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Mineral Resources of Antarctica

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Compiled and edited by

N. A. Wright *and* P. L. Williams

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ABSTRACT

Although the existence of mineral deposits in Antarctica is highly probable, the chances of finding them are quite small. Minerals have been found there in great variety but only as occurrences. Manganese nodules, water (as ice), geothermal energy, coal, petroleum, and natural gas are potential resources that could perhaps be exploited in the future. On the basis of known mineral occurrences in Antarctica and relationships between geologic provinces of Antarctica and those of neighboring Gondwana continents, the best discovery probability for a base-metal deposit in any part of Antarctica is in the Andean orogen; it is estimated to be 0.075 (75 chances in 1,000).

INTRODUCTION

This circular attempts to (1) present a survey of the known mineral resources of Antarctica and (2) estimate Antarctica's mineral-resource potential on the basis of known mineral occurrences in Antarctica and known mineral deposits of neighboring continents. It does not attempt to make any judgements on whether or not the mineral resources of Antarctica should be explored for and exploited. Rather, an objective analysis is given of the present geologic information, aimed at appraising the mineral resources of Antarctica.

About 98 percent of the surface of Antarctica is covered by ice. The lack of exposed rock means that the survey of mineral resources of Antarctica presented here is incomplete. An analysis resulting from such an incomplete survey can be potentially misleading if taken out of context. Geologic studies to date, limited almost exclusively to exposed rock masses that have been analyzed primarily for scientific purposes, have not revealed any mineral concentrations rich enough to be classified as commercially exploitable ore deposits, but the probability that mineral deposits exist in Antarctica seems to be high. The crucial factor, however, is whether they can be found. The problems of finding deposits include such things as lack of rock outcrops, an extremely thick ice cover, almost permanently frozen coastal waters, and no population. The social and economic costs of search are high, but these costs have not stopped similar ventures in the past once zeal was stimulated, even when the chances of success were small. The danger lies in an unwarranted stimulation of zeal because of either a misinterpretation of terms or a failure to separate the appraisal of the resource from the actual costs involved in exploration and development.

The resource estimates are based on (1) present knowledge of mineral occurrences in Antarctica; (2) a theoretical geologic reconstruction of the ancient supercontinent of Gondwanaland and of the relationship of the major geologic provinces of Antarctica to comparable ones in the adjacent continental masses of South America, Africa, India, and Australia; and (3) the extrapolation of known resources in these adjacent, formerly contiguous landmasses to determine the expected frequency of comparable occurrences in Antarctica. This circuitous reasoning process produces estimates of anticipated resources that are subject to continuous review, modification, and refinement. It offers the most reasonable assessment of the mineral resources of the continent in view of the extremely limited amount of exposed bedrock and the extremely limited detailed studies of these exposures.

The terminology used in this summary is based upon the definitions presented by V. E. McKelvey in 1973. Figure 1 is a classification of resources adopted jointly in 1974 by the U.S. Geological Survey and the U.S. Bureau of Mines (Pratt and Brobst, 1974, fig. 1). Within

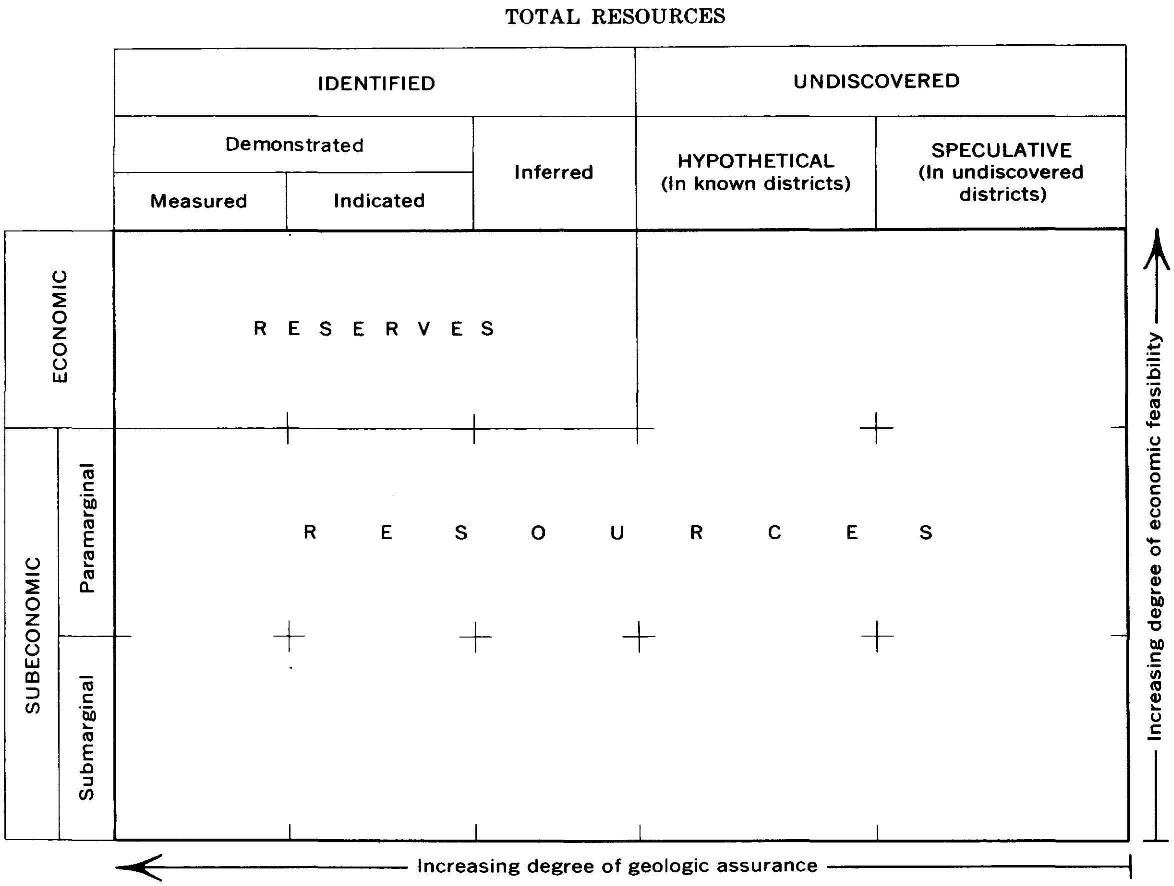


FIGURE 1.—Classification of mineral resources. Modified from Pratt and Brobst (1974, fig. 1).

the framework of figure 1, Antarctica now has no known economically recoverable resources of any category, nor does Antarctica have any known mineral districts. The few localities where valuable minerals have been identified must be classified as mineral occurrences; that is, occurrences of minerals that could constitute a resource if present in sufficient quantity but that have not been studied adequately to determine quantity. These occurrences would rate even lower than submarginal in figure 1 in degree of economic feasibility. Water and coal could constitute identified resources in Antarctica. Ice brought to the Antarctic coast by a glacier contains a volume of water that can be estimated. The coal resources in the Beacon rocks have been sufficiently measured in places to permit estimation of volumes. Present market conditions, as well as quality and location of the coal, indicate that it is not now possible for the coal resources to be considered economically usable; the identified coal and water are definitely submarginal. This conclusion is emphatically supported by the present high-cost practice of importing other energy sources to support scientific stations in Antarctica. Another example of mineral occurrence is the appearance of gas in a single drill hole, which was immediately capped. Favorable host rocks, favorable structures, and a first "smell" of gas do not constitute an identified resource; rather the gas is a proved mineral occurrence that supports estimates of the speculative resource potential for gas and oil. All mineral occurrences in Antarctica should be considered in this same context.

The resources of Antarctica are almost exclusively in the category of speculative resources on the basis of figure 1. Their position in this category is supported by the few mineral occurrences that have been found. Ranking of such resources according to feasibility of economic recovery is a futile exercise. Such ranking would depend on what, if anything, is found, where it is found, and the economic market at the time of finding.

Large accumulations of minerals very probably occur in Antarctica, for no other continent is void of mineral deposits. The major question is whether these can be found and exploited economically. Should advances in technology permit a cheaper, more precise search through the ice, exploration might be more effective in the future. Prediction of such advances in technology, however, would be the rankest sort of speculation. For the purposes of this evaluation, the knowledge that deposits of possible value should exist in Antarctica provides adequate background to stimulate productive negotiations.

The editors wish to acknowledge the generous contributions of the following people: J. C. Behrendt, A. L. Clark, S. H. Clark, C. B. Davidson, J. V. N. Dorr, L. J. Drew, A. B. Ford, P. W. Guild, R. J. Lantz, S. P. Schweinfurth, P. K. Theobald, all of the U.S. Geological Survey; J. Mulligan of the U.S. Bureau of Mines; and M. D. Turner of the National Science Foundation.

MINERAL OCCURRENCES

The symbols on figure 2 indicate mineral occurrences described in literature on the Antarctic; numbers in the symbols are keyed to table 1. No attempt has been made to indicate mineral concentrations on the map; concentrations range from less than 1 ppm (part per million) determined by chemical analysis, such as gold, to large concentrations of minerals such as coal, sand and gravel, and possibly iron. Most of the symbols, except for those for coal, sand and gravel, and iron, represent only mineral occurrences that have geologic significance as indicators of type of mineral province; they rarely represent large mineral concentrations.

SAND AND GRAVEL

Lowering of sea level during the past several thousand years has produced many raised beaches around the coastline of Antarctica (R. L. Nichols, *in* Craddock and others, 1969–70). The raised beaches are commonly wave-cut surfaces—a few to 100 m or more (300 ft or more) above sea level—mantled with alluvial material ranging in size from boulders to silt and clay; most of the deposits are made up of sand and fine to coarse gravel. Thickness is variable. Detailed descriptions of composition and tenor of deposits are nearly absent in the literature; table 1 summarizes what is known about most of the sand and gravel occurrences.

It seems unlikely that sand and gravel will ever be exported from the continent, but the availability of workable deposits may be an important factor in selecting the sites of future Antarctic bases.

OTHER NONMETALS

Most of the other nonmetallic mineral occurrences described below are in pegmatite and other crystalline rocks of Precambrian age in Queen Maud Land. Descriptions are based for the most part on reports by geologists of the Soviet Union.

Phlogopite (magnesian mica) occurs at locality 1 in the Humboldt Mountains in pods as large as 40 by 60 cm (1 by 2 ft). The pods are in pegmatite dikes injected into Precambrian metamorphic rocks. Crystals as large as 20 by 10 by 4 cm (8 by 4 by 1½ in.) are common. Concentrations estimated at about 2 percent of one metamorphic rock body measure 8 by 10 by more than 100 m (25 by 30 by more than 300 ft) (Ravich and Solov'ev, 1969, p. 279).

Beryl has been found at several localities in Queen Maud Land, but only at locality 2, the "Marble Nunataks," are there significant concentrations. There, altered pegmatite dikes contain pockets of prismatic beryl crystals 10–15 cm (4–6 in.) in diameter; crystals range in length from 0.5 to 7 cm (¼–3 in.), averaging 2 cm (¾ in.). The crystals are mostly cracked and cloudy. Associated with the beryl are topaz, tourmaline, and apatite (Ravich and others, 1968, p. 453).

Rock crystal (quartz) occurs on "Mount Titov" (loc. 65); crystals as large as 0.4 by 0.7 m (15 by 25 in.) make up 4–5 percent of slope debris. Talus in the "Marble Nunataks" (loc. 2) is rich in coarse quartz crystals as long as 20–25 cm (8–10 in.). In both localities, the quartz originated in pegmatite dikes. These occurrences are considered by the Soviets to be promising for future prospecting for optical quartz (Ravich and Solov'ev, 1969, p. 279–280).

Graphite has been described from two localities (6a and 6b) in crystalline rocks in Queen Maud Land. At locality 6a, graphite crystals 2–3 cm (¾–1 in.) in diameter make up 1–2 percent of pegmatite veins 1–2 m (3–6 ft)

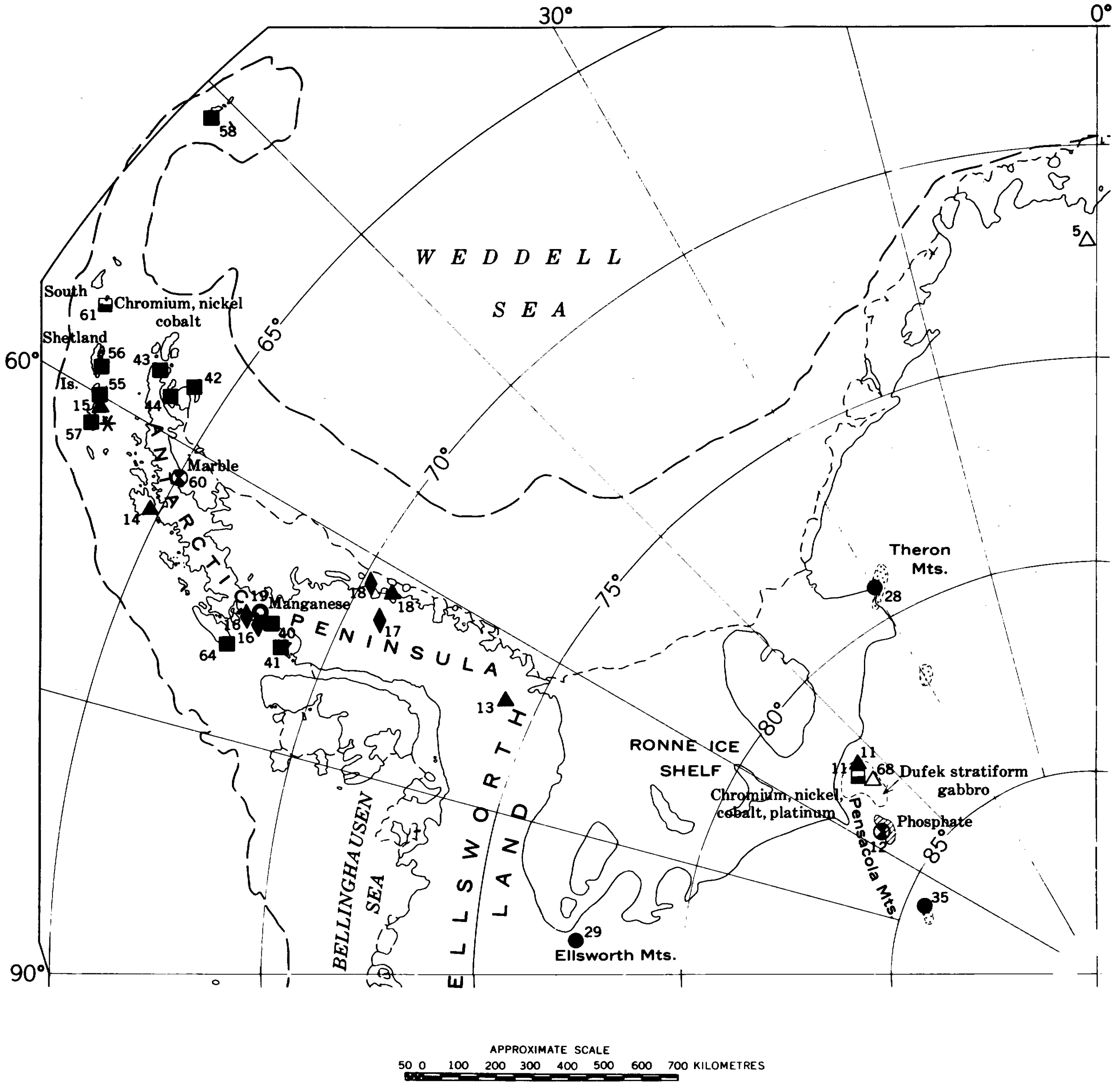
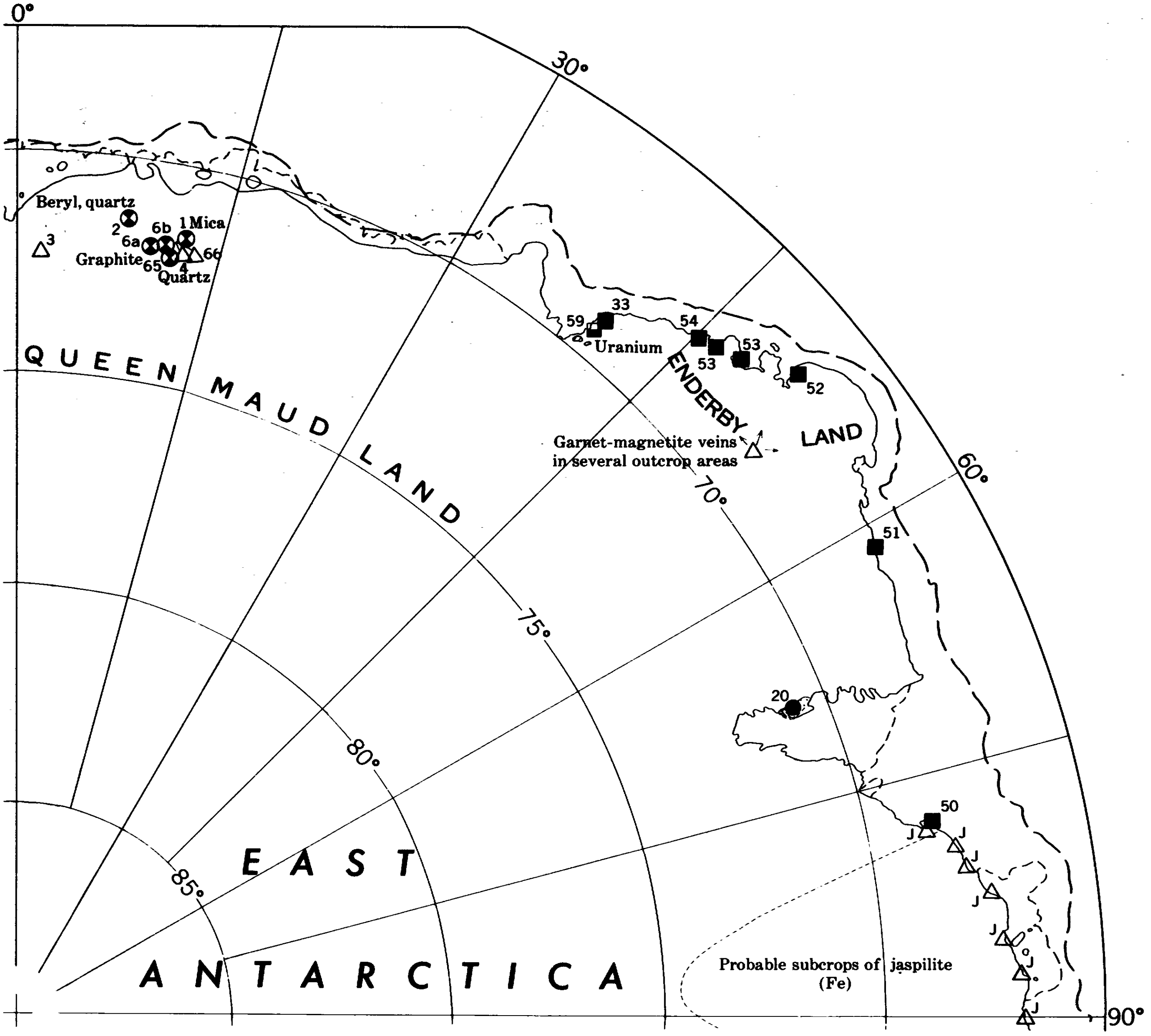


FIGURE 2.—Known occurrences of potentially valuable minerals in Antarctica.



Base modified from the American Geographical Society

EXPLANATION

(NUMBERS REFER TO LOCALITIES IN TABLE 1)

■ 41	Sand and gravel
⊗ 6	Nonmetallic minerals
△ 5	Iron
△ J	Iron, area where jaspilite boulders occur in moraines
▲ 13	Copper
♦ 16	Gold and silver
○ 20	Molybdenum
⬓ 11	Nickel, cobalt, platinum, manganese, uranium, tin
▨	Area favorable for contact-metamorphic deposits and marble
✶	Active volcano, indicated by fumarole activity
○	Area of geothermal potential, volcanic rocks less than 1 million years old
●	Coalbeds
⁘	Area underlain by coal-bearing and potentially coal-bearing rocks
♦	Proposed site for deep drilling by *Glomar Challenger*
Anticline Syncline	Fold axes in sediments of the Ross Sea shelf. Direction of plunge given where known. Data obtained during *Eltanin* cruises 27 and 32
—— ——	Approximate outer limit of Continental Shelf
— — — —	Edge of ice barriers

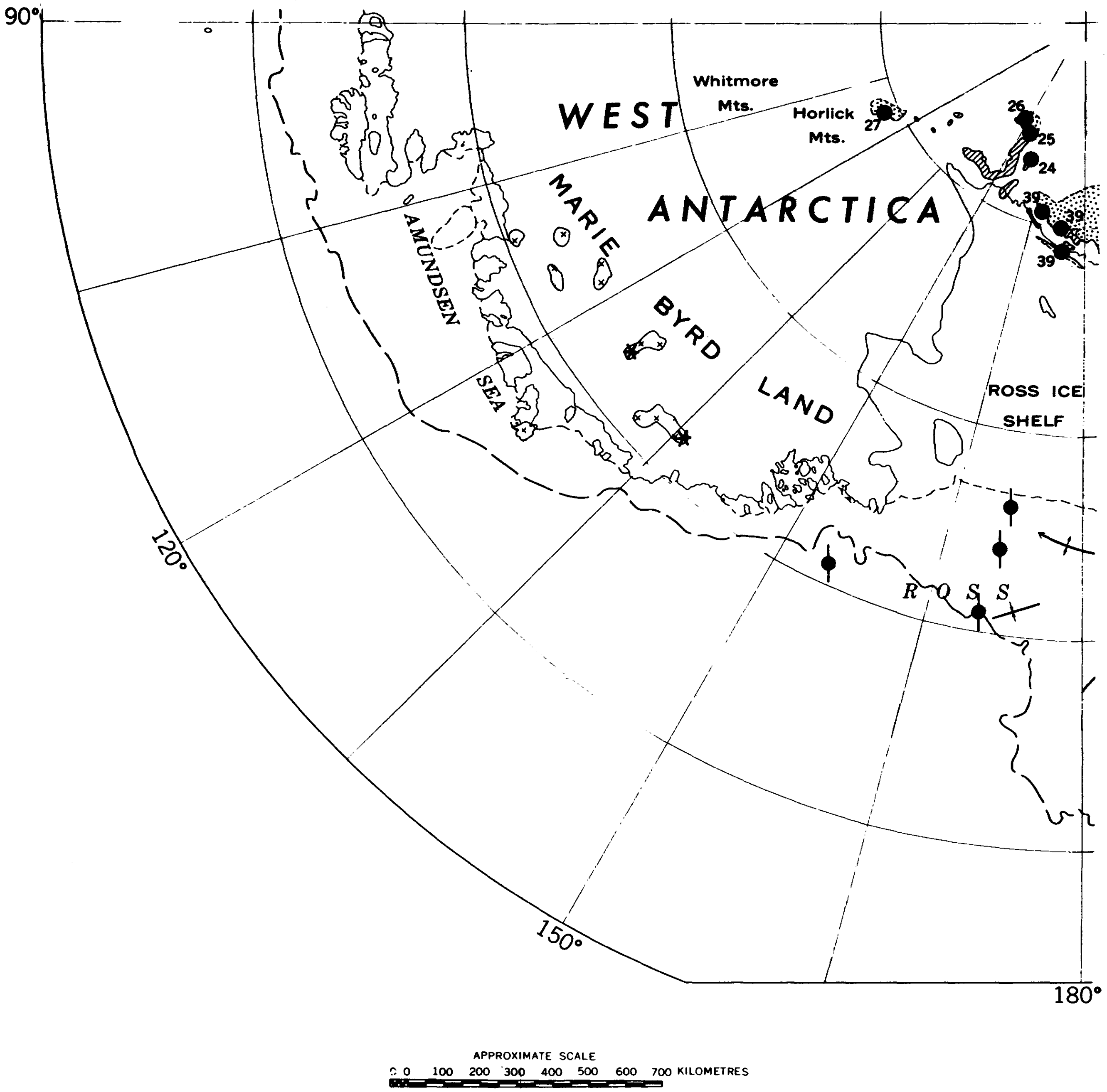
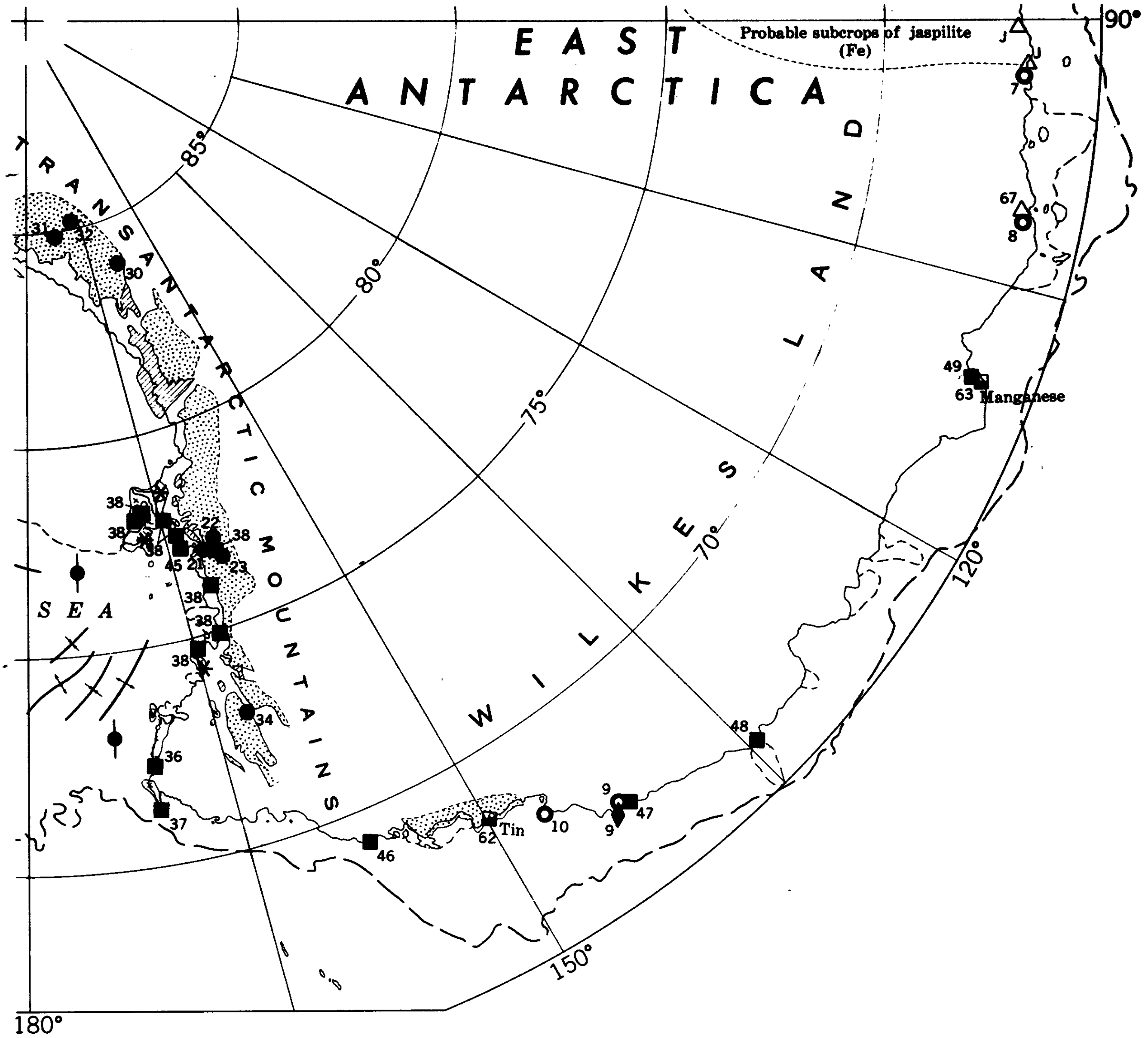


FIGURE 2.—Known occurrences of potentially valuable minerals in Antarctica—Continued.



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▲13 Copper

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○20 Molybdenum

▭11 Nickel, cobalt, platinum, manganese, uranium, tin

▨ Area favorable for contact-metamorphic deposits and marble

✳ Active volcano, indicated by fumarole activity

○ Area of geothermal potential, volcanic rocks less than 1 million years old

● Coalbeds

░ Area underlain by coal-bearing and potentially coal-bearing rocks

⍿ Proposed site for deep drilling by *Glomar Challenger*

Anticline / Syncline — Fold axes in sediments of the Ross Sea shelf. Direction of plunge given where known. Data obtained during *Eltanin* cruises 27 and 32

——— Approximate outer limit of Continental Shelf

– – – – Edge of ice barriers

TABLE 1.—*Mineral occurrences in Antarctica*

Locality No.	Place name	S. Lat.	Long.	Resource	Remarks
1	Humboldt Mountains	71°45′	11°30′E.	Mica	Magnesium rich.
2	"Marble Nunataks"	71°22′	07°35′E.	Beryl	Occurs with topaz and tourmaline.
3	"Mount Hedden"	72°05′	01°22′E.	Iron	
4	Mount Humboldt	71°45′	11°30′E.	do	Pods as much as 100 m thick.
5	Gburek Peaks	72°11′	0°15′E.	Iron and titanium.	
6	Conrad Mountains	71°48′	10°20′E.	Graphite	
7	Near Mirnyy Station	69°20′	72°34′W.	Molybdenum	
8	Bunger Hills	66°17′	100°47′E.	do	
9	Cape Denison	67°00′	142°40′E.	do	Molybdenite with arsenopyrite and sphalerite; traces silver and gold.
10	Ainsworth Bay	67°47′	146°43′E.	do	
11	Dufek-Forrestal Mountains.	82°36′	52°30′W.	Chromium, nickel, cobalt, platinum.	Disseminated in gabbro.
12	Central Neptune Range	83°50′	57°09′W.	Phosphate rock.	Pebbles and irregular pods.
13	Central Lassiter Coast ("Moats Nunataks").	74°22′	65°00′W.	Copper	Mostly chalcopyrite.
14	Copper Peak	64°43′	63°21′W.	do	Malachite stain.
15a	Coppermine Cove	62°23′	59°42′W.	do	
15	Greenwich Island	62°31′	59°47′W.	do	Average tenor less than 0.8 percent copper.
16	Stonington Island and vicinity.	68°11′	67°00′W.	Gold and silver.	Minor molybdenum.
17	"Eternity Range" (probably Leininger Peak), locality uncertain.	70°34.	62°15′W.	do	
18	Eielson Peninsula	70°35′	61°45′W.	do	With pyrite.
19	Stonington Island	68°11′	66°55′W.	Manganese and molybdenum.	
20	Beaver Lake	70°48′	68°20′E.	Coal	Beds average 0.8 m thick.
21	Mount Gran	76°59′	160°58′E.	do	
22	Willett Range	77°09′	160°25′E.	do	
23	Allan Nunatak	76°45′	159°40′E.	do	6 coal beds.
24	Nilsen Plateau	86°20′	158°00′W.	do	
25	Mount Weaver	86°58′	153°50′W.	do	7 coal beds 1.5–3 m thick.

TABLE 1.—*Mineral occurrences in Antarctica*—Continued

Locality No.	Place name	S. Lat.	Long.	Resource	Remarks
26	Mount Howe	87°21′	149°18′W.	do	Graphitic.
27	Mount Schopf and Mount Glossopteris.	84°48′	113°25′W.	do	Beds 1–3 m thick.
28	Mount Faraway	79°12′	28°49′W.	do	Low sulfur.
29	Polarstar Peak	77°32′	86°09′W.	do	Maximum thickness 30 cm.
30	Queen Elizabeth Range	84°00′	159°30′E.	do	
31	Dominion Range	85°05′	171°30′E.	do	3 m thick.
32	do	85°19′	168°00′E.	do	Anthracite, maximum thickness 5 m.
33	Ongul Islands	69°00′	39°35′E.	Sand and gravel.	Beach sand, a few metres thick.
34	Sheehan Tableland	73°00′	162°15′W.	Coal	
35	Pecora Escarpment	85°35′	70°00′W.	do	Carbonaceous siltstone.
36	Seabee Hook	72°19′	170°13′E.	Sand and gravel.	
37	Cape Adare	71°17′	170°14′E.	do	
38	McMurdo Sound area	78°–79°	163°–170°E.	do	Small to large deposits.
39	Dufek Coast area	80°–85°30′	168°–173°W.	Coal	Beds as much as 6 m thick.
40	Marguerite Bay	68°16′	66°50′W.	Sand and gravel.	Many deposits, large to small.
41	Mushroom Island	68°53′	67°53′W.	do	Small deposits.
42	Amiot Island(?)	67°36′	69°38′W.	do	Very small.
43	Hope Bay	63°23′	57°00′W.	do	
44	Herbert Sound	63°55′	57°40′W.	do	Bouldery clay.
45	Dunlop Island	77°14′	163°29′E.	do	Probably large deposit.
46	Lauritzen Bay	69°05′	156°50′E.	Sand and gravel?	
47	Cape Denison	67°00′	142°40′E.	do	
48	Lewis Island	66°06′	134°22′E.	do	
49	Windmill Island	66°20′	110°25′E.	do	
50	Vestfold Hills	68°33′	78°15′E.	do	
51	Ufs Island	67°28′	61°08′E.	do	
52	Cape Kolosov	66°29′	50°16′E.	do	
53	Alasheyev Bight	67°30′	45°40′E.	Sand and gravel.	Large, workable, and accessible deposit.
	Casey (Lena) Bay	67°36′	47°35′E.	do	
54	Shinnan Glacier	67°55′	44°38′E.	do	
55b	Greenwich Island	62°31′	59°47′W.	Sand and gravel; water.	
55	do	62°31′	59°47′W.	Sand and gravel.	Good quality; accessible.
56	King George Island	62°10′	58°25′W.	do	
57	West Livingston Island	62°38′	61°14′E.	do	Extensive deposits.

TABLE 1.—*Mineral occurrences in Antarctica*—Continued

Locality No.	Place name	S. Lat.	Long.	Resource	Remarks
58	South Orkney Island	60°35′	45°30′W.	do	Probably small.
59	Lutzow-Holm Bay	69°38′	38°18′E.	Uranium	Euxenite.
60	Hektoria Glacier	65°03′	61°31′W.	Marble	Outcrop is 100 × 200 m.
61	Aspland Island	61°30′	55°49′W.	Chromium, nickel, cobalt.	
62	Horn Bluff	68°26′	149°46′E.	Tin	Trace amounts only.
63	Clark Peninsula	66°15′	110°33′E.	Manganese (tephroite).	
64	Cockburn Island	64°12′	56°51′W.	Sand and gravel.	
65	"Titov Mountains"	71°58′	10°52′E.	Quartz	Optical quality.
66	"Mount Nikolaev"	71°58′	12°23′E.	Iron	
67	Bunger Hills	66°17′	100°47′E.	do	
68	Forrestal Range	83°00′	49°30′W.	do	
69	Mount Rucker	73°38′	64°45′E.	do	40–50 percent FeO_2.

thick. At locality 6b, gneiss layers 2–7 m (6–20 ft) thick and 100 m (300 ft) or more long contain 2–3 percent flaky graphite (Ravich and Solov'ev, 1969, p. 280).

Phosphate rock has been found in the Pensacola Mountains (loc. 12). Sandstones of middle Paleozoic age contain a few irregular layers and pods of phosphate rock as much as 1 m (3 ft) thick (Heiser Sandstone) and scattered phosphate pebbles (basal Dover Sandstone). The phosphate is of no projected economic importance, but it is of scientific interest because it is the only known phosphate occurrence in very high latitudes (J. B. Cathcart and D. L. Schmidt, oral commun., 1973).

Coarse pure-white marble has been described from the Hektoria Glacier area in Graham Land (loc. 60) by Fleet (1965). The area of outcrop is 100 by 200 m (100 by 200 yds). Marble has also been found in the Transantarctic Mountains (fig. 2).

IRON

Potentially mineable concentrations of iron are known mostly in Precambrian rocks in East Antarctica and have been described in Soviet literature (Ravich and others, 1969, p. 451–452).

In Queen Maud Land, iron occurs in garnet-magnetite veins at localities 3 and 4 ("Mount Hedden" and Mount Humboldt). At locality 3, the veins are 0.5–5 m (2–15 ft) thick; magnetite concentrations have not been stated. At Mount Humboldt, pods of iron ore containing 25 percent or more magnetite occur in bodies greater than 100 m (300 ft) thick. At locality 5 (Gburek Peaks), titanomagnetite occurs mixed with biotite in pods as much as 3 by 15 m (9 by 50 ft) and in monomineralic veins 10–30 cm (4–10 in.) thick. At locality 66, "Mount Nikolaev," glacial moraines contain considerable fragments of magnetite weighing as much as 5 kg (10 lbs). Soviet geologists consider the prospects of finding a major iron deposit in Queen Maud Land fairly good.

Elsewhere in East Antarctica, iron deposits are exposed in outcrops on the coast of Enderby Land (locations not specified) and in the Bunger Hills (loc. 67). Fragments of jaspilite (banded iron ore) occur along the coast from long 78° to 93° E. as morainal boulders as large as 2 m (6 ft); this indicates considerable amounts of iron ore beneath the ice inland from the coast. Jaspilite has also been reported (Solov'ev, 1972; Grew, E. S., oral commun., 1974) at Mount Rucker (loc. 69).

In the Forrestal Range (loc. 68), the upper part of the Dufek intrusion contains a stratiform gabbro of Jurassic age (see subsequent discussion of the Dufek intrusion). Several extensive layers of magnetite-rich rock (70–80 percent magnetite) have been reported by A. B. Ford (oral commun. 1973).

COPPER

Most copper deposits in Antarctica have been found in the Antarctic Peninsula and on islands off the coast of the peninsula. The deposits are mostly in diorite to quartz monzonitic plutonic rocks of mid-Cretaceous to early Tertiary (Andean) age. The deposits are similar to Chilean porphyry copper deposits, except that secondary enrichment is not known. None of the Antarctic deposits is known to be large. Small shows of copper, conspicuous because of the bright-green malachite and chrysocolla stains caused by weathering of sulfides, occur in many places throughout the continent.

In the central Lassiter Coast (loc. 13), low-grade copper mineralization occurs near hydrothermally altered shear zones that cut mid-Cretaceous granodiorite and adamellite. Small (a few centimetres) concentrations of massive copper sulfides occur in nonsheared rocks. Geochemical studies by the U.S. Geological Survey (Rowley, P. D., written commun., 1973) show anomalous amounts of Cu, Mo, Pb, Ag, Ni, Bi, and Co.

In other parts of the Antarctic Peninsula, Hooper (1962, p. 32) described a conspicuous green malachite stain on Green Spur, Copper Peak, Avers Island (loc. 14). The bedrock is diorite and tonalite cut by aplite dikes, which probably contain small amounts of copper sulfide weathered to malachite. Two veins (Mueller, 1963) 1–2.5 m (3–7 ft) wide occur at Greenwich Island (loc. 15) and contain 0.8 percent chalcopyrite. Small amounts of chalcopyrite from the Eielsen Peninsula (loc. 18) have been reported by Knowles (1945) in plutonic rocks of probable Andean age. Reports of several other minor occurrences of copper minerals in the peninsula have been made by P. D. Rowley and others (unpub. data).

In the northern Pensacola Mountains (loc. 11), traces of copper sulfide and green copper efflorescence occur sporadically in the outcrops of the Dufek stratiform intrusion (see discussion of Dufek intrusion).

GOLD AND SILVER

Gold and silver have been reported in trace quantities in pyrite-rich specimens of igneous and metamorphic rocks from three areas in the Antarctic Peninsula, localities 16, 17, and 18 (Knowles, 1945). Amounts of gold range from 0.3 to 2 ppm; of silver, 1 to 10 ppm. Traces of gold and silver have also been reported from sulfide-bearing quartz veins on the Adelie Coast, locality 9 (Ravich and others, 1968, p. 453). Traces of gold have also been found in rocks in Victoria Land.

Such occurrences of gold and silver are not significant for future prospecting. Most samples of pyrite and other sulfides from Antarctica or elsewhere would probably contain both elements in concentrations on the order of those reported above.

MOLYBDENUM

Small amounts of molybdenite have been reported from Precambrian crystalline rocks at localities 7, 8, 9, and 10 in East Antarctica (Ravich and others, 1968). Molybdenite is also present in West Antarctica at locality 19, Stonington Island (Knowles, 1945) and locality 13, central Lassiter coast. None of these occurrences points to large concentrations of molybdenum.

OTHER METALS

Manganese has been described from the Marguerite Bay area, Antarctic Peninsula, locality 19 (Knowles, 1945), and Wilkes Land, locality 63 (Stewart, 1964).

Tin is known only as detrital grains of cassiterite occurring in the heavy-mineral fraction of Paleozoic sandstones (Stewart, 1964).

Chromium, nickel, cobalt, and platinum occur in trace amounts in the Dufek intrusion, Pensacola Mountains (loc. 11), and are described later. They also occur in a mafic igneous rock (loc. 61) on Aspland Island, South Shetland Islands(Kosack, 1955).

Reports of uranium occurrences are, surprisingly, nearly absent in the literature. Euxenite was found as an accessory mineral in Precambrian pegmatite in the Lutzow-Holm Bay area (Saito and Sato, 1964, loc. 59). French geologists have reported anomalous amounts of radioactivity in Adelie Land.

POTENTIAL RESOURCES

MANGANESE NODULES

All the ocean area south of lat 60° S. and outside the Continental Shelf of Antarctica is floored by oceanic crust. The only presently known mineral-resource potential for this area is manganese nodules. Extensive areas of the sea floor even at these latitudes have a covering of scattered manganese nodules, nodule pavement, or concretionary masses. Specific areas have been mapped by Goodell, Meylan, and Grant (1971). Manganese nodules are of interest because of their high content of copper, nickel, and cobalt rather than their manganese content. The amounts of these accessory elements included with the manganese are strongly dependent on the latitude (Horn and others, 1972). Nodules that accumulate near the equator are metal rich, whereas those that accumulate farther from the equator are leaner in metals. For this reason, the manganese nodules of the Antarctic environment represent the least desirable segment of the nodule resources of the oceans. This is not to say, however, that they could not be considered for mining at some future date.

Figure 3 is a computer plot of manganese nodule locations in the oceans south of lat 60° S.; table 2 lists coordinates of nodule locations. This figure serves only to show that manganese nodules do occur in extreme southern waters, for portrayed nodule distribution is most probably a function of where the research ship *Eltanin* dredged. No metals-content information is available.

GEOTHERMAL ENERGY

Most potential geothermal resource areas are related to active or recently active (Pleistocene to Holocene) centers of volcanic eruption. In Antarctica, these centers are along much of the Pacific margin of the continent—along the western border of the Ross Sea, in Marie Byrd Land, and in the South Shetland Islands off the northwest coast of the Antarctic Peninsula (fig. 2).

In addition to recency of eruption, there are two other indications of the geothermal potential of a volcanic area:

1. Composition of the magma. Silica-rich magmas that erupt to form rhyolites and dacites are derived from magma chambers high in the Earth's crust, and the heat source is relatively accessible to ground water; silica-poor magmas such as basalt are usually derived from an inaccessible heat source deep in the crust.

TABLE 2.—*Marine manganese nodule occurrences of lat 60° S.*

[From dredge and trawl samples. Ship: *Eltanin*. Source: unpub. data from the Smithsonian Institution Oceanographic Sorting Center]

Cruise	Station	Lat.	Long.	Depth (m)	Remarks (percent of nodules in total sample)
5	9	61°13′	67°50.5′W.	3863	30
5	9	61°15.5′	67°41.5′W.	3711	1–5
5	10	62°17.5′	67°51′W.	3822	20
6	28	62°52.3′	59°27.2′W.	1081	Trace
10	15	64°05.1′	75°23′W.	1828	20
10	17	62°00.2′	75°10.3′W.	4389	90
10	18	62°02.7′	75°03.8′W.	4471	100
10	19	60°05.6′	75°17.3′W.	4590	20
11	7	60°54′	114°47′W.	5033	100
12	12	60°15.5′	36°19.2′W.	1581	Trace
12	19	60°33.6′	36°59.2′W.	1161	1–5
13	20	65°37.0′	123°55.4′W.	4706	40
13	22	64°15′	130°13′W.	4813	100
13	23	63°36.5′	129°53.8′W.	4819	90
14	11	62°26.3′	160°07.2′W.	2926	60
14	12	62°45.5′	159°50.2′W.	2853	1–5
15	1	61°02′	95°02′W.	4993	40
15	7	61°02′	95°57′W.	4947	50
15	8	61°07′	104°58′W.	4826	90
17	9	64°03′	135°00′W.	4773	80
17	10	65°04′	134°53′W.	4362	10
17	13	67°59′	135°36′W.	4416	90
17	29	62°12′	94°46′W.	4898	100
20	13	60°20′	137°50′W.	4278	20
21	20	61°15.5′	120°25.5′W.	4981	60
23	3	61°27′	94°58′W.	4800	60
23	7	61°19	101°32′W.	4862	80
23	17	60°24′	115°01′W.	5040	90
25	24	63°03′	128°12′W.	4682	30
33	12	69°29.2′	130°36.7′W.	3802	30
38	8	61°50.5′	149°53′E.	3000	20

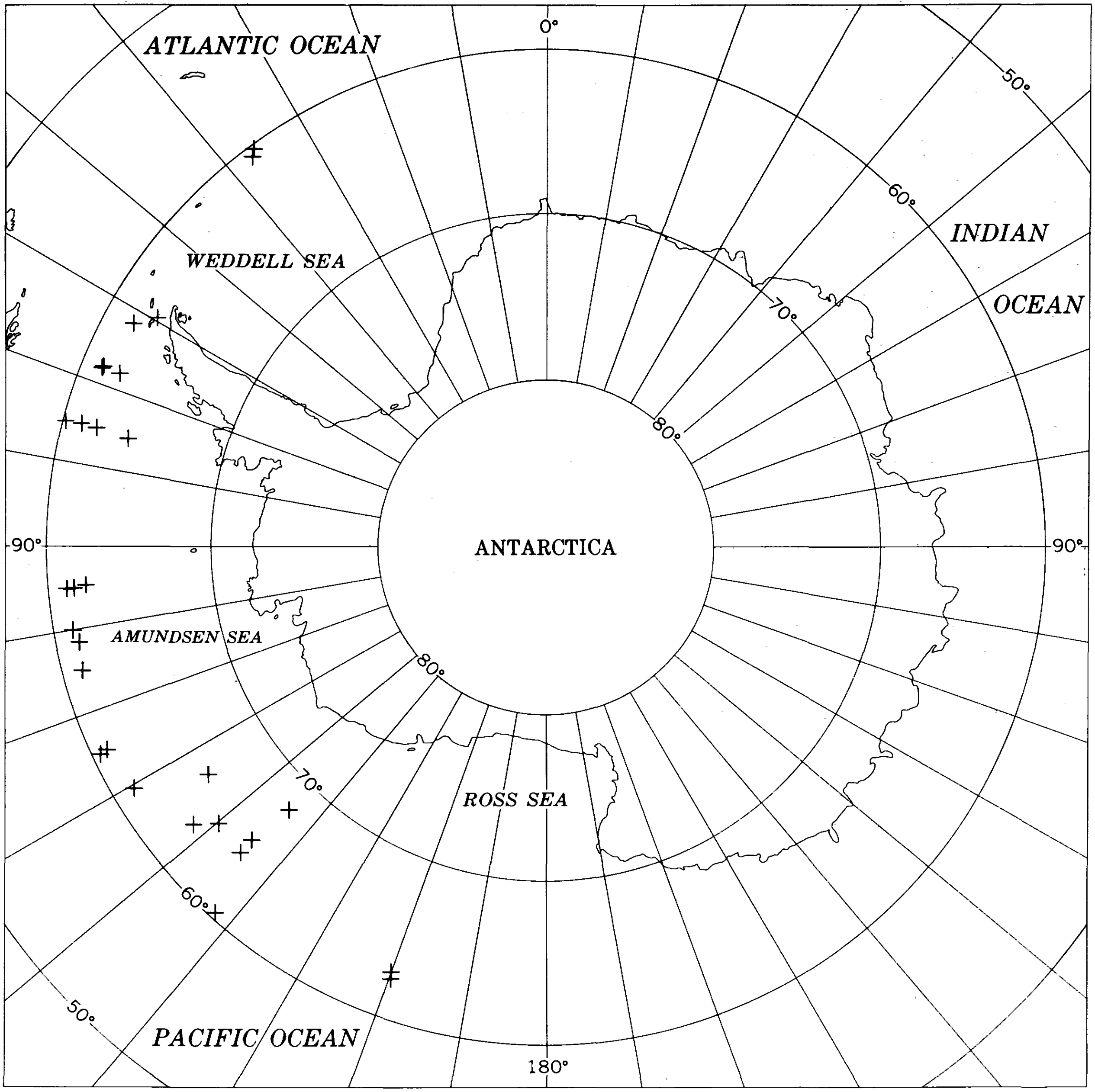


FIGURE 3.—Computer plot of manganese nodule occurrences in the oceans south of lat 60°S., based on dredge and trawl samples from *Eltanin* cruises. Source: unpublished data from the Smithsonian Institution Oceanographic Sorting Center.

2. Volume of rock. Large volcanic piles usually indicate the presence of a large magma chamber beneath the surface; these constitute a greater heat source than a small magma chamber.

Young volcanic rocks in Antarctica are mostly basalt, trachybasalt, and trachyte in the western Ross Sea region (Hamilton, 1972; Treves, 1970), basalt and felsite (the latter probably rhyolite and dacite) in Marie Byrd Land (LeMasurier, 1972), and basalt and andesite in the South Shetland Islands (Hawkes, 1961). These rock types are mostly silica poor and hence indicate a deep-seated heat source. The felsites that make up some of the stratovolcanoes of Marie Byrd Land form only a small proportion of the total volume of volcanic rocks.

The great preponderance of silica-poor volcanic rocks, indicating deep inaccessible heat sources, suggests a rather low potential for geothermal development in Antarctica. The best prospects are in areas where fumarolic activity has been observed during the present century (fig. 2) and indicates a heat source at or near the surface of the Earth. Second-rank prospects are in areas where eruptions have taken place in the last million years (fig. 2) and indicate the possibility of future eruptions. The 1-million-year figure is arbitrary; conceivably, volcanic activity could take place at any time along the Pacific margin of the continent but is much more likely to occur in areas of most recent eruption. In none of the areas judged favorable, described below, is the geothermal potential considered great. Future exploration for geothermal resources should concentrate on those young volcanic areas showing the highest degree of differentiation (Smith, R. L., oral commun., 1973).

In the Ross Sea region, large piles of young volcanic flows and palagonite breccias occur along the coast of southern and northern Victoria Land and make up several offshore islands. Fumarole activity at the summit of Mount Erebus on Ross Island was first reported in the 1840's and has probably been continuous since then. At present, the floor of the summit crater contains a pool of molten lava (A. B. Ford, oral commun., 1973). A drilling project on Ross Island was carried out during the past (1972–73) austral summer, but the geothermal gradient that was found is not known. The drill hole was still in permafrost at a depth of 200 m (660 ft), however, so a low geothermal gradient is likely. Conceivably, a small geothermal plant, if technically and economically feasible, might serve McMurdo Station (U.S.) and Scott Base (New Zealand), both of which are on Ross Island. Fumarole activity has also been reported at Mount Morning, 140 km southwest of Mount Erebus (LeMasurier and Wade, 1968).

The Hallett volcanic province of northern Victoria Land (near loc. 38) has been described in detail by Hamilton (1972). Fumarole activity has been observed only at Mount Melbourne, but very young (Holocene) cinder cones scarcely modified by glacial erosion attest to recency of activity throughout the province.

Studies in Marie Byrd Land by LeMasurier (1972) show that several volcanic piles contain lavas younger than 1 million years; the youngest rocks form small basalt cones. Ice towers caused by fumarole activity are present on the summits of Mount Berlin and Mount Hampton (Le Masurier and Wade, 1968). Lavas dated at less than 1 million years by the potassium-argon method occur at Mount Murphy, Mount Takahe, and Toney Mountain. Mount Siple, a huge volcano more than 3,000 m high on the coast of Marie Byrd Land, has not been visited because of its inaccessibility, but indirect evidence suggests that it is younger than 1 million years old.

The geologically most favorable prospect for development of geothermal power in Antarctica is Deception Island in the South Shetland Islands. Deception Island is a Pleistocene to Holocene caldera where fumarole activity has been known since 1831 (Hawkes, 1961). Two violent eruptions of basalt ejecta occurred in 1967 and 1969 and resulted in the destruction of scientific bases maintained there by Chile and Great Britain. In the 1967 event, three cinder and ash cones erupted within the caldera and coalesced to form a small island (Baker and others, 1969). The British Antarctic Survey has decided to abandon the island as a base site.

Small basaltic ash cones and scoria of Holocene age occur on King George Island in the South Shetland Islands, but fumarole activity has not been reported (Barton, 1965).

WATER (AS ICE)

The Antarctic ice cap may contain as much as 90 percent of the world's store of fresh water, an abundance for local use where energy is available to convert the ice to water. This supply is augmented by occasional ephemeral melt-water ponds. Most of Antarctica's annual precipitation goes to sea in the form of icebergs and melting glaciers.

Of direct importance to water-starved parts of the world is the possibility that some of this ice—in the form of seagoing bergs—could be transported somehow to more northern latitudes and converted to potable water (Potter, 1969). The volume of ice that breaks off into the oceans at the edge of the Antarctic Continent has been estimated (Loewe, 1967) to be about 1.4 trillion metric tons per year (1.5 trillion short tons), of which 45 billion metric tons (50 billion short tons) is produced at the edges of ice sheets, 450 billion metric tons (500 billion short tons) is from glaciers and ice streams, and 820 billion metric tons (900 billion short tons) is from ice shelves.

At present, this water seems to be a likely resource only for local use. Icebreakers require great expenditures of energy to move icebergs. Perhaps the natural ocean currents would be a possible future method of transporting the ice.

COAL

Coal deposits are known at many places around the perimeter of East Antarctica; the better known areas are shown on figure 2. Most of the coal symbols on the map indicate a measured section, commonly containing a considerable thickness of coal; other symbols indicate only an occurrence of coal or coaly shale. The stipple covers generalized areas where Permian (and in a few instances Triassic) coal-bearing formations occur in the mostly flat-lying Beacon rocks. Available information, although by no means conclusive, suggests that the coal measures extend from coast to coast under most of the great central ice mass.

Nearly all coal deposits seem to be of Permian age, and all seem to have formed in shallow swamps on rapidly aggrading broad sandy flood plains. Consequently, the coal is scattered vertically through a Permian sandstone sequence that is usually more than 500 m (1,600 ft) thick. Although individual coalbeds as much as 5 m (16 ft) thick have been reported, the coalbeds usually range in thickness from a trace to a maximum of 3 or 4 m (10 or 13 ft). Individual coalbeds tend to be lenticular and to have very limited horizontal extent. Coalbeds more than 2 km (1 mile) in horizontal extent appear to be uncommon. Most of the reported beds extend horizontally less than 1 km (0.5 mile). The coalbeds apparently range in rank from low-volatile bituminous to semianthracite. Rank determinations, however, may be uncertain because very few samples have been taken from unweathered coal. The supposed advanced rank probably precludes use of the semianthracite coal for coking or for coal gasification with the currently used techniques. The ash content commonly ranges from 8 to 20 percent. The presently known Antarctic coals will probably not be a valuable export commodity in the near future, but they could perhaps be used locally for heating and power production.

OIL AND NATURAL GAS

Sufficient information on which to base an estimate of the petroleum potential of Antarctica is not available. However, knowledge of the geologic histories of the continents and islands of the Southern Hemisphere and the results of exploration for oil and natural gas on continents other than Antarctica can offer some insight for speculation about the oil and natural gas resources that might be there.

Oil and gas are found, almost exclusively, in regionally unmetamorphosed sedimentary rocks that have been deposited in marine or near-marine environments. Wherever thick sections of such rocks are found, they may well contain at least some accumulation of oil and gas.

The onshore part of Antarctica, for all practical purposes, can be eliminated from a discussion of petroleum resources, although large basins have been inferred by geophysical soundings (for example, Wilkes basin and Polar basin). The land is covered by a very thick cap of ice that is in large part moving, and the sedimentary rocks that do stick out through the ice are largely metamorphosed, highly fractured, and intruded by igneous rocks. These conditions are not conducive to the preservation of oil and gas.

Parts of the Antarctic Continental Shelf, however, are free of ice during part of the year. If extrapolations of geology from neighboring continents and their shelves are valid, the Continental Shelf of Antarctica may be expected to contain thick unmetamorphosed sedimentary rocks. This assumption is partly confirmed for some areas, particularly the Ross Sea region, by marine geological and geophysical work from research vessels. The USNS *Eltanin* spent 10½ years in the southern oceans, much of this time on or adjacent to the Antarctic Continental Shelf (Watkins, 1973, p. 71). Scientists on board carried out a systematic program of continuous surveys of bathymetry, sediment thickness, and magnetic and gravity fields, plus bottom sampling by piston cores and dredge hauls (Capurro, 1973, p. 58; Hayes, 1973; Simmons and Landrum, 1973; Watkins, 1973), and subsequent analysis and interpretation of the data (Bandy, 1973; Cassidy and DeVore, 1973; Hayes, 1972). In addition, deep rotary-drill holes were put down and cores were recovered from the Antarctic Continental Shelf by the drilling vessel *Glomar Challenger* in 1972 (Hayes and others, 1973).

Evidence strongly suggests that the geologic history of Antarctica is linked to that of the other continents and islands of the Southern Hemisphere and India and that these land areas were once joined to Antarctica on three of its sides except for a gap on its east side between about what is now long 80°–115° E. and its west side between about what is now long 60°–150° W. The former landmass has been called Gondwana or Gondwanaland. Some time during the middle of the Mesozoic Era, the present continents and islands began to drift away from Antarctica by the mechanism of ocean-floor spreading (Craddock and others, 1969–70). At the places where they were once joined, each of the new continents has since developed continental shelves, on which thick sections of Cretaceous and Tertiary sedimentary rocks were deposited. On some continents, sediments of these ages also accumulated in basins on the parts of the continents that later became land.

Petroleum test drilling and seismic surveys have been carried out in recent years on almost all the land and continental shelves of those areas that once touched on Antarctica. As a result, several oil and gas fields have been discovered onshore in southern South America and offshore of southeastern Australia, and strong showings of gas have been found onshore in Mozambique and offshore of South Africa, all in strata of Cretaceous and Tertiary age. The thickness of the Cretaceous and Tertiary rocks on the shelves of those continents has been determined as approximately 3–5 km (about 10,000–15,000 ft). The results of drilling so far, however, indicate that most of those shelves will not be prolific producers of oil and gas, except for the area off the southeast corner of Australia called the Gippsland Basin. Gippsland Basin contains proved reserves of 345 million metric tons (2.5 billion barrels) of petroleum and 220 billion m^3 of gas (7.8 trillion ft^3); this may be because the sediments were deposited in a closed basin during Tertiary time.

Present knowledge indicates an accumulation of sedimentary rocks ranging from Tertiary to Holocene age on the shelves of Bellingshausen Sea, Weddell Sea, and Ross Sea. The Bellingshausen shelf is believed to be geologically similar to the Pacific shelf of Chile, an area that has to date yielded only natural gas. The Weddell Sea shelf is thought to have affinities with the shelves off southern South America and South Africa, where only small oil and gas fields have been discovered to date. The Ross Sea shelf may resemble the Gippsland Basin of Australia, which contains significant amounts of oil and gas.

Antarctica seems to have some petroleum potential, but lack of information precludes any real appraisal. The presence of moving ice, the great depth of water over the Antarctic shelves, and the tremendous logistical problems posed by the area constitute operational obstructions that will greatly reduce the economic viability of potential Antarctic petroleum resources. Many other unexplored areas of the world have equal or better petroleum potential and do not present the formidable problems encountered in the Antarctic.

A thick succession of Cretaceous sandstone crops out at the north end of the Antarctic Peninsula (Bibby, 1966), and a few outcrops of sediments of Tertiary age have also been found there. Cores taken recently of the sediments on the shelf of the Ross Sea contained marine and nonmarine sediments ranging in age from early to late Tertiary and younger. Natural gas was detected in some of the cores.

Recently obtained geophysical data indicate that the sedimentary rocks on the Ross Sea shelf might be as much as 3–4 km thick (10,000–13,000 ft) and that this section is probably made up of Tertiary, and possibly some Cretaceous, strata (Dennis Hayes, oral commun., 1973).

Geophysical data for part of the Weddell Sea shelf, analyzed by J. C. Behrendt (oral commun., 1973), indicate the probable presence of 3–4 km (10,000–13,000 ft) of sedimentary rocks in parts of that area also. By analogy, these sediments could well be equivalent to those on the Ross Sea shelf and the shelves of the neighboring continents.

How prolific of oil and natural gas the sediments of the Ross Sea and Weddell Sea shelves will be depends on the depositional environments and on postdepositional geologic events. Because it has affinities with the Gippsland Basin of Australia, the Ross Sea shelf may contain more oil and gas than the Weddell Sea shelf. The Weddell shelf has affinities with the shelves of southern South America and South Africa, where only small oil and gas fields have been found.

The shelf off Antarctica between what is now about long 80°–110° E. apparently had access to the open sea more often during its history than the rest of the continent. This area may be comparable with the shelf off western Australia where large petroleum and gas fields have been found in relatively undisturbed strata of Permian to Jurassic ages. A similar comparison may be made with the Antarctic shelf between about 60° and 165° W., but orogenic activity has there greatly disrupted and partially metamorphosed Jurassic and older strata. On the shelf of the Bellingshausen Sea, however, relatively undisturbed Jurassic to Holocene strata could well be present; some of the strata might be expected to contain natural gas by analogy with strata of probable Tertiary age on the Pacific shelf of Chile in which natural gas has recently been discovered.

Regardless of their potential, the continental margins of Antarctica are very different in at least one respect from the margins of other continents—they are covered by a much greater depth of water. The seaward edge of the Antarctic Continental Shelf averages at least 500 m (1,650 ft) below sea level (fig. 2) in contrast to the average depth of most of the world's shelves, which is about 200 m (600 ft). The base of the continental slope of Antarctica appears to be at about 3,000 m (9,800 ft) below sea level in contrast to about 2,500 m (8,200 ft) for most of the rest of the world. The continental slope itself is also, apparently, considerably steeper than those of other continents. It has been postulated that these characteristics of the Antarctic Continental Shelf and Slope may be the result of the weight of the ice cap on the continent of Antarctica. The shelf and slope developed normally until the growing ice cap gained enough weight to depress the entire continent (J. V. A. Trumbull, unpub. data, 1958).

ECONOMIC POTENTIAL OF THE DUFEK INTRUSION, PENSACOLA MOUNTAINS

Because of the possibly great economic potential of the Dufek intrusion (loc. 11), it is treated separately.

A great variety of economic mineral deposits are associated with stratiform igneous complexes such as the Bushveld in South Africa, the Stillwater in Montana, and the Sudbury in Ontario. Important deposits include chiefly platinum, nickel, copper, and chromium. In the Bushveld, deposits of lead, zinc, vanadium, iron, cobalt, and even tin and gold have at times also been worked. Nearly all the major deposits are associated with ultramafic rocks in lower parts of the complexes.

One of the world's largest layered complexes was discovered in 1957 when an International Geophysical Year traverse party from Ellsworth Station visited the Dufek Massif. Studies by the U.S. Geological Survey in 1965–66 showed that this complex makes up nearly the entire northern third of the Pensacola Mountains. Reconnaissance geophysical surveys indicate a minimum areal extent of about 34,000 km^2 (13,000 mi^2). The thickness is believed to be on the order of 7 km (4 mi), nearly 4 km (2½ mi) of which is exposed. Most of the body is covered by ice, but all major areas of exposed rock were either visited or viewed aerially at close range in the 1965–66 field season.

Field studies of this complex so far have been of a reconnaissance nature (Ford and Boyd, 1968). Iron is the only metal that has been found to occur in sizable concentrations. The iron occurs in the upper part of the body as magnetite concentrations (70–80 percent magnetite) as much as several metres thick. The lowest part of the body, including a possible basal ultramafic zone, is not exposed. Sporadic traces of copper sulfides and copper efflorescences occur throughout the body but seem to be more concentrated in the magnetite-rich rocks, especially in the Forrestal Range. Although chromite was reported by the 1957 visitors, its presence was not substantiated by the 1965–66 studies.

Semiquantitative and quantitative analyses of rock samples from the stratiform Dufek intrusion (U.S. Geol. Survey, unpub. data) indicate that trace-metal abundances are similar to those described for other stratiform intrusions throughout the world. Copper amounts are generally between 20 and 110 ppm and are rarely as high as 2,000 ppm. Chromium and nickel amounts are mostly less than 100 ppm and are rarely as high as about 500 and 200 ppm, respectively. The platinum-group metals are below detection limits in most rocks but reach maximum amounts of 0.03 to 0.05 ppm in rocks having abundant magnetite. The magnetite-rich rocks also show maximum vanadium amounts of about 2,000 ppm. Diamond drilling could aid in determining whether or not higher amounts of these metals exist in unexposed rocks. Although no significant concentrations of metals are now known in this complex, its petrologic similarity to other metal-producing complexes warrants its consideration as having a resource potential greater than many Antarctic mountain areas. Available data, however, are inadequate for an accurate appraisal of this potential.

The Dufek intrusion is dated radiometrically as Middle Jurassic, and thus it is probably related to the Ferrar Dolerite intrusions that are widespread in the Transantarctic Mountains. Another layered complex of the Dufek type has been reported by New Zealand field parties in the Warren Range (78° 28′ S., 158° 14′ E.) in southern Victoria Land, but little published information on this body is available. Others may exist.

MINERAL RESOURCE ESTIMATION

Substantial resources of minerals are almost certainly present in Antarctica because no other continental areas of similar size are devoid of them. These resources are probably localized in restricted areas. Long human experience in the inhabited regions of the world testifies to the sporadic occurrence of ores and the difficulty in finding them even in relatively well exposed areas where, in fact, the ores are largely hidden by soil, postmineral "cover rocks," or other impediments to exploration. The ice cover of Antarctica adds yet another dimension to the problems of finding ore deposits there. Furthermore, many of the rich ore deposits in the world are the result of supergene enrichment related to Tertiary, Quaternary, and Holocene erosion. Under the very severe glaciation which prevails in Antarctica, such near-surface deposits probably have been removed, or perhaps would never have formed.

Comparison of the geologic provinces of Antarctica with those of other Gondwana continents, the mineral resources of which are known, forms the basis of the speculation that follows. Crawford (1970) is one of several who have used this technique on a smaller scale, but he did not include Antarctica in his study. Using the Gondwanaland reconstruction seems to be the most plausible method of arriving at a basis for speculation. It seems reasonable to assume that Antarctica may contain mineral deposits that formed at the same time and under similar conditions as the known deposits of Antarctica's Gondwana neighbors. Figure 4 shows the reconstruction of Gondwanaland made by Craddock (Craddock and others, 1969–70, pl. 23), which is essentially the reconstruction first proposed by DuToit (1937). Our map shows in a very generalized way the major geologic units and the more important economic minerals they contain.

GEOLOGIC PROVINCES OF ANTARCTICA AND PRESUMED RELATIONSHIPS TO GEOLOGIC PROVINCES OF NEIGHBORING GONDWANA CONTINENTS

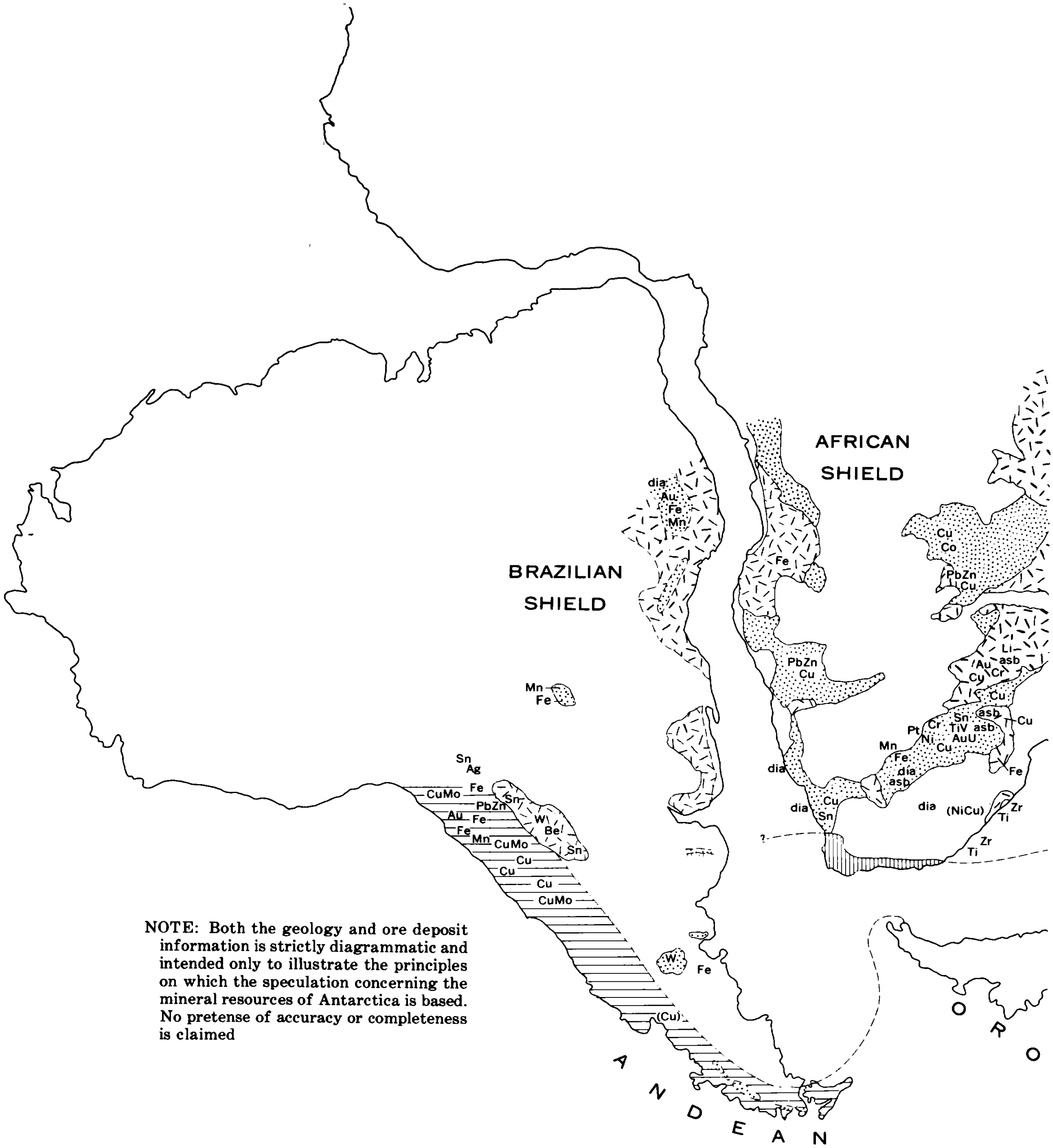
The East Antarctic shield, the oldest and most stable region of Antarctica, consists principally of Precambrian rocks, overlain in part by essentially undeformed sediments (Beacon rocks and equivalents) of Paleozoic and early Mesozoic ages. Before the breakup of Gondwana, the western two-thirds of Australia, India, and part of southern Africa were close to this part of Antarctica, at least during the later Paleozoic and early Mesozoic Eras, as witnessed by the paleontologic record. South

America, though not contiguous with Antarctica, was close to Africa (fig. 4).

The Precambrian record in other Gondwana continents encompasses 2½ billion to 3 billion years, roughly five times the later geological history. There is no assurance that the present continental fragments of Gondwanaland maintained the relative positions shown on figure 4 for all or much of this period; therefore, no actual improvement in the odds on locating ore occurrences can be gained by direct comparisons of parts of the Antarctic Precambrian shield with shield areas of other continents in an effort to deduce any such pre-Gondwana drift. Geologic mapping reveals that other continents are made up of more or less oval (or equidimensional) cores (nuclei) of very ancient rocks, largely gneiss or granite, but including belts of greenstone and primitive sedimentary rocks, which are surrounded by belts of metamorphosed sedimentary and volcanic rocks intruded by igneous rocks (fig. 4). Gold and gold-copper veins; nickel and minor copper; iron; small deposits of lithium, beryllium, columbium, tantalum, and rare-earth elements; chromite; asbestos; and tin and (or) tungsten are the more common mineral commodities found in these nuclei. Such nuclei, as mapped on other continents, reach a maximum of 1,000 km or more in maximum dimensions. The Antarctic shield certainly is large enough to include several nuclei.

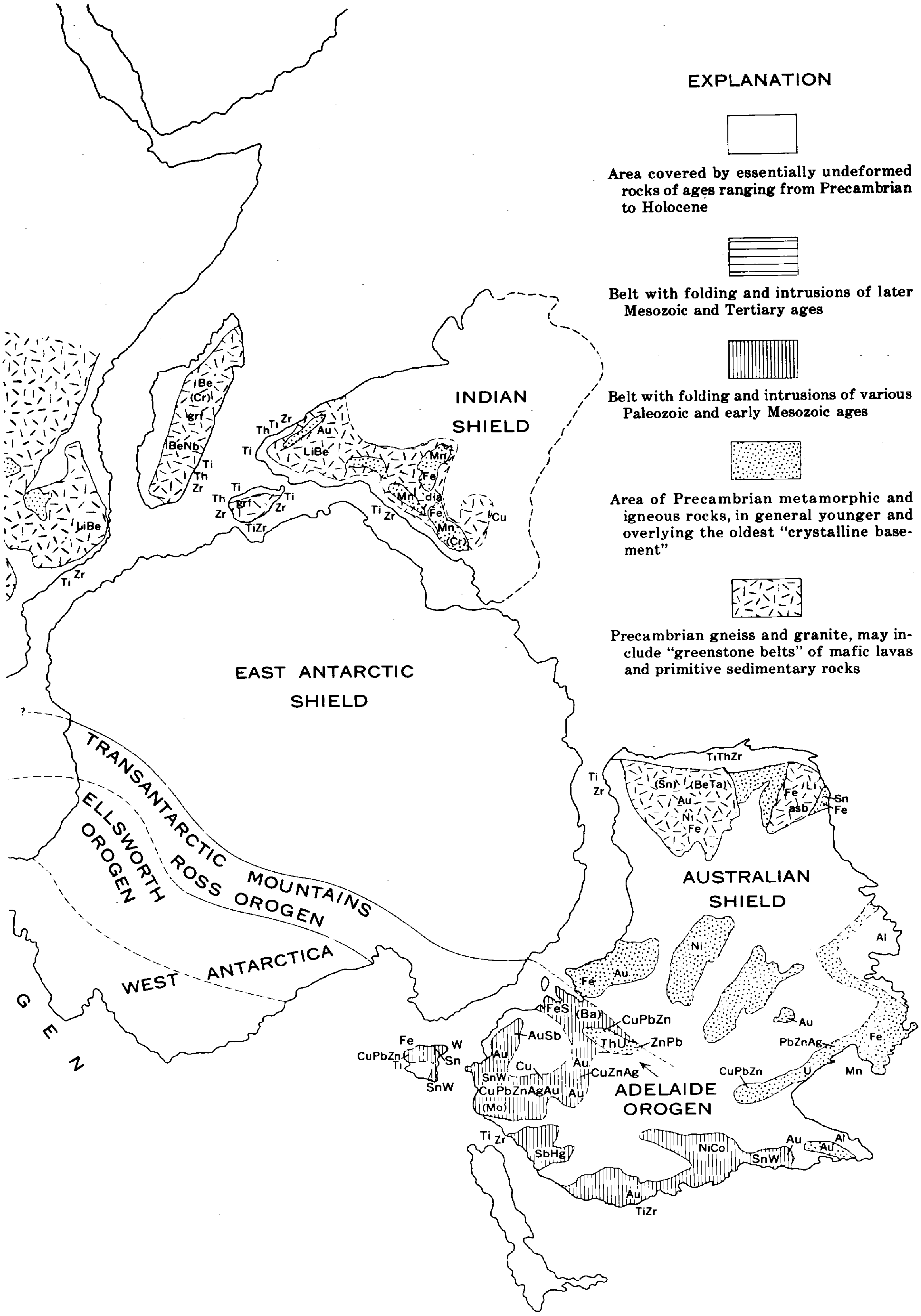
Other valuable ore deposits of the other Gondwana continents are contained in the younger Precambrian (roughly 2,200 million years or younger) sedimentary and volcanic rocks and in intrusive rocks cutting them (fig. 4). Many of these younger Precambrian deposits are stratiform and have considerably greater dimensions than the older ones; they therefore present larger and better exploration targets than those in the older Precambrian rocks. Among the known deposits that can be mentioned are: the extensive iron-formations (known variously as itabirite, banded quartz-hematite, and jaspilite) containing high-grade ore bodies and found in Australia, India, Africa, and South America; bedded manganese deposits that may or may not be associated with iron; conglomerate gold-uranium ores such as those best developed in South Africa (Witwatersrand); chromite, nickel-copper-platinum, and titaniferous magnetite-vanadium ores of the Bushveld mafic-ultramafic complex in South Africa; copper-cobalt ores of Zambia-Zaïre; and lead-zinc-copper-silver-gold ores of Australia (Mount Isa and Broken Hill). These younger Precambrian rocks, deposited unconformably on the eroded older basement, are in places themselves severely deformed, metamorphosed, and intruded and thus are very difficult to decipher. Elsewhere, however, they are slightly folded, and any extensive deposits they contain can be easily followed once they are discovered.

Most mineralization ceased in the shield areas of Gondwanaland by the end of the Precambrian; presumably this was also the case in East Antarctica. Very extensive erosion was followed by deposition of thick sediments, mostly of continental type, and of volcanic rocks of plateau basalt and allied types; such volcanic rocks are not generally accompanied by metallic ores, however. Extensive coal deposits are associated with these sedimentary rocks in Africa, India, and Antarctica. Some mineralization, however, is post-Precambrian and may even be related in a general way to the breakup of the ancient supercontinent. Many of the diamond-bearing kimberlite pipes of Africa are Cretaceous; they cut both the crystalline rocks and the sedimentary cover, and hence, they may be present below the ice in Antarctica even where the Beacon rocks overlie the Precambrian. Individual pipes, however, have cross sections measured only in tens or hundreds of metres, and only a small percentage of the pipes contain diamonds in economic quantities. The odds against finding one by blind drilling are astronomical. The early sources of South African diamonds were concentrations in alluvium (placers), and these placers still constitute the overwhelming sources elsewhere (especially southwest Africa, Angola, and Zaïre). In Antarctica, search for alluvial stones on beaches or in shallow shelf sediments might be successful. At Insizwa, South Africa, a layered gabbro that intrudes the Paleozoic-Mesozoic cover rocks contains low-grade nickel-copper ore near its base. Its similarity to the Dufek intrusive and its presence in a nonorogenic environment suggest that intrusions of this type could occur anywhere in the East Antarctic shield.



NOTE: Both the geology and ore deposit information is strictly diagrammatic and intended only to illustrate the principles on which the speculation concerning the mineral resources of Antarctica is based. No pretense of accuracy or completeness is claimed

FIGURE 4.—Schematic representation of major features of the geology and ore deposits of Gondwanaland. parentheses indicate deposits of lesser importance.



EXPLANATION

☐ Area covered by essentially undeformed rocks of ages ranging from Precambrian to Holocene

▤ Belt with folding and intrusions of later Mesozoic and Tertiary ages

▥ Belt with folding and intrusions of various Paleozoic and early Mesozoic ages

▒ Area of Precambrian metamorphic and igneous rocks, in general younger and overlying the oldest "crystalline basement"

▨ Precambrian gneiss and granite, may include "greenstone belts" of mafic lavas and primitive sedimentary rocks

Base modified from Craddock (*in* Craddock and others, 1969–70, pl. 23). Known deposits are labeled; Asb, asbestos; dia, diamond; grf, graphite.

Alluvial concentrations of titanium, thorium, and zirconium minerals are exceedingly common on all the margins of the continent of Gondwanaland that face East Antarctica (fig. 4). If once present, they have apparently not been preserved in exposed parts of Antarctica, no doubt because the movement of the ice cap or other erosional processes have removed them. Study of the shelf sediments in Antarctica might help to find remains of former deposits, and some accumulations may be present in protected spots under the ice.

Long-continued deep weathering has produced surficial bauxite deposits in parts of Gondwanaland. Conditions for its formation were probably favorable over much of geologic time, but preservation of the near-surface nonresistant ore bodies under the Antarctic ice cap seems doubtful.

Geologically, the Transantarctic Mountains of the Ross orogen combine features of the shield with those of younger belts. Precambrian rocks, affected by one or more metamorphic and intrusive events, and lower Paleozoic sedimentary and volcanic rocks were deformed and intruded by large granitic bodies during the Paleozoic Ross orogeny. The general picture is one of progressive addition to the East Antarctic shield toward West Antarctica, followed by extensive planation and deposition of continental sediments in middle and late Paleozoic time. Because the area is one of very considerable relief (as opposed to the rather uniform high ice cap over most of East Antarctica), exposures are fairly good (Craddock, *in* Craddock and others, 1969–70, pl. 20), and it is perhaps surprising that more evidence of mineralization has not been noted during their mapping.

In the reconstruction of Gondwanaland, the Ross orogen has no direct equivalent in Africa (fig. 4). Radioactive dating suggests a metamorphic event in eastern Africa roughly contemporaneous with the Ross orogeny, but no ore deposits have been found that can be attributed to this orogeny.

In the Australian Adelaide orogen, which Craddock correlates with the Ross, fairly numerous, though generally small, deposits of copper, lead, zinc, gold, barium, and manganese are known in late Precambrian and early Paleozoic sediments and volcanic rocks. In addition, important deposits of lead, zinc, silver, copper, antimony, and gold occur in older Precambrian rocks exposed within this orogen (fig. 4).

A progressive eastward younging of sedimentation, volcanism, deformation, and intrusion in eastern Australia continued through the Paleozoic and into early Mesozoic. Deposits of copper, lead, and zinc seem to correlate with periods of andesitic to rhyolitic submarine volcanism, whereas tin, tungsten, molybdenum, bismuth, gold, and other metals are probably related to somewhat later granitic intrusions in any one area. The belt, formerly called the Tasman geosyncline, is now referred to by Australian geologists as the East Australian orogenic province. Craddock distinguished a Borchgrevink orogen in Victoria Land, Antarctica, and equated it with the "Tasman"; it may be preferable to consider the entire Transantarctic Mountains province as constituting a Paleozoic-early Mesozoic orogen that in general becomes younger and dies out away from the East Antarctic shield. Mineralization generally decreases in intensity eastward in Australia and is very weak in New Zealand; the same may well be true in West Antarctica. This interpretation permits equating the Cape orogen of southernmost Africa with the outermost limit of the Paleozoic-early Mesozoic orogen of Antarctica. The Cape orogen strongly folded the latest Paleozoic rocks but did not produce any metamorphism, intrusion, or mineralization.

In summary, mineral deposits, probably of moderate size and grade, should be present in the Transantarctic Mountains. The most probable environments are: (1) layered mafic intrusions such as the Dufek; (2) sequences of marine sediments that incorporate substantial proportions of intermediate to silicic volcanic materials; (3) hypabyssal (porphyritic) intrusions of intermediate to silicic composition; and (4) contact zones of granitic intrusions, especially those near or adjacent to carbonate sequences. The area of northern Victoria Land (Craddock, *in* Craddock and others, 1969–70, pl. 20) seems to combine the last three conditions.

The Ellsworth orogen,[1] the area of West Antarctica between the Ross Sea and Weddell Sea, is largely ice covered, and the bedrock is largely below sea level. Where exposed, the rocks are Paleozoic sedimentary rocks and Mesozoic intrusions devoid of known metallic mineralization. The area has been interpreted by Craddock as constituting a Mesozoic orogen that is partly athwart the neighboring older and younger zones; it is shown somewhat differently in figure 4 from Craddock's compilation (Craddock and others, 1970, pl. 23) to accord with the general principle of transition.

The probability that significant mineral deposits are present in this zone seems to be poor. Thick sequences of clastic rocks like those exposed in the Ellsworth Mountains ordinarily do not host metallic ores, although the presence of Mesozoic intrusive rocks in the Whitmore Mountains suggests somewhat more favorable conditions there.

The general situation in this part of Antarctica is reminiscent of that in South America, which has relatively few ore deposits in the area between the shield and the Andes and particularly few in the Paleozoic-early Mesozoic stratigraphic section.

The Antarctic Peninsula and the adjacent islands, the Antarctic Andean zone, are clearly the continuation of the Andean zone of South America (fig. 4) and, together with Ellsworth Land and Marie Byrd Land, form the southern margin of the circum-Pacific belt that has been geologically active to the present time. This activity contrasts with East Antarctica and the Transantarctic Mountains, which have been inactive—except for vertical movements with or without block faulting—since Precambrian and early Mesozoic time, respectively. As the Andes and other segments of the zone contain many and, in places, large ore deposits, this is probably the most favorable area of Antarctica for exploration. There are, however, gaps in the circum-Pacific belt in which little or no important mineralization is known, and it is not possible on the basis of present information to be sure whether this region constitutes an ore-rich segment or not.

Some factors that may bear on exploration are:

1. Most of the Chilean ores occur in association with late Mesozoic and early Tertiary intrusions into Mesozoic and (or) early Tertiary volcanic and sedimentary rocks. Similar rocks are present in the Antarctic Andean zone.
2. Ores tend to be localized at or near the tops (cupolas) of intrusive masses; hence, areas in which the igneous rocks have relatively small outcrop areas surrounded by or in contact with other rock types (that is, where erosion has not been deep) are more favorable than those with great extents of intrusive material. This situation seems to be present in the Antarctic Andean zone, especially in the mountainous areas of the Lassiter Coast (east coast of Weddell Sea from 73° to 75° S.) and eastern Ellsworth Land north and northwest of the Ronne Ice Shelf. The same situation contrasts strongly with that in the nearest segment of the western South American coast, where a batholith virtually devoid of any known mineralization stretches some 2,000 km (1,200 mi) between Cape Horn and central Chile.
3. The Antarctic Andean volcanic and intrusive rocks belong to the calc-alkaline magmatic suite with which most of the copper-lead-zinc and similar ores of the world are associated.
4. The paucity of reported mineral occurrences in the Antarctic Peninsula appears to be an unfavorable factor. Long before systematic prospecting or exploration for ores takes place, there must be more evidence of mineral-rich areas, such as placer accumulations of gold, detrital ore boulders, areas of rock alteration (which often accompanies mineralization), deep staining of the rocks, or silicification. Oc-

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[1] The terms "Weddell orogeny" (Ford, 1972) and "Gondwanian orogeny" (Dalziel and Elliott, 1973) are closely synonymous with "Ellsworth orogeny."

currences of a few metals have been noted (fig. 2; P. D. Rowley and others, unpub. data, 1974), but the Antarctic Andean zone is probably not as rich, for example, as that in central and northern Chile and Peru.

The foregoing discussion concerns the "typical" Andean mineralization of Cretaceous and Tertiary ages. As with other areas of the circum-Pacific belt, Precambrian and Paleozoic rocks are present also. In some southern continents, these rocks contain sporadic but occasionally large and rich ore bodies; such deposits may occur in the Antarctic Andean zone as well.

STATISTICAL SPECULATION

The mineral-resource potential of Antarctica can only be evaluated by comparison with other regions of the Earth's crust where the resource potential is at least partially known. The procedure used in this study to estimate the frequency of mineral-deposit occurrences is therefore based on the following assumption: The geologic and physical chemical processes that caused the formation of mineral deposits in the better known parts of Gondwanaland (Australia, India, Madagascar, Africa, and South America) caused the formation of an equivalent density of deposits in Antarctica, the least known part of Gondwanaland.

The paucity of geologic data, the fact that ice covers most of Antarctica, and the limitations on time for this compilation permit a geologic analysis on only the broadest scale. No attempt has been made, for example, to take into account the apparent change in age and frequency of deposits along the Andean orogenic belt. Accuracy of the evaluation varies for any given area because: (1) The data available from metallogenic maps vary highly in quantity and extent; (2) available maps portray only known deposits or large mineral occurrences, and therefore the data are highly skewed in favor of economically viable mineral occurrences; (3) the status of exploration and development differs greatly in the various nations and political units, and the areas of greatest exploration have the greatest impact on the analysis; (4) the date of publication varies for the reference sources; consequently, some regions have recent mineral-occurrence information, whereas other regions only have much older data; and (5) the necessity of excluding smaller occurrences, for cartographic reasons, from metallogenic maps has had a profound effect in reducing the number of occurrences, particularly in figure 4.

To estimate the density of mineral occurrences in Antarctica, the following procedure was used:

1. Gondwanaland was reconstructed, using the format of Craddock and others (1969–70).
2. Major tectonic belts of Antarctica were correlated with similar tectonic belts on adjacent continents (fig. 4).
3. On the basis of existing metallogenic maps, the density of mineral occurrences—divided into the categories of (1) ferrous, (2) base, (3) precious metals, and (4) other deposits (uranium, aluminum, tungsten, asbestos, rare earths, etc.)—was calculated for each similar adjacent tectonic belt on the neighboring Gondwana continents (fig. 4).

The density of mineral occurrences per unit area within the similar tectonic belts of adjacent Gondwana continents was then extrapolated to Antarctica, and the resource potential of the continent was calculated as follows.

1. The total land area versus exposed bedrock was measured in the four major geologic provinces of Antarctica.
2. In each of the geologically equivalent land areas in Gondwanaland, the land area was measured and the major mineral deposits were counted. Four classes of deposits were distinguished, as given above.
3. The total spatial density of deposits was estimated in each subsection of Antarctica by computing a weighted average.
4. The number of deposits in the land areas not covered by glacial ice was estimated by multiplying the estimate of the total number of deposits by the proportion of land areas exposed.

The procedure used to compute the number of deposits expected to occur in each region of Antarctica is given below for the shield part of Antarctica:

Deposit	Shield					Total expected deposits for Antarctic shield[1]	Deposits expected in exposed Antarctic shield area[2]
	Australia	India	Madagascar	Africa	Total		
Ferrous metals	9	57	15	76	157	138.4	0.29
Base metals	17	5	6	49	77	68.9	.15
Precious metals	9	5	13	48	75	66.1	.14
Other	5	28	10	40	83	73.2	.15

[1] Calculated from: Total × F_A, where $F_A = 0.8817$, the area conversion factor.

[2] Calculated from: Total × F_A × F_I, where F_A is the same as above and $F_I = 0.0021$, the proportion of land area exposed in the Antarctic shield.

The area conversion factor F_A is the ratio of the area of the Antarctic shield to the total area in the four control areas of Gondwanaland (3,200,863/3,629,150 = 0.8817). All land areas are in square miles.

The proportion of land areas exposed F_I is the ratio of the area of exposed land in the Antarctic shield to the total area of the shield (7,041/3,200,863 = 0.0021).

Success in exploring for mineral deposits in Antarctica is a function not only of the number of deposits expected to exist but also of the intensity of the search. The chance of discovering a viable ore body is judged to be remote. For example, the number of base-metal deposits expected to exist in the exposed area of the Ross orogenic belt is 0.6. Assuming a chance of 1/100 of successful discovery, the expected number of deposits found on any single exploration attempt is only 0.006 or six chances in a thousand.

The histograms presented on figure 5 show the total number of mineral deposits that can be expected in Antarctica; this ranges from 380 in the Andean orogen to 33 in the Ross orogen. However, when the total number of mineral deposits is reduced by the number of deposits covered either by ice or Beacon rocks, figure 5 shows that the maximum number of mineral deposits to be anticipated ranges from 16 in the Andean orogen to less than 1 in the shield area. In table 3, the expected number of deposits in exposed areas and the expected frequency of discovery of a deposit are summarized for each of the orogenic belts.

The data presented in figure 5 show that the mineral-resource potential of Antarctica is very small because of the tremendous amount of ice cover on the continent. The potential is further reduced because the results of past exploration indicate that only a very small fraction of the mineral occurrences studied will have any significant resource potential. The costs and problems of exploration and development, in addition to the factors previously discussed, will further diminish the number of occurrences that have resource potential.

TABLE 3.—*Expected number of mineral deposits in exposed areas of Antarctica and the expected number of deposits to be discovered*

[On the basis of an assumed success rate of 1:100 for deposits once identified]

Type of deposit	Andean orogen		Ellsworth orogen		Ross orogen		Antarctic shield	
	Expected No. of deposits	Expected discoveries	Expected No. of deposits	Expected discoveries	Expected No. of deposits	Expected discoveries	Expected No. of deposits	Expected discoveries
Ferrous metals	2.5	0.025	1.0	0.01	0.6	0.006	0.29	0.0029
Base metals	7.5	.075	.7	.007	.6	.006	.15	.0015
Precious metals	3.5	.035	.1	.001	.3	.003	.14	.0014
Other	2.5	.025	.2	.002	.5	.005	.15	.0015

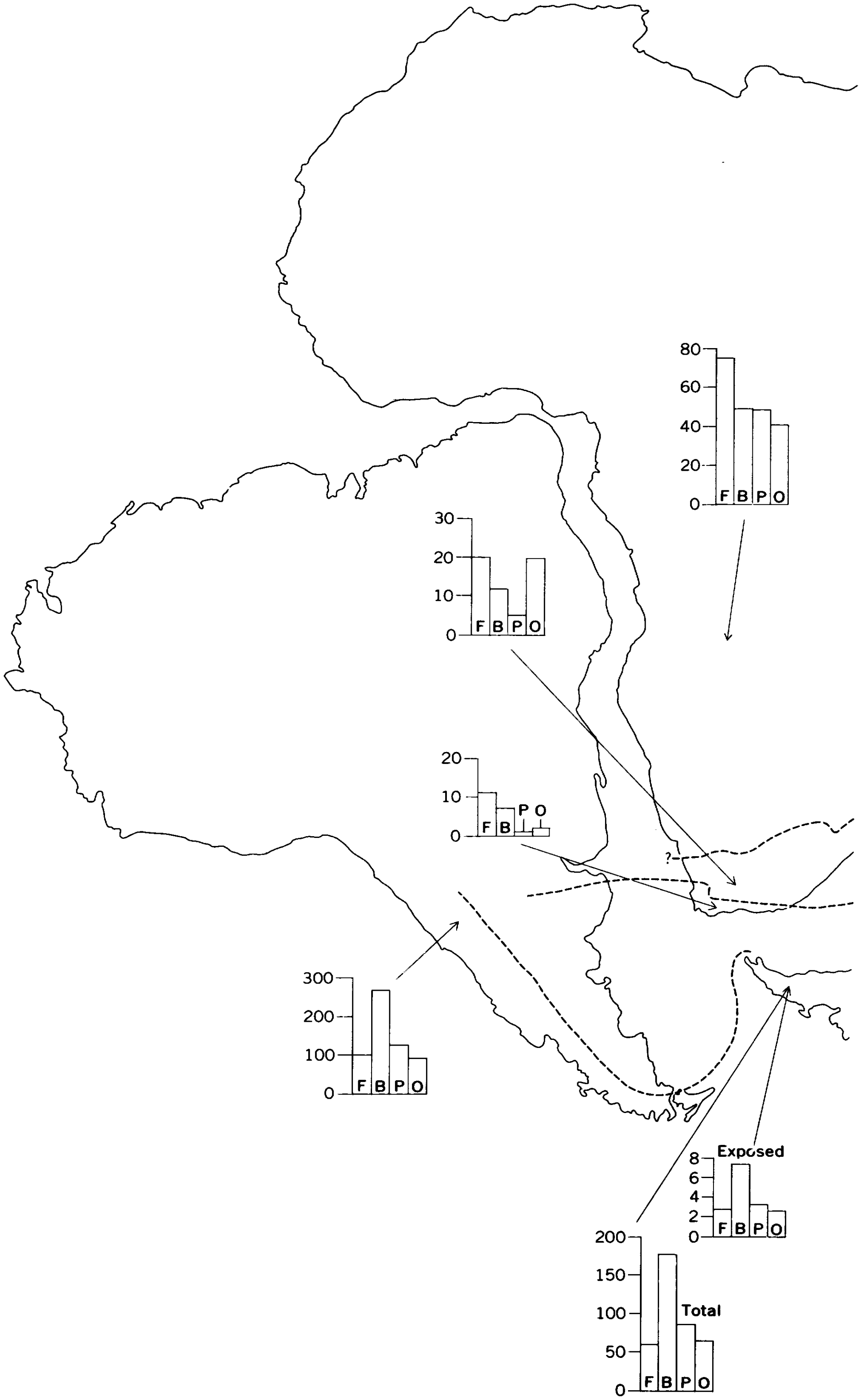
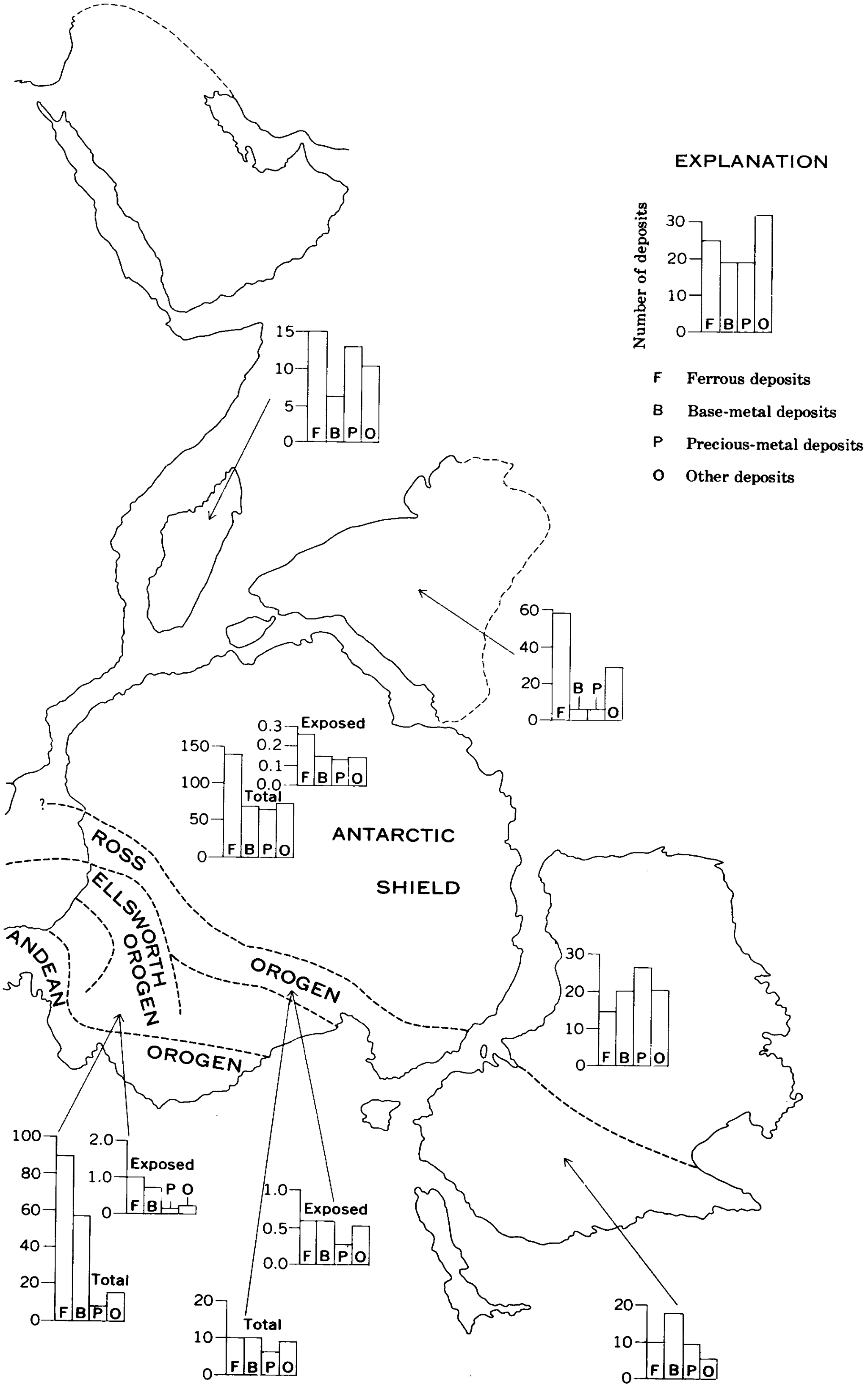


FIGURE 5.—Expected mineral deposits in Antarctica, on the basis



of mineral information from adjacent Gondwana continents.

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