeister (oral commun., 1977), and Pride and others (1981) noted a fairly extensive system of quartz veins containing pyrite, molybdenite, arsenopyrite, chalcopyrite, galena, sphalerite, and secondary copper minerals near Palmer Station (U.S.A.), southern Anvers Island. Other porphyry copper or hydrothermal vein deposits occur in the nearby Melchior Islands (locality 28, fig. 21) and Brabant Island (locality 20, fig. 21), where large areas of disseminated chalcopyrite and, locally, native copper were noted (Vieira and others, 1982). Alteration minerals are widespread in all these areas. They include K-feldspar, albite, quartz, biotite, sericite, chlorite, epidote, and calcite. Dikelike bodies of sheared, locally high temperature alteration minerals (albite, quartz, K-feldspar, biotite, chlorite, and epidote) cut plutonic rocks in some places, especially on Anvers Island. The geology of Anvers Island and adjacent small islands is complex, and detailed mapping and geochemical surveys probably will be required if any significant mineral deposits are to be distinguished from among the many mineralized and altered rocks.

Another deeply eroded Tertiary batholith complex occurs in the Argentine Islands (locality 17, fig. 21). Rocks there include a trondhjemite phase and a stratiform gabbro body (Fraser, 1964; Elliot, 1964). Hydrothermally altered rocks are widespread on the islands, and chalcopyrite, molybdenite, and other primary and secondary copper and iron minerals have been reported from the area. The islands were reinvestigated by Hawkes and Littlefair (1981), who recognized zones of potassic and propylitic altered rocks within granodiorite of 70 and 58–55 m.y. (Rb-Sr whole-rock and K-Ar ages; Rex, 1976; British Antarctic Survey, 1981; Gledhill and others, 1982; Pankhurst, 1982) and younger quartz monzonite plutonic rocks and volcanic rocks that are intruded by the plutons. Quartz-molybdenite-chalcopyrite veinlets and peripheral quartz-magnetite and quartz-pyrite veinlets occur within the potassic zone, and disseminated pyrite and magnetite occur within the propylitic zone. Hawkes and Littlefair (1981) interpreted the minerals of the potassic zone to represent the roots of a porphyry copper-molybdenum deposit.

Adelaide Island to the south (locality 29, fig. 21) is geologically similar to Anvers Island. It and nearby small islands are underlain by deeply eroded, locally brecciated, composite Andean plutons (Dewar, 1970; British Antarctic Survey, 1981) that have Rb-Sr whole-rock ages of 62–60 m.y. (Pankhurst, 1982). The rocks range in composition from gabbro to trondhjemite and granodiorite. Disseminated pyrite and quartz veins containing pyrite, magnetite, molybdenite, and "copper minerals" occur locally within altered plutonic rocks. Molybdenite, magnetite-limonite masses, disseminated pyrite, quartz veins containing "copper minerals," quartz-magnetite- pyrite veins, and quartz-specularite veins occur adjacent to plutonic rocks in sedimentary and volcanic rocks of the Antarctic Peninsula Volcanic Group (Nichols, 1955; Dewar, 1970). As with Anvers Island, Adelaide Island may be underlain by porphyry-type or plutonic porphyry-type deposits and (or) hydrothermal vein deposits. Alternatively, any deposits that might have occurred on Adelaide Island may have been largely removed by erosion.

Small, widely scattered areas of altered rocks or of mineralized rocks containing pyrite, chalcopyrite, magnetite, molybdenite, secondary copper and iron minerals, and other minerals occur in about 30 places on the southern Black Coast, Lassiter Coast, and northern Orville Coast (fig. 21; Rowley and others, 1977; Vennum, 1980; British Antarctic Survey, 1981; Rowley, Kellogg, and others, in press) and in several dozen other places on the Orville Coast and in eastern Ellsworth Land. All known mineralized and altered rocks in the southern Antarctic Peninsula occur in Lower Cretaceous (Farrar and Rowley, 1980; Farrar and others, 1982) Andean plutons, or in wallrocks adjacent to the plutons. These wallrocks consist of either volcanic rocks of the Mount Poster Formation (Middle? and Upper Jurassic) of the Antarctic Peninsula Volcanic Group or sedimentary rocks of the Latady Formation (Middle and Upper Jurassic) (Williams and others, 1972; Rowley and Williams, 1982; Rowley, Vennum, and others, 1983).

In addition to the many scattered occurrences of metals in the southern Antarctic Peninsula, three noneconomic "plutonic" porphyry-type deposits have been discovered. The mineralization affected plutons of Early Cretaceous age (Farrar and Rowley, 1980; Farrar and others, 1982; Rowley, Farrar, and others, in press). One deposit, a copper-molybdenum deposit, is exposed in the Copper Nunataks of the central Lassiter Coast (locality 30, fig. 21; Rowley and others, 1975, 1977; Rowley, Farrar, and others, in press). The Lassiter Coast copper deposit contains disseminated and vein-type pyrite, chalcopyrite, molybdenite, and magnetite, and subordinate secondary copper and iron minerals. Mineralized rocks are within a sheared, brecciated, and altered (propylitic, argillic, phyllic, and weak potassic grades) granodiorite batholith and granite stock. The batholith and the stock, respectively, are about 25 km and at least 8 km in known longest diameter and yield K-Ar ages of 108 and 97 m.y. Both plutons are intruded by dacite porphyry dikes, which are the possible sources of the mineralization. Average metal values from rocks of the most mineralized nunatak, which is intruded by the granite stock, do not exceed 200 ppm copper, 100 ppm lead, and 50 ppm molybdenum; higher values may occur laterally beneath the ice or at depth (Rowley and others, 1977).

The Sky-Hi Nunataks copper deposit of eastern Ellsworth Land (locality 31, fig. 21) contains disseminated and vein-type pyrite, chalcopyrite, and magnetite within a small sheared and altered (propylitic, argillic, phyllic, and weak potassic grades) granodiorite stock that is cut by dacite porphyry dikes (Rowley, 1978, 1979; Rowley and Pride, 1982; Rowley, Farrar, and others, in press). The stock is 1 to 2 km in diameter and about 122 m.y. old (Farrar and Rowley, 1980). Average values of the exposed plutonic rocks do not exceed 200 ppm copper and 50 ppm zinc. Small quartz veins in volcanic rocks of the Mount Poster Formation in nearby nunataks, however, contain pyrite, chalcopyrite, molybdenite, and secondary copper minerals; semiquantitative spectrographic analyses of mineralized rocks in these veins locally show values of as much as 7,000 ppm copper, 1,500 ppm zinc, 1,900 ppm lead, 110 ppm molybdenum, and 40 ppm silver.

Shear zones, altered rocks (propylitic, argillic, phyllic, and weak potassic grades), and low-grade mineralized rocks also occur within the Merrick Mountains stock (locality 32, fig. 21) of eastern Ellsworth Land (Rowley, 1978; Rowley, Farrar, and others, in press; Vennum and Laudon, in press). These features are lithologically similar to but less widespread than those in the Lassiter Coast and Sky-Hi copper deposits. The Merrick Mountains stock, consisting of quartz diorite and subordinate granodiorite cut by rhyodacite porphyry dikes, is about 10 km in longest diameter and has a Rb-Sr biotite and whole-rock age of 107 m.y. (Halpern, 1967). Disseminated and vein-type pyrite, chalcopyrite, magnetite, and secondary copper minerals are widely scattered within the stock. Analyses locally show values of as much as 10,000 ppm copper, 700 ppm zinc, 300 ppm lead, and 50 ppm silver in veins, but average values of exposed plutonic rocks probably do not exceed 100 ppm copper.

Scattered minerals of copper and related metals occur in other parts of the Antarctic Peninsula, but are either too low grade, too poorly exposed, or too poorly studied to enable appraisal of their significance (Rowley and Pride, 1982). For example, pyrite, chalcopyrite, and hematite veins occur in sedimentary rocks and sills of an Upper Jurassic and Lower Cretaceous island arc sequence on South Georgia (locality 33, fig. 20; Stone, 1980; Tanner and others, 1981). Atacamite stains occur in Quaternary volcanic rocks on Montagu Island (locality 34, fig. 20), South Sandwich Islands (Holdgate and Baker, 1979). Disseminated sulfide minerals were found in Paleozoic(?) schist and an Andean dike on southeastern Coronation Island (locality 35, fig. 20), South Orkney Islands (Dalziel, 1972; Thomson, 1974). Veins containing chalcopyrite, copper oxides and carbonates, magnetite, ankerite, and barite occur in Tertiary(?) volcanic rocks (British Antarctic Survey, 1979) on Greenwich Island (locality 36, fig. 21), South Shetland Islands (Mueller, 1964). Minor pyrite and propylitically altered rocks occur on Low Island (locality 37, fig. 21; Smellie, 1980) among rocks of the Antarctic Peninsula Volcanic Group and intrusive breccia of Andean plutons (British Antarctic Survey, 1979). Adie (1957, 1964) noted veins and small masses of pyrite and chalcopyrite at the contacts between sedimentary rocks of the Trinity Peninsula Formation and Andean quartz diorite and diorite plutons in northeastern Graham Land (locality 38, fig. 21); here, a pluton has K-Ar ages of 392–358 m.y. (Rex, 1976; British Antarctic Survey, 1979). Aitkenhead (1975) mapped small quartz veins containing pyrite and secondary copper minerals at the northeastern contact between the 174- to 139-m.y.-old (K-Ar ages, Rex, 1976; British Antarctic Survey, 1979) Mount Reece Granite and the Trinity Peninsula Formation (locality 39, fig. 21). At the contacts between Andean plutons and rocks of the Trinity Peninsula Formation in the Oscar II Coast (locality 40, fig. 21), Fleet (1968) observed metallic minerals, including pyrite, chalcopyrite, bornite, and secondary copper minerals. Pyritic hornfels within rocks of the Antarctic Peninsula Volcanic Group occur in the southern Biscoe Islands (locality 41, fig. 21; Goldring, 1962). Numerous scattered areas of copper and iron minerals occur within or adjacent to Andean plutonic rocks farther south along the east coast of the Antarctic Peninsula, in the Foyn and Bowman Coasts (locality 42, fig. 21; British Antarctic Survey, 1981); Rb-Sr whole-rock and K-Ar ages of plutonic rocks just north and south of this area range from 209 to 174 m.y. (Rex, 1976; Pankhurst, 1982). Chalcopyrite and secondary copper minerals in an Andean(?) hornblendite at "Cape Eielson" (now Cape Boggs, locality 43, fig. 21) on the northern Black Coast were discovered by Knowles (1945). Skinner (1973) and the British Antarctic Survey (1982) noted several localities containing copper and iron minerals in rocks of the Antarctic Peninsula Volcanic Group near Andean plutonic rocks on the west coast of northern Palmer Land (locality 44, fig. 21). The British Antarctic Survey (1982) noted copper and iron minerals in or near plutonic rocks at localities in the Wilkins Coast (locality 45, fig. 21), northern Black Coast (locality 43, fig. 21), Batterbee Mountains (locality 46, fig. 21), and Journal Peaks (locality 47, fig. 21). Of these, the localities in the Batterbee Mountains occur in plutonic rocks containing Rb-Sr mineral ages and K-Ar ages of 137 to 128 m.y. (Rex, 1976; British Antarctic Survey, 1982). Small amounts of pyrite, molybdenite, and secondary copper minerals occur at the intrusive contact of an Andean pluton on an island just northwest of Alexander Island (locality 48, fig. 21; Care, 1980). Minor pyrite, hematite, magnetite, and cassiterite occur in fractures near Andean plutons and dikes in southern Alexander Island (locality 49, fig. 21; Bell, 1973).

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Rowley and Pride (1982) and the British Antarctic Survey (1981) summarized reports of small amounts of metallic (mostly copper and iron) minerals in numerous places in and north of the Marguerite Bay area of the west-central Antarctic Peninsula. Most rocks here consist of the Antarctic Peninsula Volcanic Group and a high-grade metamorphic complex of uncertain age and origin (Dalziel, 1982; Pankhurst, 1983), all of which are intruded by plutonic rocks. Rb-Sr whole-rock and mineral ages and K-Ar ages range from 207 to 83 m.y. for the metamorphic complex and from 119 to 67 m.y. for the plutonic rocks (Grikurov and others, 1966; Halpern, 1972; Rex, 1976; British Antarctic Survey, 1981; Gledhill and others, 1982; Pankhurst, 1982). On the north side and north of Marguerite Bay (locality 50, fig. 21), for example, occurrences of iron and copper minerals were noted in several places by the British Antarctic Survey (1981). Stonington Island (locality 51, fig. 21), farther south, contains scattered pyrite, magnetite, molybdenite, chalcopyrite, and secondary copper, iron, and manganese minerals (Knowles, 1945; Nichols, 1955; Fraser, 1965; Grimley, 1966). South of Stonington Island, in the central Marguerite Bay area (locality 52, fig. 21), minor amounts of pyrite, magnetite, molybdenite, secondary copper and iron minerals, and other metallic minerals have been reported at about 10 localities (Knowles, 1945; Nichols, 1955; Adie, 1955; British Antarctic Survey, 1981). Minor pyrite and secondary copper minerals have been noted at two localities (locality 53, fig. 21) in the southern Marguerite Bay area (Knowles, 1945; Nichols, 1955). Most of these areas were subject to only insignificant mineralization; a few, however, should be mapped in detail before their resource potential can be determined.

Elsewhere in West Antarctica, "copper shows" are reported by Wade (1976) along joints on nearly all mountains and nunataks in Marie Byrd Land (fig. 20), where calc-alkaline plutons of late Paleozoic through Cretaceous age have intruded Paleozoic and Mesozoic metamorphic and sedimentary rocks. Vennum and Nishi (1981) noted secondary copper minerals in the southern Ellsworth Mountains (fig. 20).

In the Transantarctic Mountains, copper and related base and precious metals define the Ross subprovince of the Transantarctic metallogenic province (Rowley, Ford, and others, 1983). For example, minor amounts of disseminated copper sulfides and "blue and green copper stains" were noted in and adjacent to middle Paleozoic plutonic rocks at Copper Cove (locality 54, fig. 20), near Hallett Station (New Zealand-U.S.A.) in northern Victoria Land (Harrington and others, 1964). Bornite in the Douglas Conglomerate was found near a lower Paleozoic pluton about 30 km south of the mouth of the Byrd Glacier (locality 55, fig. 20; Edmund Stump, oral commun., 1982). Copper minerals also have been seen near other plutons in the central Transantarctic Mountains (S. G. Borg and Edmund Stump, oral communs., 1982). Sparse metallic minerals in shield rocks of eastern Wilkes Land (fig. 20), adjacent to the Transantarctic Mountains, may be related to mineralization in the subprovince. For example, minor concentrations of pyrite, chalcopyrite, and arsenopyrite occur in quartz-albite veins in Precambrian phyllite in the "Lev Berg Mountains" (locality 56, fig. 20) of the Oates Coast (Ravich and others, 1965).

In East Antarctica, disseminated chalcopyrite occurs scattered in metamorphic rocks and quartz-feldspar veins in Precambrian crystalline basement rocks of Queen Maud Land (Ravich and others, 1965). In the Ahlmann Ridge area (locality 57, fig. 20) of western Queen Maud Land, Neethling (1964, 1969) mapped intensely hydrothermally altered rocks and copper, iron, and lead sulfides within intrusive rocks having K-Ar ages of 1.0 to 0.8 b.y. He also mapped altered rocks and thin layers and disseminations of pyrite, chalcopyrite, specularite, siderite, and secondary iron and copper minerals in older Precambrian sedimentary rocks in this area. Secondary minerals of copper and genetically related metals have been noted in many parts of Enderby Land (Crohn, 1959; Trail and others, 1967; Lovering and Prescott, 1979). These same minerals also were observed in high-grade Precambrian rocks in many places near Casey Station (Australia) and the nearby Windmill Islands (locality 11, fig. 20; Lovering and Prescott, 1979).

Copper minerals have been found in some stratiform mafic intrusions in Antarctica, but they generally are of minor importance. Minor chalcopyrite, pyrite, pyrrhotite, bornite(?), and atacamite occur scattered in the Dufek intrusion (locality 16, fig. 20), especially in layers containing abundant iron-titanium oxide minerals (Ford, this volume). Copper minerals occur within cumulus layers in Andean stratiform intrusions in the Argentine Islands (locality 17, fig. 21; Fraser, 1964; Elliot, 1964). A lithologically similar occurrence is about 45 to 60 m above a magnetite-limonite cumulate layer in an Andean pluton in the Terra Firma Islands (locality 18, fig. 21; Adie, 1955; Nichols, 1955).

MOLYBDENUM

In addition to the occurrences of molybdenite associated with copper mineralization, molybdenite is widespread in Precambrian pegmatite and granite dikes in the Mirny Station (U.S.S.R.) area (locality 58, fig. 20), the Bunger Hills (locality 10, fig. 20), and Queen Maud Land. Molybdenite also occurs in Precambrian(?) granite near Ainsworth Bay (locality 59, fig. 20; Ravich and others, 1965). Molybdenite is associated with pyrite, sphalerite, and arsenopyrite in quartz veins that cut gneiss at Cape Denison, Adélie Coast (locality 12, fig. 20; Mawson, 1940). None of these molybdenum occurrences contain economic concentrations.

NICKEL, CHROMIUM, AND COBALT

Chromite is present in disseminated form and in thin cumulus or tectonic (schist) layers in a dunite intrusion on Gibbs Island (locality 60, fig. 21), South Shetland Islands (Tyrrel, 1945; Matthews, 1959; Cox, 1964; Dalziel and Elliot, 1973; Dalziel, 1972, 1975; de Wit and others, 1977; I. W. D. Dalziel, oral commun., 1977). The intrusion apparently is related to an upper Paleozoic or lower Mesozoic subduction complex (de Wit and others, 1977). The dunite was originally reported (Kosack, 1955) from Aspland Island, about 10 km west of Gibbs Island, but no intrusion is shown on the geologic map of Aspland Island (British Antarctic Survey, 1979). The intrusion may contain nickel and cobalt minerals and perhaps graphite and asbestos. The chromite occurrence is not believed to be of commercial value (I. W. D. Dalziel, oral commun., 1977).

Disseminated chalcopyrite and pyrrhotite occur near Precambrian or Paleozoic gabbroic intrusions and dolerite dikes in Queen Maud Land (Ravich and others, 1965). Anomalous trace amounts (Ford, this volume) of cobalt, chromium, and nickel show up in some rock analyses of the Dufek intrusion (locality 16, fig. 20). Large concentrations of minerals containing these elements have not been found, although Ford (this volume) suggested that the lower unexposed parts of the intrusion may contain sizable concentrations of chromium and nickel. Hamilton (1964) reported that rocks from the base of a stratiform sill of Ferrar Dolerite in the dry valleys area (locality 61, fig. 20) are enriched in cobalt, chromium, nickel, vanadium, copper, and phosphorus.

URANIUM AND THORIUM

Euxenite occurs as an accessory mineral in an Ordovician(?) pegmatite in the Lutzow-Holm Bay area (locality 62, fig. 20; Saito and Sato, 1964; McLeod, 1965). Crohn (1959) reported anomalous amounts of radioactivity at several places in Enderby Land; most of these amounts apparently emanate from monazite in pegmatite veins. French geologists have noted anomalous amounts of radioactivity in the Adélie Coast (fig. 20; Wright and Williams, 1974). Airborne gamma-ray surveys of parts of the Transantarctic Mountains and Marie Byrd Land (Dreschhoff and Zeller, 1979; Dreschhoff and others, 1981, 1983; Zeller and others, 1979, 1982) have disclosed small radioactivity anomalies over pegmatite dikes and plutonic rocks of the Mount Dromedary igneous complex (locality 61, fig. 20) of Cambrian-Ordovician age (Warren, 1969) and in nearby fluorite veins in the dry valleys area of southern Victoria Land (locality 61, fig. 20). These airborne surveys also found radioactivity anomalies that proved, on field inspection, to be underlain by thorium- and uranium-bearing minerals as well as rare-earth- and tin-bearing minerals within sandstone of the basal (Devonian) parts of the Beacon Supergroup in the Darwin Glacier area (locality 63, fig. 20) of the Transantarctic Mountains. Stump and others (1981) noted uranium minerals in a pegmatite vein in the upper Scott Glacier area of the Transantarctic Mountains (locality 64, fig. 20). No occurrences in Antarctica contain commercial quantities of radioactive minerals.

PRECIOUS METALS

Significant concentrations of precious metals have not been recorded in Antarctica. Minor gold and silver have been noted in assays of sulfide minerals found near Andean plutonic rocks from several places in the Antarctic Peninsula (Knowles, 1945). These are at Stonington Island (locality 51, fig. 21), central Marguerite Bay area (locality 52, fig. 21), Welch Mountains (locality 65, fig. 21; "Eternity Range" of Knowles, 1945; Singleton, 1980b) of the Black Coast, and Cape Eielson (now Cape Boggs, locality 19, fig. 21). Semiquantitative spectrographic analyses reveal anomalous amounts of silver in the Lassiter Coast copper deposit (as much as 300 ppm; locality 30, fig. 21; Rowley and others, 1977), the Sky-Hi Nunataks copper deposit (as much as 4 ppm, not including the values from the nearby quartz veins; locality 31, fig. 21), and from the Merrick Mountains stock (as much as 50 ppm; locality 32, fig. 21). Silver values reported by Alarcón and others (1976) from Brooklyn Island and Pelseneer Island in the Wilhelmina Bay area (locality 24, fig. 21) of the Danco Coast are as much as 35 ppm and 32 ppm, respectively.

Traces of gold and silver occur in pyrite-quartz veins in the Cape Denison area of the the Adélie Coast (locality 12, fig. 20; Mawson, 1940; Ravich and others, 1965). Traces of these metals also have been noted in Victoria Land (fig. 20; Fairbridge, 1952).

Platinum-group metals may be present within the Dufek layered gabbro, especially within the unexposed basal parts of the intrusion. To date, however, none have been identified from the intrusion, although anomalous trace amounts of these metals show up in some rock analyses (Ford, this volume).

OTHER METALLIC MINERALS

Lead and zinc minerals have been noted above, in the section on copper minerals, within base-metal veins in the Hurd Peninsula area of Livingston Island (locality 22, fig. 21; Caminos and others, 1973; del Valle and others, 1974; Cox and others, 1980). Anomalous trace values of lead and zinc also occur in rocks from the Lassiter Coast copper deposit (as much as 7,000 ppm lead and 700 ppm zinc; locality 30, fig. 21; Rowley and others, 1977), Sky-Hi copper deposit (as much as 80 ppm lead and 700 ppm zinc, not including the values from the nearby quartz veins; locality 31, fig. 21), Merrick Mountains stock (as much as 300 ppm lead and 700 ppm zinc; locality 32, fig. 21), and the Wilhelmina Bay area (as much as 900 ppm lead and 150 ppm zinc; locality 24, fig. 21; Alarcón and others, 1976). Lead and iron sulfides have been reported from the Haines Mountains (locality 66, fig. 20) of the Edsel Ford Ranges of Marie Byrd Land (Fairbridge, 1952; Kosack, 1955). Here, the mineralization was localized where Cretaceous plutons intruded Cretaceous or older metasedimentary rocks. Lead and zinc sulfides and related minerals were noted by Mawson (1940) from the Cape Denison area (locality 12, fig. 20).

Manganese stains at several places in the Antarctic Peninsula were noted earlier in this report. Small lenses containing tephroite and rhodonite and small amounts of barite, secondary copper minerals, and other manganese minerals occur in chemical and clastic metasedimentary rocks of amphibolite facies and in garnet-bearing gneiss near Casey Station (locality 11, fig. 21; Mason, 1959; Lovering and Prescott, 1979; Lovering and Plimer, 1983). Rocks analyzed from some of these lenses contained 39 percent manganese (Mason, 1959; McLeod, 1965). Ages of metamorphism are Early to Middle Proterozoic, whereas the source area for the clastic material in the sedimentary rocks is of Archean age (Lovering and Plimer, 1983).

Trace amounts of tin, as cassiterite, occur in an erratic from the Terra Nova Bay area (locality 67, fig. 20) of Victoria Land (Stewart, 1939); Cambrian-Ordovician plutons and sedimentary rocks of the Beacon Supergroup constitute the nearest rocks exposed on land. Cassiterite also was found in the heavy-mineral fraction of a Paleozoic sandstone in the Beacon Supergroup from Horn Bluff (locality 68, fig. 20), George V Coast (Mawson, 1940). Bell (1973) reported cassiterite near an Andean pluton in southwestern Alexander Island (locality 49, fig. 21). A tin-bearing mineral was noted by Zeller and others (1979) in the Darwin Glacier area (locality 63, fig. 20) of the Transantarctic Mountains.

Bismuthinite, spodumene, and related bismuth- and lithium-bearing minerals were found by Gunter Faure (oral commun., 1982) in lower Paleozoic pegmatite dikes and veins in the Shackleton Limestone south of Byrd Glacier (locality 55, fig. 20).

MICA

Phlogopite occurs in Precambrian rocks in Enderby Land and in the Humboldt Mountains (locality 15, fig. 20) of Queen Maud Land (Ravich and Solov'ev, 1969). Crystals as much as 5 cm in diameter occur in pockets about 6 to 10 cm long, mostly in diopside layers or lenses in silicate marble or in veins in migmatite. Phlogopite also is present within diopside boudins near pegmatite dikes in the Humboldt Mountains (Ravich and Solov'ev, 1969; Ravich and Kamenev, 1975). Here, phlogopite crystals as long as 20 cm and as thick as 4 cm occur in pockets as much as 60 cm in diameter. Phlogopite constitutes 2 to 4 percent of the boudins. Most commercial phlogopite deposits are of this type, and for this reason Ravich and Kamenev (1975) consider the deposits to be of some potential value.

Ravich and others (1965) and Ravich and Kamenev (1975) reported that muscovite crystals as much as 10 cm in diameter and 5 cm thick are widespread in Precambrian(?) pegmatites in the Humboldt Mountains (locality 15, fig. 20), in Enderby Land (fig. 20), and along the Prince Olav Coast (fig. 20).

GRAPHITE

Graphite is present within Precambrian biotite-garnet gneiss in central Queen Maud Land. It occurs as flakes 1 to 4 mm long, forming 2 to 10 percent of some gneiss layers; layers are as much as 100 m long and 7 m thick (Ravich and others, 1965; Ravich and Solov'ev, 1969). Graphite also occurs in pegmatite dikes, in coarse-grained marble, and in calcite veins cutting the gneiss. Larger but less abundant flakes, 2 to 3 cm in diameter, occur in 1- to 2-m-wide pegmatite dikes (Ravich and Solov'ev, 1969). Clasts of graphite-bearing gneiss also are abundant in moraine deposits in many parts of East Antarctica, and Ravich and others (1965) considered large deposits to be quite likely in these parts of the shield.

PHOSPHATE

Primary sedimentary phosphorite occurs in middle Paleozoic strata of the Elbow Formation and Dover Sandstone of the Beacon Supergroup in the Neptune Range, Pensacola Mountains (locality 16, fig. 20; Cathcart and Schmidt, 1977). It is found in individual beds rarely exceeding 0.5 m in thickness; although the beds underlie an area about 90 km by 30 km, they are not considered to be an economic source of phosphate. Primary sedimentary phosphate also is present as sparse phosphate pebbles within the Triassic Fremouw Formation in the Beardmore Glacier area (locality 69, fig. 20), central Transantarctic Mountains (Barrett, 1969).

COAL

Coal is widespread in Permian through Triassic rocks in Antarctica. Thick beds of coal are known in the Devonian through Jurassic Beacon Supergroup of the Transantarctic Mountains and of the Beaver Lake area in the Prince Charles Mountains (locality 2, fig. 20). None of the deposits are economically recoverable; ones near coastal areas may have the greatest potential for development. The deposits in the Prince Charles Mountains (Bennett and Taylor, 1972), in a Permian part of the Beacon Supergroup, might be somewhat more favorable for development because of their proximity to promising iron deposits and to the coast. Mining of coal to supply local energy needs is a distinct possibility. Summaries of coal occurrences were made by Wright and Williams (1974) and Splettstoesser (1979, 1980, in press).

OTHER NONMETALLIC MINERALS

Green translucent beryl crystals as long as 8 cm have been noted in pegmatites in many parts of the crystalline basement of East Antarctica. The largest known occurrence is in the "Marble Nunataks" northwest of the Humboldt Mountains (locality 15, fig. 20; Ravich and Kamenev, 1975) of central Queen Maud Land, where crystals as long as 7 cm occur in pockets as long as 30 cm. According to Ravich and Solov'ev (1969), one to two beryl pockets are present in each 10 square meters of pegmatite exposure.

Rock crystal (clear quartz) occurs in cavities within zoned pegmatites at 10 localities in the Humboldt Mountains (locality 15, fig. 20; Ravich and Solov'ev, 1969; Ravich and Kamenev, 1975). Smoky and violet crystals as much as 0.7 m long are most common. In some places the crystals form as much as 5 percent of the volume of talus debris, as for example, at "Mount Titov" (locality 70, fig. 20), south of the Humboldt Mountains.

Gemstone localities are rare: the few occurrences reported include minor aquamarine crystals in pegmatite in the "Mount Titov" area (locality 70, fig. 20; Ravich and Solov'ev, 1969), topaz and tourmaline elsewhere in Queen Maud Land (Ravich and others, 1965), and topaz (with fluorite) near Cretaceous plutons in the Rockefeller Mountains (locality 71, fig. 20) of Marie Byrd Land (Wade, 1945). All occurrences are of unknown grade. Garnet is abundant in Antarctica but no reports of gem-grade garnet are known, with the possible exception of green garnet in calc-silicate inclusions in the Dufek intrusion (Aughenbaugh, 1961; Walker, 1961; A. B. Ford, written commun., 1981).

Upper Permian or Triassic nepheline syenite plutons in Queen Maud Land (Ravich and Solov'ev, 1969) are enriched in zirconium and the rare-earth elements niobium, lanthanum, and cerium.

Two veins of radioactive fluorite, each about 1 m thick and more than 100 m long, occur in Cambrian marble (Warren, 1969) adjacent to a granite dike in the dry valleys area of South Victoria Land (locality 61, fig. 20; Zeller and others, 1981).

Native sulfur occurs at Zavodovski Island (locality 72, fig. 20; Kosack, 1955) and in small amounts near fumaroles on Bellingshausen Island (locality 73, fig. 20; Holdgate and Baker, 1979). Both islands are in the South Sandwich Islands and contain active volcanoes (Gass and others, 1963; Holdgate and Baker, 1979). Minor amounts of native sulfur (Roobol, 1980) occur at Deception Island (locality 74, fig. 21), an active volcano in the South Shetland Islands. Sulfur also was reported from Castle Rock (Ferrar, 1907) and Mount Erebus (Kyle and others, 1982) near McMurdo Station (U.S.A.) on Ross Island (locality 75, fig. 20), sites of Quaternary volcanism.

Evaporite salts are forming in many places in Antarctica, generally on sea ice, on rocks, and even within lakes along coastal areas. In the Vestfold Hills (locality 8, fig. 20), for example, salt deposits contain as much as 30 percent total dissolved solids, mostly of sodium and chloride (McLeod, 1965).

Pure coarse-grained white marble occupies a 200 m by 100 m area in the Hektoria Glacier area (locality 76, fig. 21) of Graham Land (Fleet, 1968). Marble doubtless also occurs in many other metamorphic areas of Antarctica, especially in Proterozoic and lower Paleozoic sedimentary rocks of the Transantarctic Mountains, Marie Byrd Land, and Ellsworth Land (McLeod, 1965).

CONCLUSIONS

Metallic and nonmetallic minerals are widespread throughout most of Antarctica, especially in Precambrian rocks, in rocks of the Beacon Supergroup of East Antarctica, and in Mesozoic and Cenozoic rocks of the Antarctic Peninsula. The deposits are similar to those in other Gondwana continents. Nearly all mineral occurrences are small and isolated, and presently have no commercial importance. Mineral concentrations at some localities, however, are great enough that additional study or exploratory drilling would be warranted if they were situated on a continent more favorable for development. Of the deposits that have been discovered in Antarctica, only iron in the Prince Charles Mountains and coal in the Prince Charles Mountains and Transantarctic Mountains might be mined if located on another continent. The iron, copper, and coal deposits probably can be considered "conditional resources", as defined by Brobst and Pratt (1973); huge rises in unit prices are necessary before they could become commercial. The remaining metallic and nonmetallic occurrences in Antarctica probably fall under the heading "hypothetical resources" (Brobst and Pratt, 1973); they are either too poorly studied or require huge rises in unit prices before they could be commercially exploited.

Additional discoveries of metallic and nonmetallic resources are probable in Antarctica as knowledge of the geology, geochemistry, and geophysics of the landmass and its offshore areas increases. It is doubtful, however, that any metallic or nonmetallic mineral resources in Antarctica will be exploited for many years, unless world economic or political conditions change drastically.

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The Dufek Intrusion of Antarctica and a Survey of its Minor Metals and Possible Resources

By Arthur B. Ford

The Dufek intrusion, in the northern Pensacola Mountains of Antarctica (figs. 22 and 23), is one of the world's largest differentiated, layered mafic igneous complexes. It approaches South Africa's Bushveld Complex in size and is an order of magnitude larger than any other known body of this type (table 1). The intrusion is mostly covered by ice. However, reconnaissance geophysical surveys that incompletely define its perimeter indicate an extent greater than 50,000 km^2 (Behrendt and others, 1980). The intrusion was discovered in 1957 during IGY (International Geophysical Year) explorations of ice shelves bordering the southern Weddell Sea (Aughenbaugh, 1961; Walker, 1961). Layered cumulates of chiefly gabbroic composition, but including pyroxenitic and anorthositic compositions, constitute most of the limited areas of outcrop. The basal part of the body is not exposed; the uppermost part consists of late granophyric differentiates that cap the layered cumulate sequence. The body intrudes rocks as young as Permian, and K-Ar (potassium-argon) dating indicates it is coeval with Middle Jurassic tholeiitic basalt magmatism of the Ferrar Group that occurred throughout the Transantarctic Mountains.

Magmatic ore deposits and mineral occurrences of great variety occur in mafic igneous complexes of the stratiform type, nearly all major examples of which contain economically significant resources of one or more metals (Wilson, 1969). Deposits are notably concentrated in lower parts of the bodies in association with early-formed ultramafic and mafic rocks, but they are also known in upper parts. South Africa's Bushveld Complex is an exceptional example, both in size (table 1) and in wealth of known resources, which include the world's largest economically important reserves of chromite, platinum-group elements, and vanadiferous iron ore (Willemse, 1969a).

The great size of the Dufek intrusion and its overall similarity with other stratiform mafic complexes have prompted considerable speculation regarding mineral resources (for example, Runnells, 1970; Wright and Williams, 1974; Wade, 1976; Turner, 1978; Lovering and Prescott, 1979; and Zumberge, 1979a, b). Interest in the Dufek's resource potential was early aroused by mention of ultramafic rock, chromite, and copper minerals in first reports on the body by Aughenbaugh (1961) and Walker (1961) and by a then-possible correlation in age with the Precambrian Bushveld Complex (Harrington, 1965, p. 18), before later fieldwork on the Dufek (Ford and Boyd, 1968) demonstrated its post-Permian age.

Geologic field studies on the intrusion, following its 1957 discovery, have been carried out by the U.S. Geological Survey during three brief summer seasons: 1965–66 (2 months), using helicopters, all major outcrop areas were sampled and mapped at 1:250,000 scale (Ford and others, 1978a, b); 1976–77 (1 month), detailed sampling and 1:50,000-scale geologic mapping was carried out in the area of Dufek Massif (Ford and others, 1977); and 1978–79 (1 month), detailed sampling and 1:50,000-scale geologic mapping was concentrated in the southern Forrestal Range (Ford and others, 1979). A 1965–66 reconnaissance geophysical study of the entire Pensacola Mountains (Behrendt and others, 1974), including the areas of Dufek Massif (Behrendt and others, 1973a) and the southern Forrestal Range (Behrendt and others, 1973b), was extended northward in 1978–79 aeromagnetic surveys made in order to determine the extent of the intrusion under ice near the southern margins of Ronne and Filchner Ice Shelves (Behrendt and others, 1980). Geologic and geophysical studies also have been carried out, since 1975–76, by Soviet parties working from Druzhnaya Base on Filchner Ice Shelf, but the exact nature and results of this work are not known to the author.

Only a few percent of the area of the intrusion is exposed. Even this small part cannot be considered as having been "explored" or even "prospected" in the mining sense. As is generally the case in present studies in Antarctica (Splettstoesser, 1976), the scientific goals of geologic work to date (1983) on the intrusion have resulted in only limited knowledge of resources. For example, chemical analysis of mineral suites for investiga-

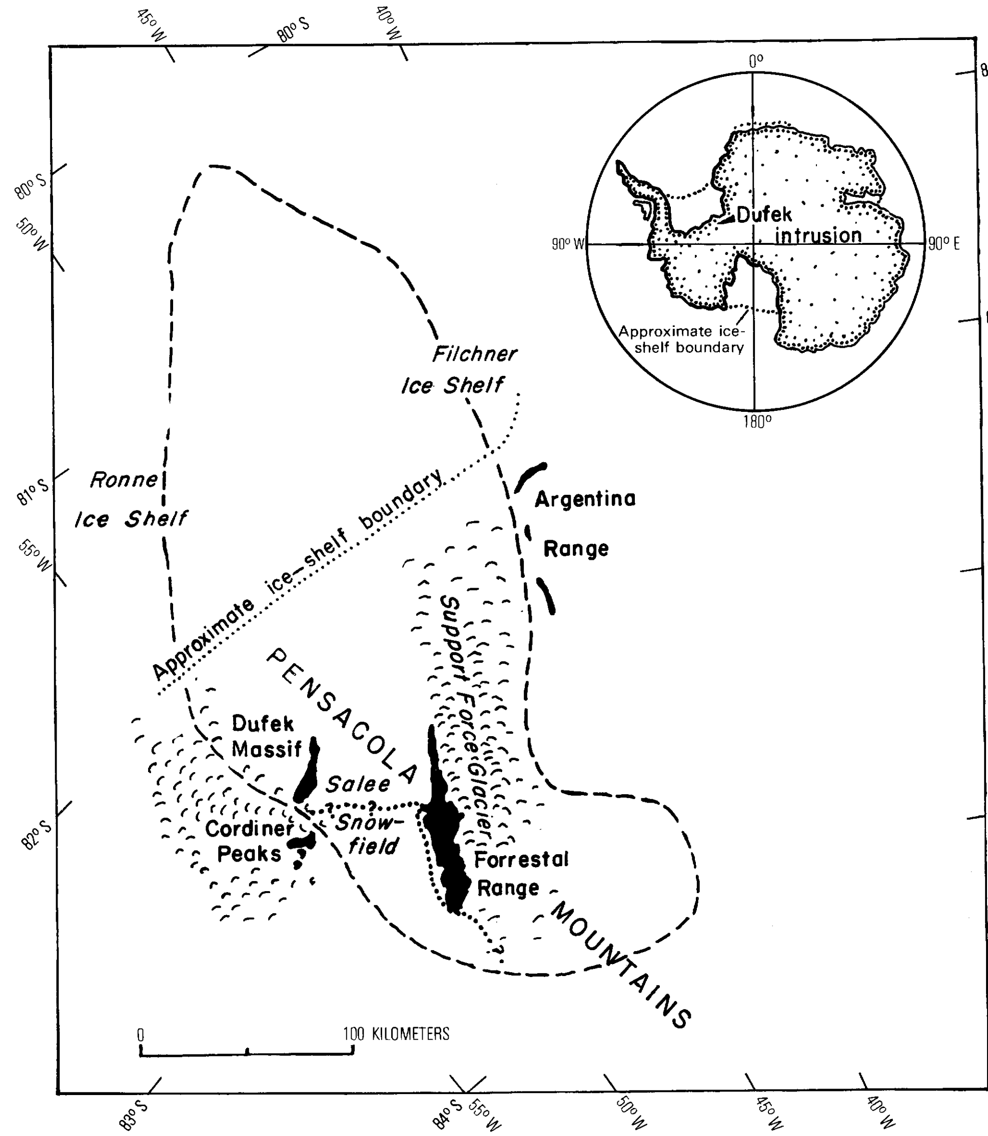

FIGURE 22.—Location of Dufek intrusion in Antarctica and its approximate outline under ice (dashed line), as inferred from geophysical surveys of Behrendt and others (1980). Major areas of rock outcrop shown in black lie in northern one-third of the Pensacola Mountains. Dotted line near Forrestal Range shows contact of the intrusion mapped by Ford and others (1978b); queries indicate uncertainty.

TABLE 1.—*Comparison of areas of selected mafic stratiform intrusions, modified from Willemse (1969a)*

Intrusion	Area (km^2)
Skaergaard intrusion (Greenland)	100
Stillwater Complex (Montana)[1]	200
Sudbury Complex (Ontario)	1340
Ingeli-Insizwa Complex (South Africa)[2]	1800
Great Dyke (Zimbabwe)	3260
Duluth Complex (Minnesota)	4710
Dufek intrusion (Antarctica)[3]	50,000+
Bushveld Complex (South Africa)	67,000

[1]Original area much larger: now greatly deformed and tilted vertically.
[2]Willemse (1969a) gave smaller areas for separate bodies at Insizwa and Ingeli Mountain: size from Wager and Brown (1967), who consider them parts of same original sheet.
[3]From Behrendt and others (1980).

tion of differentiation trends (Himmelberg and Ford, 1976, 1977) shows variations in minor-metal abundances that may be useful for interpreting geochemical resource data.

For the present study, selected minor metals in a reconnaissance suite of 24 mostly typical-appearing rocks were analyzed to investigate ranges of concentrations in a variety of lithologies and of differing stratigraphic level. Most samples approximately represent major layers from which they were obtained; a few contain visible sulfides or more than about 20 percent iron-titanium oxide minerals. Thus, the data contribute only indirectly to a resource study by providing (1) a preliminary survey of normal ranges of element concentration, or "background" values, needed for recognizing anomalous ones that may be found in the future; and (2) information on element associations that may be useful in identifying geochemical tracers, or "pathfinders," as in Levinson's (1974) use of easily analyzed copper, nickel, and chromium as tracers for platinum. Present data, however, are considered inadequate to define accurate background values for principal lithologies or for different stratigraphic levels. For a body of such immense size and lithologic variety, a much larger data base is necessary for accurate definition of normal ranges of element concentrations.

The question of whether the Dufek intrusion contains mineral resources has no clear answer at the present time. Many factors contribute to difficulty in assessing its resource potential. A chief one is the entirely unknown nature of the unexposed basal part of the body (fig. 23), equivalent parts of which in similar bodies contain economically significant deposits of metals (Wilson, 1969). If planned diamond drilling of the body (Turner, 1978) is someday accomplished, though designed primarily for scientific purpose, direct or indirect information may be furnished to aid in evaluating the resource potential of this now unknown part of the intrusion. Other factors include the reconnaissance nature of present work and the lack of opportunity for detailed restudy in the field or sample recollection based on laboratory results. An adequate appraisal of resources requires extensive geochemical surveys of the type recommended and described by Levinson (1974).

All potentially economically useful materials of the intrusion belong to the class "speculative resources," defined by Brobst and Pratt (1973) as being undiscovered resources that may exist in an unknown district in either a known form or an as-yet-to-be recognized form of deposit. This report describes the Dufek intrusion and a variety of resources that might occur in its various parts. However, the extremely limited amount of geochemical data and lack of resource-oriented field study prevent estimation of either potential abundances or probability of occurrence of such resources at the present time. Factors relating to economics and logistics, environmental concerns, and politics of mineral exploitation in Antarctica are treated elsewhere (Potter, 1969; Zumberge, 1979a, b).

ACKNOWLEDGMENTS

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GEOLOGY

AGE AND CORRELATION

The Dufek intrusion is dated on the basis of conventional K-Ar age determinations on plagioclase, averaging 172±4 m.y. (million years), as having formed near the beginning of the Middle Jurassic (Ford and Kistler, 1980). The age is within experimental error of a 179±5 m.y. K-Ar age for diabase sills in Permian siltstone of the Pecora Formation in the southernmost Pensacola Mountains and of a 169±4 m.y. K-Ar minimum age for basalt and diabase dikes in the Devonian Dover Sandstone and the Permian(?) and Carboniferous(?) Gale Mudstone in the Cordiner Peaks (Ford and Kistler, 1980). The ages closely compare with the 175 m.y. age of the dominant phase of diabase sill emplacement and flood basalt eruptions of the Ferrar Group elsewhere in the Transantarctic Mountains (Elliot and others, in press). The Ferrar Group of the Transantarctic Mountains consists of tholeiite characterized by unusually high SiO_2 content and high $^{87}Sr/^{86}Sr$ ratios (about 0.711) that distinguish it from other Jurassic tholeiite in Antarctica. The dikes and sills in the Pensacola Mountains are considered to be comagmatic with the Ferrar Group of the Transantarctic Mountains on the basis of closely comparable chemistry and age (Ford and Kistler, 1980). The Dufek intrusion correlates with this major episode of voluminous tholeiitic magmatism in Antarctica.

TECTONIC SETTING

The Dufek intrusion lies in a recurrently activated mobile belt adjoining the Precambrian craton of East Antarctica, in which major compressive deformation occurred near the end of the Precambrian, in the Beardmore orogeny; in the early Paleozoic Ross orogeny; and again in the Triassic(?) Weddell orogeny[1] (Ford, 1972). The latest folding event can be dated only as having occurred during or after the Late Permian and before the early Middle Jurassic emplacement of the Dufek intrusion. Comparison with events elsewhere suggests a Triassic age of the deformation.

The Dufek intrusion is orders of magnitude larger than any other known intrusive member of the Ferrar Group, and thus an explanation for its origin and location seems to call for uniqueness in setting, and deep crustal or mantle processes related to rifting and magma generation. Transantarctic Mountains rifting related to Ferrar magmatism generally followed the line of Paleozoic or older tectonic mobility across the continent, on the Pacific side of the Precambrian craton. Ford and Kistler (1980) suggested that the rift belt may be an intracontinental failed arm of a Jurassic radial rift system centered near the present Weddell Sea and related to initial breaks in the fragmentation of Gondwana. The Dufek intrusion lies at the Weddell Sea end of the rift belt and thus may not be far from the inferred Jurassic rift intersection and related triple junction in the present southernmost Atlantic Ocean. If so, mantle processes associated with such a system may account for the mafic magmatism of the immense scale represented by this igneous intrusion. The tectonic setting of the intrusion is unique in the Ferrar igneous province in that the Pensacola Mountains are the only part of the Transantarctic Mountains showing evidence of strong compression near the beginning of the Mesozoic. Elsewhere, mobility ceased by Devonian time and was followed into the Jurassic by deposition of the sedimentary platform cover of the Beacon Supergroup. Considerable difference in the grain of crustal structure, therefore, obviously existed between the Pensacola Mountains and elsewhere in the rift belt at the time of the Jurassic magmatism.

The mobile-belt setting of the intrusion appears to differ greatly from the nonorogenic, cratonic setting of large Precambrian stratiform intrusions such as the Bushveld Complex (Naldrett and Cabri, 1976), though all are probably related to rift-type crustal structures. As tectonic setting and, perhaps more importantly, age may be important factors in mineralization (Naldrett and Cabri, 1976), differences in those factors may be

[1] Local name for a poorly dated orogeny probably correlative with some phase of the Triassic Gondwanide orogeny that was widespread in the Southern Hemisphere.

of significance in making comparisons for the purpose of evaluating the resource potential of the Dufek intrusion.

LITHOLOGY AND STRATIGRAPHY

Rocks of gabbroic composition make up 90 percent or more of exposed parts of the intrusion. They are interlain in many areas with rocks of pyroxenitic or anorthositic composition. Except in dikes and the capping layer of granophyre, textures and structures are like those in other layered intrusions that are interpreted in terms of cumulus processes of crystal movement and accumulation on the floor of a magma chamber (Wager and Brown, 1967; Jackson, 1971). Transport mechanisms of crystals may be varied and complex, involving currents of varied nature (Irvine, 1980), and many aspects of cumulus theory may be questioned (McBirney and Noyes, 1979). Rocks of this sedimentlike origin are termed "cumulates" and consist of primary depositional (cumulus) phases in a cementing (postcumulus) matrix of phases formed in whole or part from intercumulus liquid (Jackson, 1971). The chief cumulus phases in the lower exposed part of the intrusion (Dufek Massif) are plagioclase and calcium-rich and calcium-poor pyroxenes; and iron-titanium oxides are additional major cumulus phases in the upper exposed part (Forrestal Range), as shown in figure 23. Cumulus apatite and iron-rich olivine occur in trace amounts only in upper parts of the body, except for local apatite concentrations of as much as several volume percent in the uppermost cumulates.

Individual cumulus minerals show marked concentration at many different stratigraphic levels, forming nearly single-mineral cumulates that are conspicuous, but volumetrically minor, in the overall gabbroic lithology. Such rocks include pyroxene cumulates of the Neuburg and Frost Pyroxenite Members of the Aughenbaugh Gabbro and plagioclase cumulates of the Walker Anorthosite, the Spear Anorthosite Member of the Aughenbaugh, and the Stephens Anorthosite Member of the Saratoga Gabbro (fig. 23). Additionally, iron-titanium oxide cumulate (magnetitite) forms numerous, generally thin layers and lenses as much as about 1 m thick in the Saratoga Gabbro.

The stratigraphic thickness of the body near its south end is estimated to be 8–9 km, of which only about 1.8 km of a lower (not lowest) part is exposed in Dufek Massif and about 1.7 km of the upper part is exposed in the Forrestal Range (Ford, 1976). The entire exposed sequence consists of cumulates, except for a 240+ m-thick, apparently conformable, capping layer of the Lexington Granophyre. Major unexposed parts in this area are a basal section, estimated from geophysical evidence to be 1.8–3.5 km thick (Behrendt and others, 1974), and an inferred intermediate interval estimated to be 2–3 km thick concealed by Sallee Snowfield.

STRUCTURE

LAYERING

The most conspicuous primary structure is compositional layering (fig. 24) that occurs on various scales throughout the body. Layers reflect variable proportions with stratigraphic level of the cumulus minerals. Though individually of generally uniform lateral thickness, different layers range widely in thickness from a few centimeters or less to tens of meters or more. Tabular plagioclase is generally alined ("igneous lamination" of Wager and Brown, 1967), but is randomly oriented in the layering plane.

Major layers having meter-scale thickness of generally 1–15 m show marked contrast in form with the more characteristically present minor layers having millimeter- or centimeter-scale thickness. Major layers are generally of uniform thickness and show extremely great lateral continuity, with ratios of lateral extent to thickness on the order of 10^3:1 or greater. Ratios of extent to thickness are probably at least as high as those (10^4:1 to 10^5:1) characteristic of other stratiform intrusions (Jackson, 1971), considering their continued extent under ice cover. Most major layers of single-mineral cumulate show sharp basal contacts and gradation upward into gabbroic cumulates; a few show both lower and upper contacts as being sharp. Those with gradational tops are termed "modally graded" (Irvine, 1982) and those having uniform proportions of cumulus minerals with stratigraphic level, up to a sharp top contact, are termed "isomodal" (Jackson, 1971). The Neuburg and Frost Pyroxenite Members each consist of one or more modally graded major layers of pyroxene cumulate. The Spear and Stephens Anorthosite Members each consist of several such layers of plagioclase cumulate. Isomodal major layers of plagioclase cumulate occur within gabbroic cumulates at several stratigraphic levels.

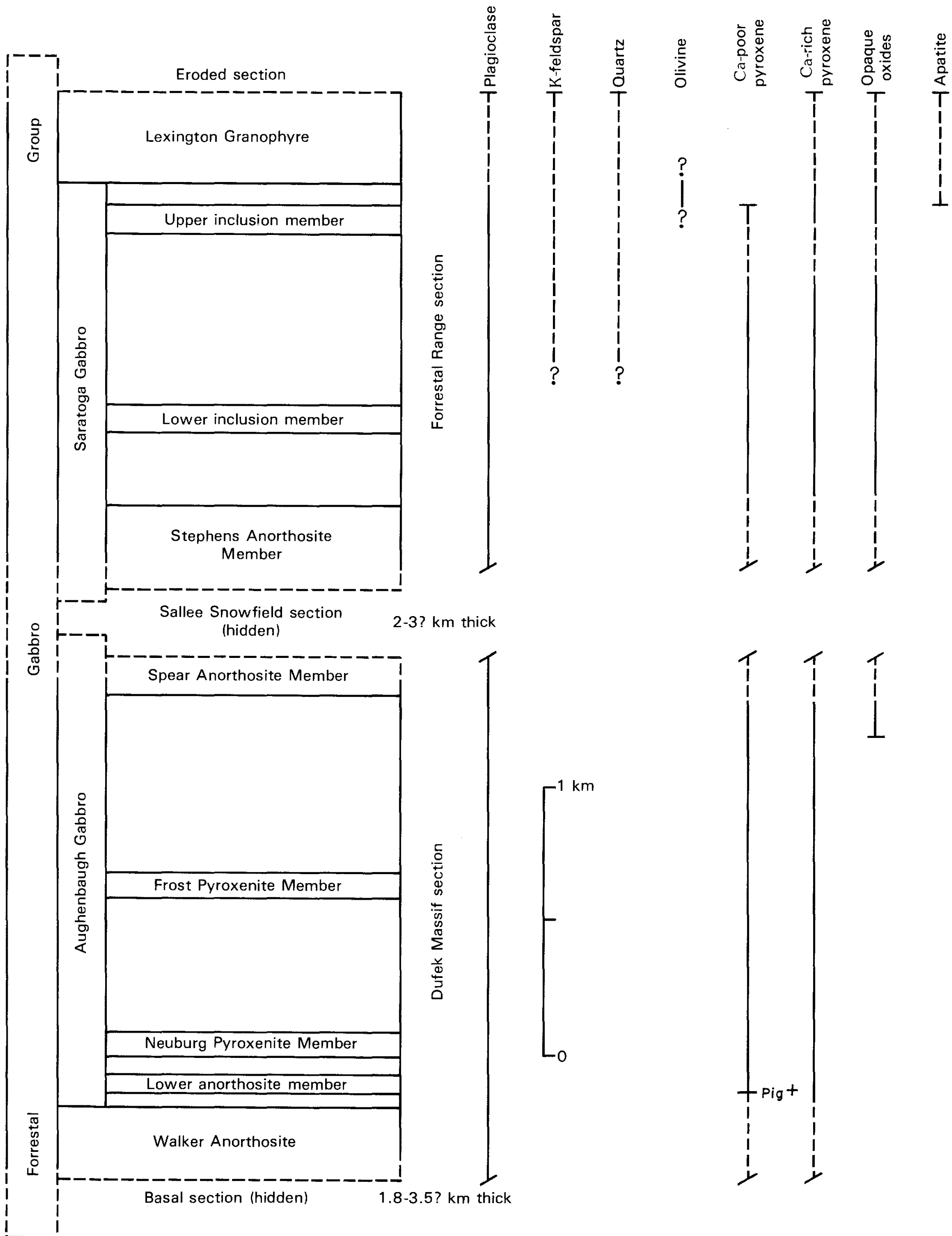

FIGURE 23.—Rock-stratigraphic nomenclature of Dufek intrusion and generalized range of minerals. Solid vertical lines show cumulus minerals; dashed lines, noncumulus or postcumulus minerals; queries indicate uncertainty. Pig+, lowest occurrence of cumulus (inverted) pigeonite. (Modified from Ford, 1976 and Himmelberg and Ford, 1976.)

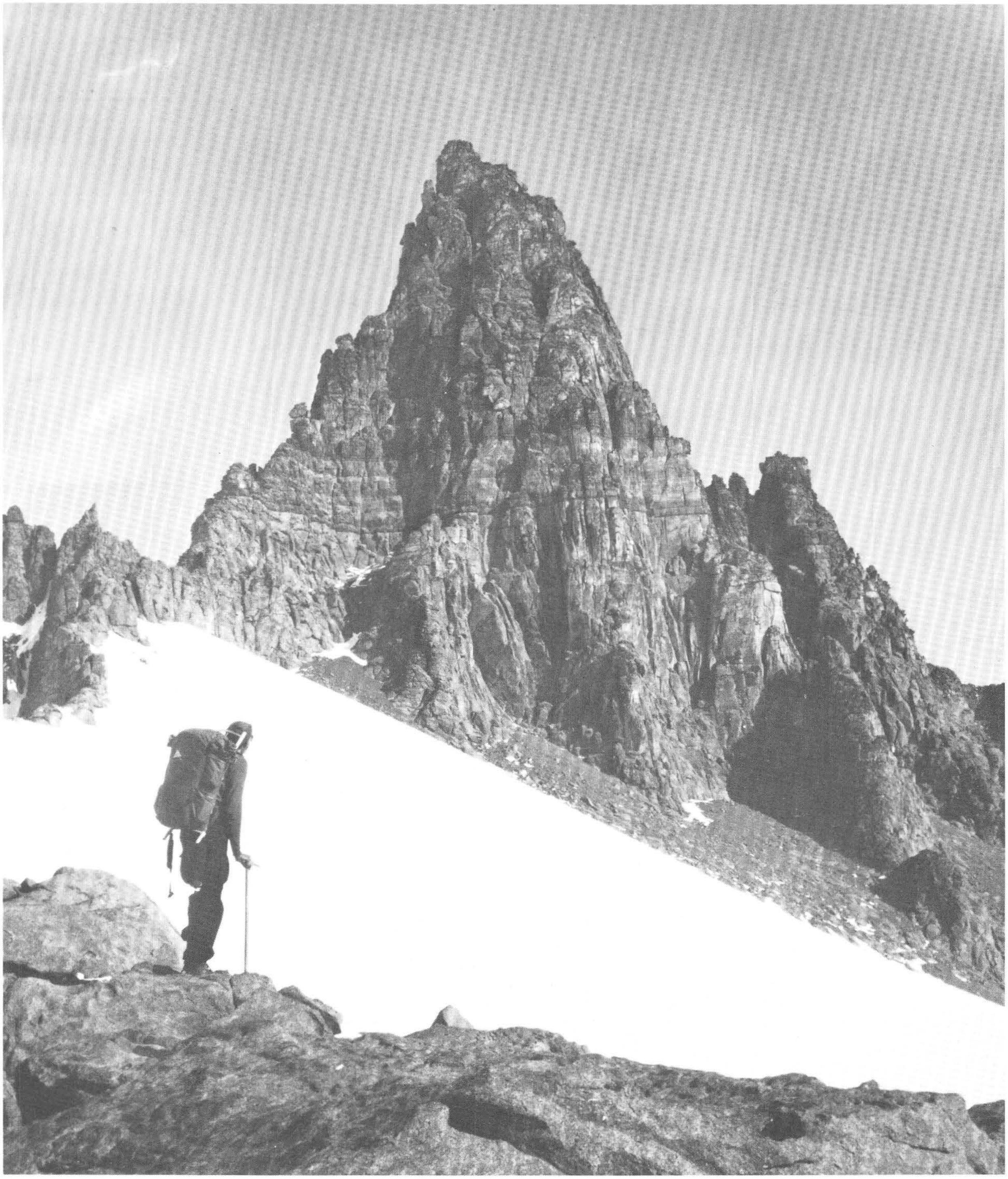

FIGURE 24.—Summit of Aughenbaugh Peak showing layers of pyroxenite (dark bands) of Frost Pyroxenite Member of Aughenbaugh Gabbro.

The sharp upper contact of the Walker Anorthosite suggests that this unit is probably also of isomodal type, but with an exceptional thickness of greater than 240 m. Contrasting with major layers, millimeter- and centimeter-scale layers generally are discontinuous and rarely traceable for more than a few tens of meters, have gradational upper and lower contacts, and commonly show rhythmic-appearing repetition. Whereas modally graded major layers may have formed by deposition from crystal-laden currents, thinly layered to uniform cumulates probably originate by other mechanisms such as bottom crystallization (Irvine, 1980).

TROUGH STRUCTURE

Large channel-like structures possibly resembling the "trough banding" in the Skaergaard intrusion, Greenland (Wager and Brown, 1967), are known to be associated with several modally graded major layers: those in Frost Pyroxenite Member are filled with pyroxene cumulate, and those in Stephens Anorthosite Member are filled with plagioclase cumulate (fig. 25). Trough axes approximately parallel the layering plane. The truncation of laminae in underlying cumulates indicates erosion by currents along the floor, possibly related to convection or density flow (Irvine, 1980) analogous to cut-and-fill channels in sedimentary rocks. Smaller troughs of as much as about 1 m depth in the iron-enriched upper part of the intrusion are filled with iron-titanium oxide cumulate. Current activity was probably common (Irvine, 1980) during formation of most of the layered sequence and obviously was an important process in locally concentrating some of the minerals.

INTRUSIVE FORM

The large ratio of inferred area to thickness, approximately 5×10^3:1, suggests an overall sheetlike form of the body. Naldrett and Cabri (1976) classified the Dufek in a category "sills and sheets equivalent to flood basalts," along with the much smaller Palisades sill of New Jersey and the Ingeli-Insizwa intrusion of Natal, South Africa. A body of such enormous dimensions and apparent volume (~400,000 km^3?) doubtless must have a far more complex structure than the simple, broad synclinal sheet of lopolithlike form apparent in its small area of exposure (Ford and others, 1978a, b).

Although neither floor nor roof is exposed, discordancy is shown at the single small exposure of the contact, in the Forrestal Range, where a steep wall of noncumulus gabbro, marginal to the layered cumulate sequence, cuts folded Devonian quartzite at high angle. General discordancy of the body is shown by the regional truncation of north-northeast-trending folds in Precambrian to Permian country rocks across the entire breadth of the northern Pensacola Mountains. Thus, the intrusion obviously lacks the concordancy of a classic lopolith, a form originally proposed but no longer held for the Bushveld Complex (Willemse, 1969a).

How a body of this size could be related to only a single intrusive center, if it is, is difficult to conceive. No center has yet been geophysically identified. The approximate outline of the intrusion, determined by geophysical surveys of Behrendt and others (1974, 1980), includes a large, lobate extension southeast of the Forrestal Range, under the Support Force Glacier and adjoining ice sheet (fig. 22). Other lobes conceivably exist, though have not been identified in the reconnaissance surveys. In the Bushveld Complex, a pronounced, multiple lobate outline reflects presence of five adjoining basin-shaped bodies with inferred intrusive centers (Willemse, 1969a). It seems possible, if not likely in view of a size comparable to the Bushveld, that the Dufek intrusion similarly consists of more than a single body, even though all its exposed rocks are apparently related to but one.

SYNCLINAL STRUCTURE

The overall structure is that of a broad syncline, or elongate funnel(?), with a N. 20°–25° E.-trending subhorizontal axis centered in the Forrestal Range. Latest silicic differentiates (Lexington Granophyre) occupy the axial belt and are underlain by mostly well layered, iron-enriched gabbroic cumulates (Saratoga Gabbro). A 5°–10° southeast-dipping homoclinal sequence of layered cumulates (Walker Anorthosite and Aughenbaugh Gabbro) of Dufek Massif forms the apparent west limb of the syncline. Rocks of the Dufek Massif section are therefore believed to extend beneath and beyond Sallee Snowfield and to underlie those of the Forrestal Range section (fig. 23).

The synclinal structure was originally considered to be of possible tectonic origin on the basis of comparable structural geometry in folded country rocks (Ford and Boyd, 1968). However, a distinct, though slight, regional angular discordance of as much as about 10° has since been found within the cumulate sequence near the synclinal axis and about 1 km from the top of the body (Ford and others, 1979). The discordance is postulated to be the result of rather sudden subsidence at a late stage of consolidation. Downward movements in solidified cumulates may in part have

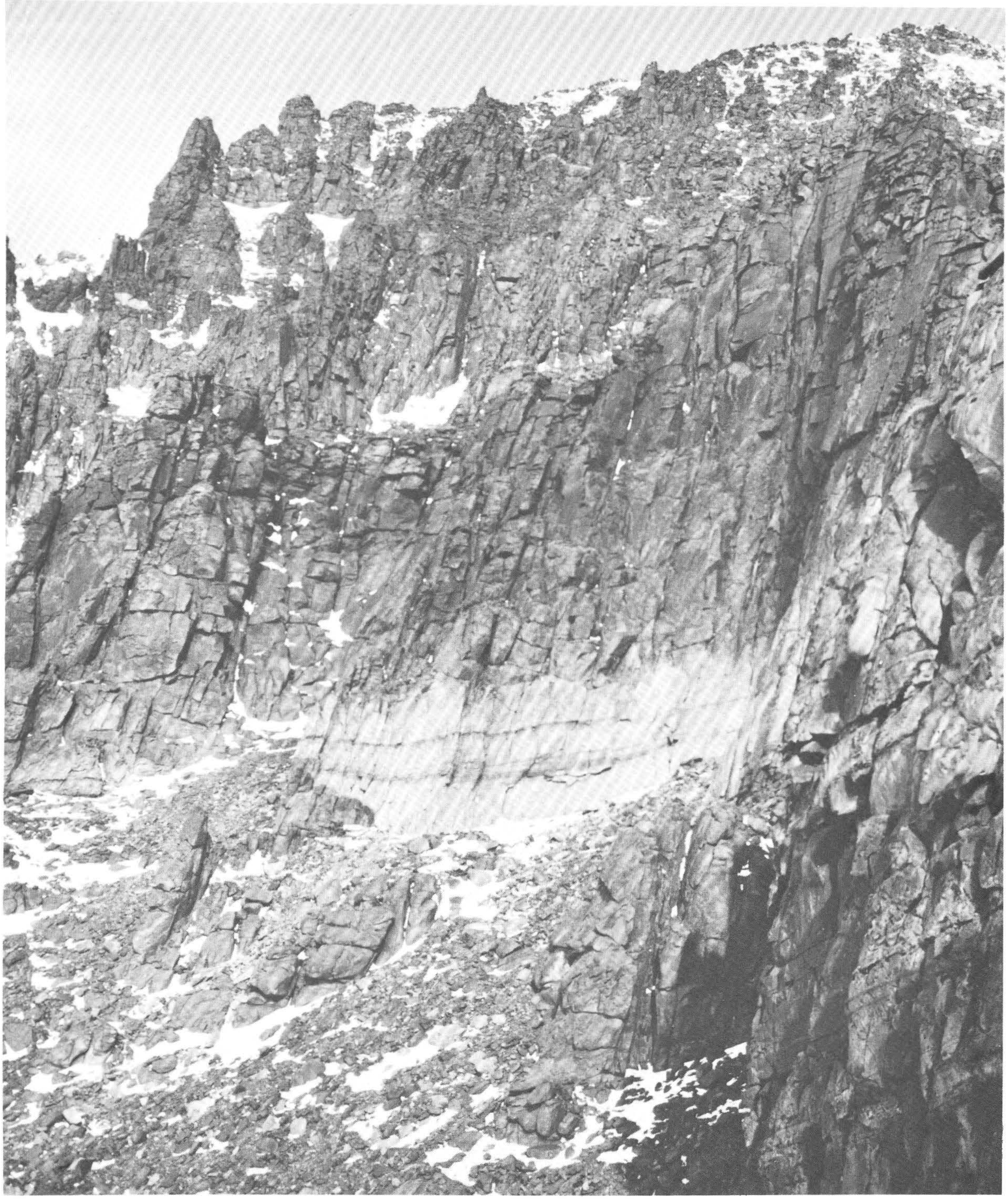

FIGURE 25.—Cross section of anorthosite-filled channel structure of at least 10 m thickness in dark, iron-rich layered gabbro in southern Forrestal Range.

been distributed along a pervasive system of subvertical microshears generally paralleling the axial plane of the syncline. An abundance of large anorthosite and leucogabbro inclusions showing chaotic array in the gabbro layer above the discordance (fig. 16 *in* Ford, 1976) suggests that subsidence was associated with considerable disruption within the chamber.

FAULTS

Layered cumulates on the northwest side of Dufek Massif show northwestward downdropping along several strands of the Enchanted Valley fault (Ford and others, 1978a). Although exposed displacements are small, the faults are probably surface expressions of part of a major high-angle fault zone along the west side of the Pensacola Mountains that shows about 4 km west-side downdropping based on geophysical evidence (Behrendt and others, 1974). Behrendt and others (1980) suggested occurrence of a major fault, also along the southeast side of the Forrestal Range, on the basis of about 2 km local relief, but this fault is not exposed. Other concealed faults in the vicinity are inferred to be older than the intrusion (Ford and others, 1978b).

GENERAL MAJOR-ELEMENT CHEMICAL TRENDS

LAYERED ROCKS

Layered bodies of this type show similarities with sedimentary sequences, and therefore relative ages of layers are generally inferrable by superposition (Jackson, 1971). Using stratigraphic levels, results of magma differentiation can generally be tied to an age sequence of chemical variation of rocks and minerals. Owing to mineral sorting, however, chemistry of rocks may differ greatly from that of magma from which they formed, as in the extreme cases of single-mineral cumulates such as those of the Frost Pyroxenite and Stephens Anorthosite Members. If many uniform cumulates, even though thinly layered, form by in-place crystallization on the floor (Irvine, 1980), their compositions may approach magma compositions, but some movement of intercumulus liquid into overlying magma would be expected. The compositions of such "average" rocks—those in which proportions of cumulus crystals approximate proportions of primocrysts precipitating from coexisting liquid (Wager and Brown, 1967)—in the Dufek intrusion show trends similar to chemical trends of cumulus minerals (fig. 26).

In the Dufek intrusion, gabbroic rocks of average-appearing mineralogy and lacking evidence of sorting exhibit a pattern of compositional change with stratigraphic level generally similar to that in other mafic stratiform intrusions. Stratigraphically related changes include a slight upward decrease in SiO_2; a strong upward increase in TiO_2; a slight upward increase in K_2O; and a slight upward increase in P_2O_5 until just below the granophyre layer where a sharp, nearly tenfold increase to about 2.0 weight percent occurs (Ford, unpublished data). The most conspicuous variation is in strong enrichment in iron relative to magnesium, as shown by the mafic index (fig. 26*A*). Average-appearing cumulates of Dufek Massif have mafic index values between about 50 and 65, whereas those of the Forrestal Range, representing a later stage of differentiation, have mafic index values between about 75 and 90. The latest-stage rocks (Lexington Granophyre) have mafic indexes of about 90 or greater. Rocks of the hidden Sallee Snowfield section are inferred to have characteristics intermediate between those of adjoining parts of the exposed sections. The hidden basal section can only be inferred as possibly having characteristics similar to basal parts of other stratiform mafic intrusions.

CUMULUS MINERALS

Coexisting cumulus pyroxenes in the series augite-ferroaugite and bronzite-inverted pigeonite also show general iron enrichment with higher stratigraphic level in the layered sequence (fig. 26*B*). Cumulus plagioclase varies upward from about An_{80} in Walker Anorthosite to An_{50} in uppermost cumulates below the Lexington Granophyre (Abel and others, 1979). Compositional ranges and the generally systematic variations with stratigraphic level more or less parallel those of pyroxenes and plagioclase in other layered intrusions (Wager and Brown, 1967), though differences also exist. On the other hand, except for decrease upward in the minor constituents Al_2O_3 and V_2O_3 in ilmeno-magnetite, compositions of cumulus iron-titanium oxides show no systematic variation, owing to subsolidus recrystallization and lower temperature equilibration (Himmelberg and Ford, 1977).

INFERRED ORIGINAL MAGMA

Bulk metal content of a stratiform complex obviously relates in some degree to physical-chemical characteristics of an original magma or magmas,

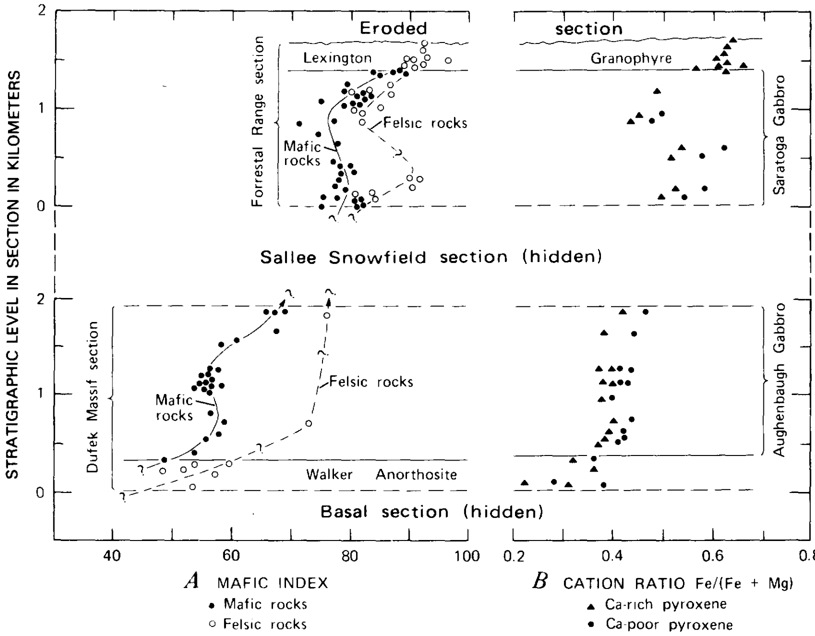

FIGURE 26.—Chemical variation in Dufek intrusion. *A*, mafic index ($FeO + Fe_2O_3 \times 100/(FeO + Fe_2O_3 + MgO)$) of rocks (queries indicate uncertainty); *B*, cation ratio, Fe/(Fe + Mg) in pyroxenes. (From Ford, 1976 and Himmelberg and Ford, 1976.)

though concentration into usable deposits depends on many additional factors. Determination of an original magma composition for such a differentiated body is difficult, and any approach can be questioned. Compositions have been inferred from those of little-differentiated rocks from chilled margins or satellitic dikes and sills (Jackson, 1971), or by using weighted-average bulk composition of the entire differentiated-rock sequence (Maske, 1966). Possibility of multiple emplacement, magma inhomogeneity, and chemical interchange with wall rocks or other chemical gain or loss make either approach uncertain, though an average bulk composition might provide a useful test for a composition inferred from other evidence (Gunn, 1966).

Evidence for estimating an original Dufek magma composition is lacking from the intrusion itself: the iron-enriched composition of the only exposed contact rocks shows chilling of differentiated magma (Ford, 1970), and lack of exposure of major parts of the layered sequence precludes use of an average bulk composition. Lacking better evidence, an original composition is tentatively inferred to be represented by the average composition of the little-differentiated satellitic dikes in the Cordiner Peaks (Ford and Kistler, 1980). The dikes are the hypabyssal bodies of the Ferrar Group nearest to the Dufek intrusion. Their average composition is that of a quartz-normative hypersthene tholeiite not greatly unlike compositions inferred for other stratiform complexes, except chiefly for the far more magnesian Great Dyke of Zimbabwe (table 2). Higher SiO_2 content than in the other inferred magmas may account for an absence of cumulus magnesian olivine in all known parts of the Dufek's layered sequence, in contrast to its occurrence in mafic lower parts of the other bodies, even at stratigraphic levels having comparable plagioclase compositions (Wager and Brown, 1967). However, as discussed later, rocks of the lower-exposed Dufek Massif section are believed to lie stratigraphically higher than comparable parts containing cumulus olivine (and chromite) of other layered intrusions (fig. 27). A siliceous nature of the magma may also account for the high average SiO_2 content (about 52 percent) of the entire lower exposed section of the intrusion, in which traces of postcumulus quartz are common (Ford, 1970).

TABLE 2.—*Chemical analyses, in weight percent, of little-differentiated rocks inferred to represent original magmas of selected mafic stratiform intrusions*

[Dufek intrusion (Cordiner Peaks dikes) from Ford and Kistler (1980); others (chilled border rocks) from Jackson (1971)]

	Dufek	Bushveld		Stillwater		Great Dyke
		1	2	1	2	
SiO_2	53.3	51.45	50.55	50.68	49.41	48.68
Al_2O_3	15.5	18.67	15.23	17.64	15.78	9.89
Fe_2O_3	1.5	.28	1.04	.26	2.11	1.15
FeO	8.0	9.04	10.07	9.88	10.25	9.43
MgO	6.6	6.84	8.30	7.71	7.36	19.96
CaO	10.3	10.95	11.30	10.47	10.88	7.54
Na_2O_3	1.9	1.58	2.24	1.87	2.19	1.33
K_2O	.72	.14	.19	.24	.16	.43
TiO_2	.65	.34	.66	.45	1.20	.57
P_2O_5	.15	.09	.12	.09	.11	.04
MnO	.13	.47	.23	.15	.20	.17
H_2O+	.89	.34	.24	.42	.23	.39
Total--	99.7	100.22	100.18	99.92	99.95	99.92

THE QUESTION OF MULTIPLE EMPLACEMENT

The formation of a magma chamber of the apparently immense volume of this intrusion by input of a single batch of magma is difficult to envision. However, the generally regular compositional variation shown by progressive iron enrichment of pyroxenes (fig. 26) and albite enrichment of plagioclase (Abel and others, 1979) up to a stratigraphic level about 1 km below the top of the body provides no evidence otherwise for the major part of the stratigraphic sequence.

A strong reversal in chemical trends of rocks and all investigated cumulus minerals, including trends of some minor elements in ilmeno-magnetite (Himmelberg and Ford, 1977), occurs at about 1 km depth in the layered sequence (fig. 26; Abel and others, 1979). As trends of all major cumulus minerals are involved, the reversal is probably best explained as being the result of an influx of new magma following a long period of differentiation. A marked reversal in the upper part of the Bushveld Complex is interpreted similarly (von Gruenewaldt, 1979). The added magma probably mixed to a large extent with residual differentiated magma, and further differentiation led to renewed iron enrichment and eventual development of the granophyre layer that caps the cumulate sequence (fig. 26). The reversal occurs at or near the previously described leucocratic inclusion-rich layer lying on the regional angular discordance within the cumulate sequence. This association suggests that introduction of new magma was somehow related to the subsidence event inferred from the discordancy, perhaps in part by the withdrawal of magma from depth.

Major chemical-trend reversals may also exist in unknown parts of the body. However, the apparent mergence of trends leading up to and up from the hidden Sallee Snowfield section (fig. 26) shows no evidence for one in that section. Even less is inferrable about the nature of the hidden basal section. For the Bushveld Complex, von Gruenewaldt (1979) questioned whether a tholeiitic magma could have produced the large volume of ultramafic rock present, and therefore postulated an initial emplacement of magma of ultramafic composition. Emplacement of early ultramafic magma is also postulated for the Stillwater Complex (Todd and others, 1982). A similar occurrence must be considered possible in the unexposed basal part of the Dufek intrusion.

Distinct reversals in plagioclase trends, with stratigraphic level, occur in or near major modally

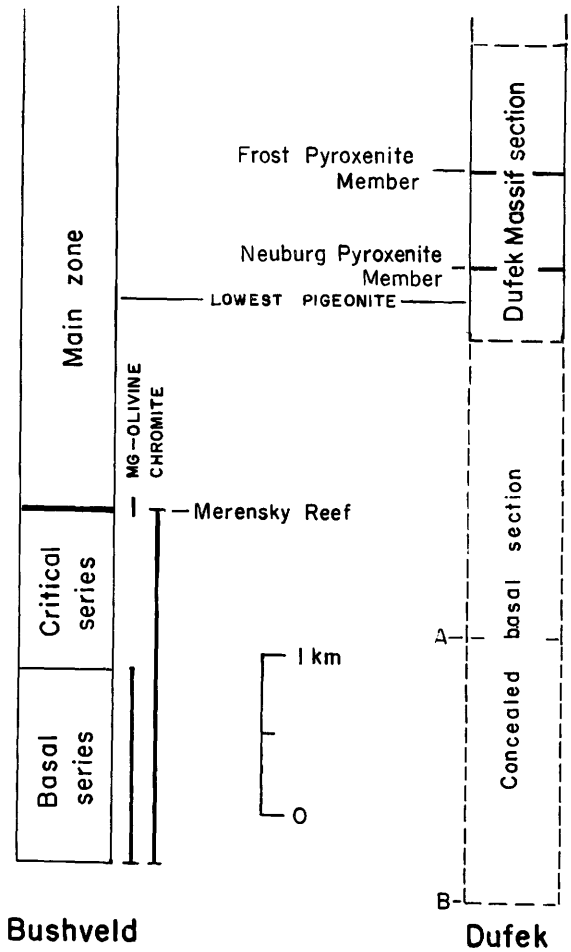

FIGURE 27.—Possible comparison between lower parts of the Bushveld Complex and the Dufek intrusion based on lowest occurrence of cumulus (inverted) pigeonite as a correlation marker. A and B show minimum and maximum thickness estimates of the concealed basal section of the Dufek intrusion, from Behrendt and others (1974). (Modified from Ford and others, in press.)

graded layers of the Neuberg and Frost Pyroxenite Members and the Stephens Anorthosite Member (Abel and others, 1979), where they are not accompanied by pyroxene reversals. The presence of such marked difference in fractionation trends of different coexisting mineral series at these localities seems to require some mechanism other than addition of magma from either an external source or by shifting in the chamber, both of which should be reflected in trends of all coexisting cumulus minerals. Irvine's (1980) explanation for the origin of included blocks of leucocratic rock in layered gabbro by the accumulation of some plagioclase near the chamber roof at the same time that other plagioclase is deposited along with mafic minerals at the floor may have a bearing on the origin of the single-mineral (plagioclase) reversals in the Dufek intrusion. If plagioclase resides in a cloud of crystals near the roof for some time while other plagioclase and pyroxenes crystallize from differentiating magma near the floor, an episode of current downflow would deposit earlier formed crystals on later ones, which might account for the differences in fractionation trends of plagioclase and pyroxene in the intrusion. Reversals marked by only plagioclase, therefore, are not believed to be indicative of multiple emplacement.

SULFIDE-MINERAL OCCURRENCES

Minor amounts of sulfide minerals are scattered widely throughout the layered sequence and in all lithologies. Their distribution is highly sporadic along as well as across layering. Concentrations of more than a few percent are not known. Walker (1961) reported occurrences of bornite(?), chalcopyrite, and pyrite along the northern base of Dufek Massif. Green efflorescences of atacamite are common and conspicuous, in many places where parent copper sulfide is not visible. Sulfide mineralogy has not been studied in detail, but chalcopyrite and pyrite or pyrrhotite megascopically appear to be the chief primary phases. Occurrences are much more numerous in the Forrestal Range than in the Dufek Massif, with greatest frequency being in iron-titanium oxide-rich layers. In Dufek Massif, their typical association with hornfels xenoliths suggests an origin related to reaction and magma contamination. Occurrences in iron-rich layers in the Forrestal Range appear similar to those in the upper part of the Bushveld Complex, in which sulfide precipitation is related to magnetite crystallization (von Gruenewaldt, 1976).

MINOR METALS IN THE INTRUSION

This report summarizes results of a reconnaissance geochemical survey of abundances of titanium, nickel, chromium, cobalt, vanadium, copper, platinum, palladium, rhodium, and sulfur in rocks of the Dufek intrusion (Ford and others, 1983). Platinum-group elements were analyzed by the method of Haffty and others (1977), which has lower determination limits of 10 ppb (parts per billion) for platinum, 4 ppb for palladium, and 5 ppb for rhodium. Titanium was determined, along with major elements, by the method of Shapiro (1975). Total sulfur was determined by X-ray fluorescence, and other elements by quantitative spectrographic methods.

Twenty-four samples were analyzed in this study, most selected on the basis of representing typical lithologies at a variety of stratigraphic levels. From the highly variable distribution of sulfide minerals along layering, it is obvious that there must be considerable lateral variation in minor-metal abundances. Significant lateral variation in platinum-group element abundance, for example, is known to occur in the Stillwater Complex of Montana (Page and others, 1972).

INFERRED ORIGINAL MAGMA

As inferred from compositions of little-differentiated satellitic mafic dikes of the Cordiner Peaks, the original magma apparently contained about normal amounts of most analyzed metals for a magma of quartz tholeiitic composition. The dike rocks contain an average (nine analyses) of 11 ppb platinum, 8 ppb palladium, 5 ppb rhodium, 112 ppm (parts per million) copper, 252 ppm vanadium, 44 ppm cobalt, 168 ppm chromium, 89 ppm nickel, and 0.65 percent TiO_2 (Ford, unpublished data). In comparison, the inferred original basaltic magma of the Stillwater Complex contained 12 ppb platinum, 55 ppb palladium, and 5 ppb rhodium (Page and others, 1976).

VARIATION WITH STRATIGRAPHIC LEVEL

The nonparametric Spearman's rank correlation coefficient, r_s, is used in this study for determining degree of correlation of element abundances with stratigraphic level owing to smallness of the sample set, an apparent non-normal distribution, the presence of censored data, and the unknown thickness of concealed intervals. The strongest positive correlations with stratigraphic level are shown by Fe_2O_3 and TiO_2, followed closely by copper (table 3). Vanadium and cobalt show moderate positive correlation, and chromium and SiO_2 show moderate negative correlation with stratigraphic level. The statistic r_s, however, only shows degree of linear correlation. The correlations of table 3 are generally consistent with overall variations in element abundances with stratigraphic level in the Skaergaard intrusion that Wager and Brown (1967) showed to be nonlinear for most elements. Elements such as nickel and those of the platinum group show no statistically close correlation with stratigraphic level (table 3), but comparison of average abundances between the lower and upper parts of the body (table 4) indicates presence of broad variations with stratigraphic level. For convenience of reference, arbitrary terms for the sequence of solidification of the intrusion are used in the following discussion as shown in table 4.

PLATINUM-GROUP ELEMENTS

Rhodium is below limits of determination in all samples, except for a single sample of melagabbroic cumulate from near the base of the Forrestal Range section that contains 12 ppb rhodium. The sample contains a trace of visible sulfides and an abundance (34 percent) of iron-titanium oxide minerals. Platinum or palladium contents are determinable in five of 13 (38 percent) analyzed early-stage cumulates and in six of nine (67 percent) analyzed late-stage cumulates. The high percentage of samples with platinum-group element concentrations below limits of determination precludes calculation of exact averages. Table 4, accordingly, shows ranges of possible averages based on possible concentration ranges for samples below limits of determination. The maximum analyzed platinum content of 35 ppb is in the above-mentioned sample containing 12 ppb rhodium. The maximum analyzed palladium content of 44 ppb is in a gabbroic cumulate from about 350 m height in the Forrestal Range section that contains 9 percent iron-titanium oxide minerals and is free of visible sulfides. No platinum-group minerals have yet been identified, but a detailed search for them has not been made.

The platinum-group elements show no statistical correlation with stratigraphic level (table 3). Late-stage cumulates are obviously enriched in the elements compared to early-stage cumulates, as shown by their greater percentage of platinum-group element occurrences above determination limits and by greater average abundances, which suggests enrichment during differentiation periods represented by the two exposed sections.

COPPER AND SULFUR

Copper correlates strongly with stratigraphic level (table 3), which, along with its more than six-fold increase in average abundance from early- to late-stage cumulates (table 4), suggests marked enrichment during differentiation. Copper enrich-

TABLE 3.—*Spearman rank correlation coefficients for chemical constituents with stratigraphic level and mineral content (modal volume percent) in 22 analyzed cumulates of the Dufek intrusion*

	Height	Minerals	
		Iron-titanium oxides	Pyroxenes
SiO_2	−0.55	−0.60	0.01
Fe_2O_3	.93	.89	.19
FeO	.63	.27	.78
MgO	−.06	−.18	.91
TiO_2	.88	.87	.26
MnO	.33	.21	.92
Ni	−.20	−.15	.62
Cr	−.47	−.45	.33
Co	.51	.44	.74
V	.62	.61	.28
Cu	.81	.83	.18
Pt + Pd	.29	.53	.00
S	.37	.56	.21
Ni/Co	−.84	−.52	.11
Mafic index	.84	.89	−.17

ment is accompanied by sulfur enrichment, though to a much lesser degree. Both elements show strong depletion upward from late-stage cumulates to latest-stage granophyre, but average abundances in the granophyre are somewhat greater than in early-stage cumulates.

TITANIUM, VANADIUM, AND COBALT

An increase in titanium, vanadium, and cobalt by differentiation is shown by correlations with stratigraphic level in table 3. TiO_2 has an approximate tenfold, vanadium a more than threefold, and

TABLE 4.—*Summary of minor-element content of typical rocks from the layered sequence of the Dufek intrusion, from data in Ford and others (in press)*

[If parentheses are shown, all values are below limit of determination. Where a range in average is shown, true value lies between indicated limits, based on limits of determination. Analyzed samples of cumulates include rocks of gabbroic, anorthositic, and pyroxenitic composition that contain only traces of, or no, visible sulfides. See text for analysis of sample containing 2 percent visible sulfides]

Solidification stage	Number of samples		Pt	Pd	Rh	S	Cu	V	Co	Cr	Ni	TiO_2
			(ppb)					(ppm)				(wt.pct)
Latest (granophyre of Forrestal Range).	2	range:	(<10)	(<4)	(<5)	130–140	32–36	6–15	7–8	<2–2	(<2)	0.68–1.6
		average:	0–9	0–3	0–4	135	34	11	8	2	<2	1.2
Late (cumulates of Forrestal Range).	8	range:	<10–35	<4–44	<5–12	20–800	90–460	80–2,000	38–120	2–65	2–190	1.2–8.6
		average:	9–17	9–11	2–5	226	195	698	70	20	49	3.9
Middle (concealed)	---	---	---	---	---	---	---	---	---	---	---	---
Early (cumulates of Dufek Massif).	13	range:	<10–15	<4–10	(<5)	40–190	12–40	55–460	8–90	14–480	12–150	.06–.87
		average:	3–10	1–4	0–4	101	29	198	50	174	76	.34
Earliest (concealed)	---	---	---	---	---	---	---	---	---	---	---	---

cobalt only a slight increase in average abundance upward from early- to late-stage cumulates. Farther upward, all show a large decrease into the granophyre layer. The granophyre, however, is significantly enriched in TiO_2 compared with early-stage cumulates, in contrast to cobalt and, particularly, vanadium.

CHROMIUM AND NICKEL

An approximate eightfold upward decrease in average abundance of chromium shows significant depletion of the element with differentiation from early- to late-stage cumulates (table 4), a depletion shown much less markedly by chromium correlation with stratigraphic level (table 3). The average nickel abundance in late-stage cumulates is strongly weighted by a single sample of iron-titanium oxide-rich cumulate (the same previously described sample having exceptional abundances of rhodium and platinum) that contains 190 ppm nickel. Excluding that sample, nickel would average 34 ppm and have a range of 2 ppm-65 ppm in late-stage cumulates. Although nickel shows only slight negative correlation with stratigraphic level its approximate twofold decrease from early- to late-stage cumulates suggests slight to moderate depletion during differentiation. The granophyre is markedly depleted in both elements compared to all the underlying cumulates. The strong negative correlation of the ratio nickel/cobalt with stratigraphic level and average values of 1.12 and 0.70, respectively, in early- and late-stage cumulates show a variation similar to those in other differentiated mafic bodies (Wager and Brown, 1967; Fleisher, 1968).

MINERAL ASSOCIATIONS

Except for a reconnaissance survey of titanium and chromium in pyroxenes, and of titanium, chromium, and vanadium in iron-titanium oxides (Himmelberg and Ford, 1976, 1977), data are unavailable for minor-metal contents of individual minerals. In both the calcium-rich and calcium-poor series of pyroxenes, TiO_2 shows no systematic variation with stratigraphic level whereas Cr_2O_3 occurs in amounts as much as 0.2 percent in calcium-rich pyroxene and 0.08 percent in calcium-poor pyroxene in cumulates of the Dufek Massif section, but Cr_2O_3 is not detected in the minerals in the Forrestal Range section. TiO_2 occurs in the ranges of 1.06 to 11.3 percent in magnetite, 11.1 to 18.8 percent in ilmeno-magnetite, and 49.0 to 52.3 percent in ilmenite. Cr_2O_3 occurs in the ranges 0.01 to 0.64 percent in magnetite and 0.04 to 0.47 percent in ilmenite. Neither TiO_2 nor Cr_2O_3 in oxide minerals shows systematic variation with stratigraphic level, owing to subsolidus recrystallization. On the other hand, V_2O_3 content of ilmeno-magnetite in composite grains with ferrian ilmenite shows rather systematic upward decrease from 2.21 percent in a cumulate from near the top of the Dufek Massif section to 0.11 percent in one of the uppermost cumulates of the Forrestal Range section. The upward decreasing V_2O_3 in ilmeno-magnetite is inferred to result from differentiation (Himmelberg and Ford, 1977). The V_2O_3 trend with stratigraphic level shows a marked reversal at or near the strong reversals found in compositional trends of other minerals that are inferred to be related to a late-stage addition of magma.

Correlations in table 3 and figure 28 show relations that may or may not be meaningful in terms of host mineralogy. Oxide phases are obviously the principal hosts for titanium (Himmelberg and Ford, 1977) and accordingly show high correlation ($r_s = +0.87$) with TiO_2. Their nearly-as-high correlation with copper ($r_s = +0.83$) reflects the common field observance of copper-sulfide traces in iron-ti-

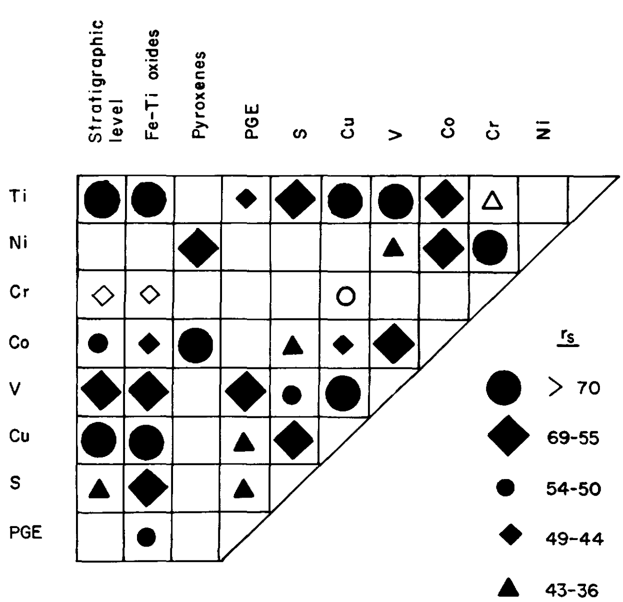

FIGURE 28.—Correlation of analyzed elements in 22 cumulates of the Dufek intrusion. Open symbols indicate negative r_s (Spearman rank correlation coefficient); solid, positive. PGE, platinum-group elements. (Modified from Ford and others, in press.)

tanium oxide-rich layers. Platinum-group elements and vanadium also have much stronger positive correlation with oxides than pyroxenes, in contrast to chromium, nickel, and cobalt. In a study of inter-element correlations, platinum is found to have much greater correlation with TiO_2 and vanadium ($r_s = +0.64$ for both) than any other element (Ford, unpublished data). Though of uncertain genetic significance, the correlations may have practical value for indicating possible mineralogical tracers in a search for resources. For example, iron-titanium oxide-rich layers would seem to be more likely hosts for a deposit of platinum-group metals than pyroxenitic layers, at least in exposed parts of this body.

SPECULATIVE RESOURCES

Available reconnaissance data are inadequate for a resource appraisal of even the small parts of the intrusion exposed in Dufek Massif and the Forrestal Range. The nature of the great extent of perhaps 95 percent or more of the body under cover of ice is open to almost any speculation. Lacking direct information on such a large part of it, inferences on possible resources might be made using the concept of "unit regional value," based on known resources in better studied equivalent geologic terranes (Griffiths, 1978). This approach was used by Wright and Williams (1974) to predict the number of mineral deposits expected to occur in Antarctica. For the Dufek intrusion, an estimation of possible resources might similarly be based on the known resources in the similar layered mafic intrusions of table 1. Many factors, however, can complicate probability estimates for resource occurrence by this method, even for comparatively well known areas (Singer and Ovenshine, 1979). For intrusive complexes, factors bearing on differences such as age, compositions of mantle source terrane and derived magma, crystallization sequences, reaction and assimilation of wall rock, emplacement style, and tectonic setting are largely unknown and can greatly limit estimation of resource potential by analogy. Each of the possible models in table 1 has unique petrologic and resource characteristics: some contain highly economic deposits, others have marginally or submarginally economic deposits, and others appear barren. Among them, the Bushveld Complex is the leader by far in terms of its variety and abundance of recoverable resources.

RESOURCES IN SIMILAR COMPLEXES

BUSHVELD COMPLEX

After an initial description of the complex in 1872, an early and long overlooked report in 1907 of platinum in chromite bands, and much scientific study and prospecting for obvious mineral deposits through the 1920's, it was not until 1923 that a chance discovery of platinum was made during gold panning in the material of a termite mound—a discovery that stimulated a thorough exploration and soon led alluvial panners, in 1924, to the richly platiniferous "mother lode" of the Merensky Reef (Hall, 1932). The Merensky has since become one of the world's leading producers of platinum-group metals (Page and others, 1973).

The complex has little rival for its diversity and wealth of economic minerals (von Gruenewaldt, 1977). Reserves of chromite, platinum-group metals, and vanadiferous iron ore are the largest of their kind in the world; but the registry of economic materials also includes copper and nickel in the Merensky Reef, and gold, tin, tungsten, molybdenum, copper, lead, zinc, and fluorite in hydrothermal or contact-metamorphic deposits (Willemse, 1969a). Hall's (1932) list additionally includes vanadium, silver, bismuth, arsenic, and cobalt; and Cameron (1971) mentioned titanium as an additional possible resource. Resources of platinum-group metals are believed to total about 656 million troy oz (Page and others, 1973). Probable reserves of chromite exceed 1 billion tons, according to Cameron and Desborough's (1969) estimate. More recently, Thayer (1973) estimated reserves of high-chromium ore ($Cr_2O_3 > 46$ percent) at 50 million tons and a total potential chromite resource exceeding 6.1 billion tons.

SUDBURY INTRUSION

The Sudbury intrusion of Ontario, commonly termed the "Sudbury Nickel Irruptive," is best known for its highly productive sulfide ores that have yielded more than one half of the total world nickel supply since about 1905 (Cornwall, 1973). Sudbury deposits have produced approximately $12 billion worth of nickel, copper, cobalt, selenium, tellurium, platinum-group metals, gold, silver, iron, and sulfur in the 85 years preceding 1972 (Card and others, 1972). Identified nickel resources are believed to total 400 million tons at a grade of 1.5 percent nickel (Cornwall, 1973). Some uncertainty exists on the cumulate origin of

Sudbury rocks and, thus, on comparability of the body with other stratiform intrusions (Wager and Brown, 1967). Moreover, in the possibility of its origin by meteorite impact, the Sudbury may be unique, and the combination of events needed to form its type of deposits may be so uncommon as to make occurrence of similar deposits unlikely (Foose and others, 1980).

GREAT DYKE

The Great Dyke, Zimbabwe, has no close rival for its immense identified resources of high-chromium ore, estimated by Thayer (1973) to total about 1 billion tons. Thayer estimated total chromium resources as exceeding 1.6 billion tons. A widespread but thin layer of disseminated platinum metal is also known, though of subeconomic grade (Worst, 1960).

DULUTH COMPLEX

Enormous identified resources of low-grade (0.21 percent nickel) nickel-sulfide ore in the Duluth Complex of Minnesota are estimated to total 6.5 million tons (Cornwall, 1973). Copper sulfides are also of potential economic significance (Cox and others, 1973). Exploration has been recently undertaken, but no major mining development has yet occurred.

STILLWATER COMPLEX

Chromite and copper-nickel sulfide deposits in the basal part of the Stillwater Complex, Montana, were known, prospected, and locally mined by the 1930's (Howland and others, 1936). Scientific reconnaissances by H. H. Hess (1960) and others starting in the 1930's, and the early reporting of platinum-group metals higher in the complex as well as in basal units (Howland and others, 1936) eventually attracted the mining company exploration in 1967 that led to discovery in 1973 of significant platinum-group metal resources in the upper part of the complex (Conn, 1979). The metal-rich zone termed the "J-M Reef," which is as much as several meters thick and extends nearly the entire length of the intrusion, is a counterpart of the Merensky Reef of the Bushveld Complex and is one of the richest known deposits of platinum and palladium in the world (Todd and others, 1979, 1982).

The complex contains the largest potential chromite and platinum-group metal resources and second largest nickel resources in the United States (Page and Dohrenwend, 1973). According to Page and Dohrenwend, the ultramafic zone has produced about 900,000 tons of chromite concentrate and contains unmined reserves of 2.5 million tons of Cr_2O_3, with total potential resources of 10.7 million tons of Cr_2O_3. They estimated that potential platinum-group metal resources probably exceed 150 million troy oz, an estimate made prior to availability of data on deposits of the metals now known in the J-M Reef in sulfide-bearing anorthositic layers above the ultramafic zone. Grades of mineralization in the newly discovered platinum-group element deposits are reportedly two to four times those typical of the Bushveld's Merensky Reef (Conn, 1979). One section of the deposit, 5.5 km in length, has an average grade of 0.65 troy oz of platinum and palladium per short ton through a thickness of 2.1 m (Todd and others, 1979). The nickel and copper potential of sulfide deposits in the basal zone also appears significant. Resources of 150 million tons of 0.25 percent nickel and 0.25 percent copper ore are identified (Cornwall, 1973) and speculative resources are much greater.

INGELI-INSIZWA COMPLEX

The Ingeli-Insizwa Complex, South Africa, is a 600- to 900-m-thick layered gabbroic intrusion correlative with the Jurassic Karroo Dolerite (Maske, 1966). The olivine-rich basal zone of the basin-shaped, sill-like body contains local concentrations of copper-nickel sulfides and platinum-group minerals (Scholtz, 1936; Mertie, 1969). Extensive exploration, including diamond drilling, has not revealed presence of deposits of economic significance (Dowsett and Reid, 1967).

SPECULATIVE RESOURCES IN THE DUFEK INTRUSION

The preceding examples show clearly that stratiform mafic intrusions similar to the Dufek contain many types of materials that are economical to exploit in the areas in which they occur. Deposits vary greatly in form, type, and grade: some are of enormous size and almost inestimable value, particularly those of platinum-group metals; and others are only marginally or submarginally economic. The precipitation of metals from magmas and their concentration into usable deposits involve many factors (Naldrett and Cabri, 1976; von Gruenewaldt, 1979; Cameron, 1971) that are presently little known or entirely unknown for the

Dufek intrusion. Although significant metal deposits have not been found, considering the immense size of the unexposed parts of the body, and the many evident similarities with other stratiform intrusions known to be economic, it is probably safe only to conclude that there is little likelihood that no significant resources exist in the body.

In view of the limited data, speculations as to the nature of possible resources must at present primarily be based on comparisons with other intrusions of similar type. Many similarities and many obvious differences exist in making comparisons. Except for the noneconomic (as now known) Skaergaard intrusion of Tertiary age and the subeconomic Jurassic Ingeli-Insizwa Complex, unifying themes seen in the other possible models of table 1 are that (1) all are of Precambrian age; (2) all are located in present-day midcontinental cratons; (3) all formed from basaltic magma, in most cases inferred to be tholeiitic; (4) all are stratiform bodies of cumulates apparently formed by crystal accumulation, with the possible exception of the Sudbury Complex; and (5) all contain significant resources, though of variable form and grade.

Questions that can be raised about the significance of similarities and differences between the Dufek and other stratiform mafic intrusions have no clear answers. Similarities with other intrusions in textures, structures, and general differentiation patterns are indicative of overall similarity in processes of magma consolidation. To what extent have compositions and geotherms of mantle sources of magmas varied with time in the geochemical evolution of the Earth, and thus of what resource significance is the much younger age (Jurassic) of the Dufek? Findings that ore-forming processes have not operated uniformly throughout time, leading to the concept of "metallogenic epochs" (Craig, 1979), might indicate that the Dufek should only be compared with the Ingeli-Insizwa Complex of similar age. Derivation of sulfur-rich magmas and sulfide mineralization may be a function of depth of mantle melting (Naldrett and Cabri, 1976). If so, and in view of possible mantle heterogeneity for the Jurassic in Antarctica (Kyle, 1980) and the possible origin of Ferrar Group magmatism by Pacific margin subduction (Elliot, 1976), of what significance is the mobile-belt setting of the Dufek intrusion, rather than a craton setting, in terms of mantle dynamics and composition of mantle-derived magmas? Are the generally minor-appearing differences in the tholeiitic compositions of inferred original magmas relevant in terms of resources, particularly in the more siliceous apparent nature of the Dufek magma, and how accurately do those compositions correspond with actual original magmas? Do concealed parts of the Dufek contain ultramafic cumulates or evidence, as in the Bushveld and Stillwater Complexes, for an early ultramafic phase of magmatism? Might Irvine's (1975) mechanism relating magmatic sulfide and chromite ores in some layered intrusions to sudden contamination of magma with felsic material also have operated in the Dufek intrusion, though effects of such a mechanism might be questioned (Naldrett and Cabri, 1976)? Those and many other possible questions make comparison with any model highly uncertain. Although comparison with the Ingeli-Insizwa intrusion seems attractive in the aspect of age similarity, the significant size difference makes other models more attractive.

At the present preliminary stage of investigation, probably few if any types of deposits are known in similar bodies that arbitrarily can be excluded as occurring in the Dufek intrusion, particularly in view of the immense areas of concealed rock. Accordingly, nearly all types of deposits must be considered to be possible speculative resources in this body, though however unlikely for some. Resources of varied type might be encountered in almost any part of the body. In intrusions of this kind, certain metals typically show selective concentration by differentiation at certain stratigraphic levels, such as chromite near the base and iron, titanium, and vanadium in upper parts (Wager and Brown, 1967). Considerable differences exist in the type, size, and grade of metal deposits known in other comparatively well studied stratiform intrusions (Wilson, 1969). Even for those intrusions, factors controlling ore occurrence are uncertain and arguable, particularly for metals associated with sulfide mineralization (Naldrett and Cabri, 1976; von Gruenewaldt, 1979). The scarcity of data for the Dufek intrusion obviously restricts predictability for occurrence of possible resources.

CONCEALED SECTIONS

There is probably little question that of the two concealed sections in the southern part of the intrusion (fig. 23) the basal one has more resource significance. Whereas general characteristics of the Sallee Snowfield section can probably be inferred to be similar to those of middle parts of other intrusions, and intermediate between those of the two exposed Dufek sections, the basal section may be comparable to lower parts of other complexes. Early-stage mafic or ultramafic cumulates in other complexes are associated with a variety of metal deposits, particularly chromium, platinum-group metals, nickel, and copper (Wilson, 1969; Naldrett and Cabri, 1976; Page and Dohrenwend, 1973).

Whether ultramafic layers occur in the concealed basal section is one of the major questions in a resource appraisal of the intrusion. Preliminary interpretation of geophysical data suggests their possible presence (Behrendt and others, 1974). The SiO_2 content of the inferred original tholeiitic magma is only 2–3 percent higher than in inferred Bushveld and Stillwater magmas (table 2). Whether such a magma could have produced any early ultramafic cumulates is unknown. As in the Bushveld Complex (von Gruenewaldt, 1979) and the Stillwater Complex (Todd and others, 1982), a possibility exists for an early ultramafic phase of magmatism, though no evidence for it has yet been found.

Cumulus magnesian olivine and chromite have not been found in any exposed part of the Dufek intrusion. However, Himmelberg and Ford (in press) presented indirect evidence that olivine may be a member of the mineral-crystallization sequence of the magma. The cumulus mineralogy of lowest-exposed gabbroic cumulates (plagioclase + calcium-rich pyroxene + calcium-poor pyroxene) is the same as in the Bushveld and Stillwater Complexes at stratigraphic levels above their upper limits of magnesian olivine and chromite. If those minerals are present in the concealed basal section, prediction of their stratigraphic occurrence can at present only be based, uncertainly, on stratigraphic comparison with other minerals known in similar intrusions. In the Bushveld Complex, cumulus (inverted) pigeonite first occurs at a stratigraphic level of about 3.6 km, where plagioclase has a composition of An_{60-69} (Wager and Brown, 1967). In the Dufek intrusion, cumulus pigeonite (also inverted) first occurs just above the Walker Anorthosite (Himmelberg and Ford, 1976), at an exposed height of about 300 m and where plagioclase composition is An_{63} (Abel and others, 1979). The occurrence is about 2.1–3.8 km above the base, using Behrendt's and others (1974) 1.8–3.5 km thickness estimate for the concealed basal section. Thus, the first occurrence of cumulus pigeonite may be at comparable stratigraphic levels in the two intrusions and where compositions of coexisting plagioclase are about the same. In the Bushveld Complex, cumulus magnesian olivine and chromite occur up to the level of the platiniferous Merensky Reef, about 2.3 km above the floor and about 1.3 km below the first occurrence of cumulus pigeonite (Wager and Brown, 1967). Thus, as inferred by comparing depths below respective cumulus pigeonite arrival "markers," the economically important Merensky would have an equivalent stratigraphic position in the Dufek intrusion somewhere in the middle or upper part of the hidden basal section (fig. 27). In the Stillwater Complex, the platinum-group metal-rich deposits of the J-M Reef occur about 425 m above the ultramafic zone (Todd and others, 1979). The top of the ultramafic zone is about 1.2 km above the floor (Wager and Brown, 1967), and thus the economically significant deposits of platinum-group metals and chromite in the complex would have an equivalent position in the Dufek intrusion somewhere in the lower or middle part of the concealed basal section. In view of such possible comparisons, speculative resources of the basal section must be considered to include metals in deposits known in equivalent parts of similar intrusions, namely chromium, platinum-group metals, and possibly copper and nickel.

DUFEK MASSIF SECTION

Only traces of disseminated sulfide minerals have been found in Dufek Massif. Amounts of analyzed minor metals are generally low (table 4) and about normal for the host lithologies, including pyroxene-rich cumulates of the Neuburg and Frost Pyroxenite Members of the Aughenbaugh Gabbro. The correlations of figure 27 suggest that the pyroxenitic units lie considerably higher in the stratigraphy than does the pyroxenitic Merensky Reef in the Bushveld Complex. Unusually high amounts of chromium (480 ppm) and vanadium (460 ppm) occur only in samples from thin layers containing cumulus iron-titanium oxides near the top of the section. As now known, they have little resource significance, and therefore this exposed part of the intrusion shows no evidence for occurrence of possible resources.

FORRESTAL RANGE SECTION

Trace or minor amounts of sulfide minerals, as much as a maximum known of only 2–3 percent, are common in cumulates of this upper part of the intrusion. Among typical cumulates containing no or only traces of visible sulfides (table 4), the maximum analyzed amounts of copper (460 ppm) and sulfur (800 ppm) occur in a gabbroic cumulate containing abundant (11 modal percent) iron-titanium oxide minerals, from about 1150 m height in the section. The same sample contains a higher than average content (25 ppb) of platinum (Ford and others, 1983). One atypical cumulate (not included in table 4 averages) containing 2 percent visible sulfides, 18 percent oxide minerals, and 70 percent pyroxenes, from about 1080(?) m height in the section, was also analyzed and found to contain 13 ppb platinum, 6 ppb palladium, 4,700 ppm sulfur, 2,000 ppm copper, 2,000 ppm vanadium, 100 ppm cobalt, 44 ppm chromium, 65 ppm nickel, and 7.5 percent TiO_2. Concentrations of the analyzed platinum-group elements in this section and the Dufek Massif section are generally similar to those in typical rocks of the Bushveld Complex above its Merensky Reef (Page and others, 1982).

Occurrences of sulfide minerals and secondary copper-bearing efflorescences are most commonly found in cumulates with abundant iron-titanium oxide minerals. In a correlation study of major and minor elements, copper and sulfur were determined to have strongest correlation ($r_s = +0.85$ and $+0.84$, respectively) with Fe_2O_3 (Ford, unpublished data) and with Fe-Ti oxide minerals (fig. 28). Sulfide occurrences appear to be similar to those in the iron-enriched upper part of the Bushveld Complex, for which von Gruenewaldt (1976) postulated the precipitation of sulfides as a result of reduction of sulfur solubility in the magma due to lowering of iron content by the crystallization of magnetite.

Although known sulfide occurrences in the Forrestal Range are of insignificant size, larger deposits conceivably exist in hidden equivalent parts of the body. Copper-nickel sulfide deposits of possible economic interest are known in comparable parts of the Bushveld Complex (von Gruenewaldt, 1976), and therefore the possibility exists that similar deposits occur in the upper part of the Dufek intrusion. If present, however, they would probably have little potential resource significance by themselves, but might be of interest if they are found to be associated with other resources, such as vanadium, titanium, or platinum-group metals.

Seams and channel-like masses of magnetitite (iron-titanium oxide cumulate) are common in many parts of the Forrestal Range. Although many are present, most seams have a thickness of as much as only about 10 cm. The largest channel-like mass observed is about 2 m thick. The larger and more abundant magnetitite seams in the upper Bushveld Complex are of economic interest chiefly for vanadium but have had some development for iron (Willemse, 1969b) and may also be of interest for titanium (Cameron, 1971). As in the Bushveld, layers of magnetitite in the Dufek intrusion are commonly associated with layers of plagioclase-rich cumulate (anorthosite and leucogabbro). Samples of Dufek magnetitite have not been chemically analyzed, but analyses of samples containing 18 and 34 modal percent oxide minerals show contents of 7.5 and 8.6 percent TiO_2, respectively, and 0.2 percent vanadium. For comparison, magnetitite ore of the Bushveld contains 14–20 percent TiO_2 and 0.3–2 percent V_2O_5 (Willemse, 1969b). The maximum known content of V_2O_3 in Dufek ilmeno-magnetite is 2.21 percent (2.68 percent V_2O_5); and eight analyzed grains of the mineral from different stratigraphic levels average 14.1 percent TiO_2, with a range of 11.1 to 18.8 percent (Himmelberg and Ford, 1977). A deposit consisting entirely of ilmeno-magnetite in the Dufek intrusion, accordingly, might have vanadium and titanium contents approximating those of ore deposits in the Bushveld Complex. Vanadium content of Bushveld magnetitite ore decreases with increased stratigraphic level (T. G. Molyneux data, *in* Willemse, 1969b), and similarly, V_2O_3 content of ilmeno-magnetite shows systematic decrease with increased stratigraphic level in the Dufek intrusion (Himmelberg and Ford, 1977). The comparisons with the Bushveld suggest that vanadium and possibly titanium should be considered of potential resource interest in the Forrestal Range section, and particularly if associated with other types of resources.

Platinum-group metals are probably of greatest potential resource interest in the Forrestal Range section, though no occurrence of significant size is known and no minerals of the group have been identified. The summary of reconnaissance geochemical data in table 4 shows a distinct increase in platinum and palladium abundances in this section compared to the Dufek Massif section, suggesting an enrichment with differentiation. Average sulfur content shows similar upward increase between sections, but sulfur and platinum-group element abundances have little statistical correlation (fig. 28). Although platinum-group elements seem to be collected from magmas by crystallizing sulfides, in many cases they are redistributed by secondary processes (Naldrett and Cabri, 1976), which might account for lack of significant correlation. The previously mentioned correlations of platinum with vanadium and TiO_2 suggest that platinum occurrences might be expected in iron-titanium oxide-rich cumulates. If metal deposits, particularly those associated with sulfides, can be related to sudden contamination of magma by felsic materials (Irvine, 1975), deposits might be associated with the anorthosite and leucogabbro inclusion-rich layer about 1 km below the top of the Forrestal Range section. Although the section is stratigraphically higher in this intrusion than the platinum-group metal deposits are in the Bushveld and Stillwater Complexes, the apparent enrichment of the metals with differentiation suggests that they should be considered a speculative resource in this part of the intrusion.

OUTLOOK

Historically, as exemplified by economic developments in the Bushveld and Stillwater Complexes, many years can elapse even in nonpolar areas between discovery, early scientific study, and eventual commercialization of a stratiform complex, particularly for inconspicuous deposits such as platinum. A much greater lag can be expected for any exploitation of Antarctica's possible mineral resources, considering (1) economic factors of logistics (Potter, 1969); (2) difficulties in polar mining operations (Hall, 1975; Splettstoesser, 1976); (3) environmental requirements for safeguarding an unusually fragile ecosystem (Zumberge, 1979b); (4) the still unresolved matter of land ownership and problems in issuance of licenses or leases and sales of mineral rights (Zumberge, 1979a); (5) the small number of geologists who have worked in any particular area and with the primary objective of making reconnaissance scientific surveys, which greatly limits chances for accidental discoveries; and (6) lack of prospecting activity or other work focused on a search for minerals.

Based principally on comparisons with similar intrusions that contain economic deposits, speculative resources of the Dufek intrusion are considered to include chromium, copper, nickel, vanadium, titanium, iron, and platinum-group metals, however unlikely some may be in terms of any possible economic utility. In presently known or inferred world abundances (Brobst and Pratt, 1973), only platinum-group metals would probably be of much future economic interest. However, recovery of those metals might make byproduct recovery of others also feasible.

Prospecting for metals of the platinum group will be unusually difficult, requiring innovative and costly methods. As exemplified by the Bushveld's Merensky Reef, chance and intuition can be important factors in initial discoveries. Traditionally, the most successful prospecting technique seems to be a search for placer accumulations and the tracing of alluvial occurrences back to their lode source (Page and others, 1973). However, in Antarctica, an absence of any significant river or stream erosion since the probable early Cenozoic onset of continental glaciation, and the present ice cover of all lowland intermontane basins preclude that type of prospecting of the Dufek intrusion. As in the Stillwater Complex (Page and others, 1976), the metals probably have a highly sporadic occurrence, both along and across layering. A search will require extensive and detailed geochemical surveys, but might be aided by present findings that higher than average platinum-group element values seem to be associated with layers rich in iron-titanium oxide minerals and that, as in the Stillwater Complex (Page and others, 1972), more easily analyzed vanadium seems to have potential for use as a geochemical tracer for platinum (fig. 28).

Other continents have long histories of geologic and mining exploration by great numbers of prospectors, geologists, geochemists, and geophysicists, yet new mineral discoveries, often on old workings, are continually being made, generally using increasingly sophisticated methods. The probability of an accidental discovery obviously depends in great measure on the numbers of visitors to an area, even though engaged only in scientific studies. The probability should increase considerably if visitors were directing efforts toward a minerals search. The example of the Stillwater Complex shows the importance of concerted, large-scale prospecting efforts by companies in the discovery of inconspicuous platinum-group metal deposits. With little question, the Dufek intrusion would by now have been similarly explored if it were located nearly anywhere but in Antarctica, a continent which has not yet attracted any commercial mineral exploration. The short periods of work by only a few visitors to the body, only for geographic exploration and a variety of scientific studies, have provided little basis for the operation of chance in an accidental discovery of a mineral deposit. Until a directed search is made, any potential resource of the intrusion will doubtless remain in the "speculative" category.

Although little likelihood is foreseen for near-future recovery of any conceivable resource, if marketable resources are someday identified, their transport would probably be simpler than from many other inland parts of Antarctica. Ships supplying scientific stations now make regular summer visits along the north edge of Filchner Ice Shelf, about 600 km north of Dufek Massif, the route to which was long ago first traversed by oversnow tracked vehicles (Aughenbaugh, 1961).

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