Chapter 4

Potential Mineral Resources in Antarctica

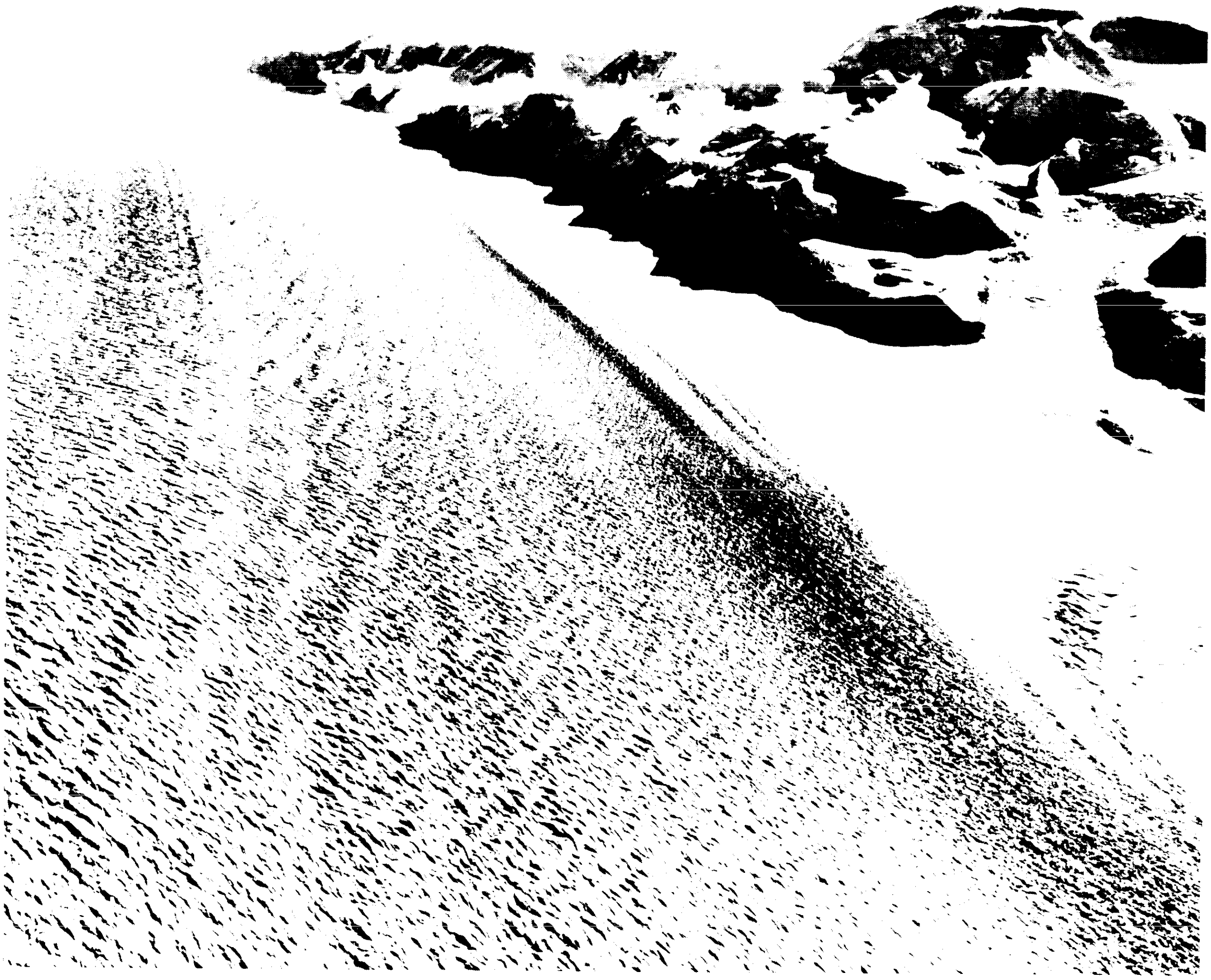

Photo credit: U.S. Geological Survey

Byrd Glacier

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SUMMARY

Scientists have discovered occurrences (small amounts) of several minerals **in Antarctica, but there are no known mineral deposits of commercial interest.** Mineral deposits are likely to have formed in Antarctica, just as they have on adjacent continents once connected to Antarctica, but because nearly 98 percent of the continent is covered by ice, few mineral deposits are likely to be exposed.

Development of any resources found in Antarctica will be expensive. At current prices, a metallic mineral deposit found in Antarctica would not be economic to develop unless of world class size or grade with an in-place value of $200 to $400 per ton, depending on location. An oil field would have to contain at least several billion barrels of recoverable oil. Even at this size, world oil prices would at least have to double before the field could be economically developed. Mineral development in Antarctica could be driven by political or strategic motives rather than by a quest for profit. Some believe these motives may become important; OTA does not view them as being as significant as market incentives.

The probability of finding mineral deposits is highest on the Antarctic Peninsula, in part because more rock is exposed there. Outside the Antarctic Peninsula the probability of finding mineral deposits in exposed areas is small. Based on the geology of the Peninsula region, the deposits most likely to be found are base metals (copper, lead, and zinc) and precious metals (gold and silver). The hard mineral deposits with the best prospects for economic recovery in Antarctica are low-volume, high-value deposits, such as gold, particularly if such deposits can be found in accessible locations. The Dufek intrusion in the northern Pensacola Mountains could host platinum-group metals, chromium, copper, cobalt, and nickel. However, discovery of a mineral deposit in a relatively inaccessible inland area, such as the Pensacola Mountains, would greatly diminish its prospects for economic recovery. Virtually all of the potentially economic minerals known to occur in Antarctica are currently abundant in other, more accessible areas of the world.

The offshore sedimentary basins surrounding Antarctica offer the best prospects for petroleum exploration. The Weddell and Ross embayments in West Antarctica, and Prydz Bay and the Wilkes Basin in East Antarctica are among the basins most likely to contain petroleum, based on what is known about the thickness, organic content, age, and thermal history of the sedimentary rock. However, until these basin areas are more fully explored, particularly by drilling, meaningful estimates of petroleum potential cannot be made. For the most part, the sedimentary basins on the surrounding continents that have analogs in Antarctica are not major petroleum producing provinces.

INTRODUCTION

The resource potential of Antarctica is receiving increased global attention as a result of technological developments, continued scientific research, and the drive to develop additional sources of energy and minerals supply. At present there are no known economic mineral deposits in Antarctica. However, scientists postulate that high grade mineral deposits exist there, as they do in all large land masses. Such mineral deposits would be difficult to locate: the extensive ice cover and limited opportunity for exploration are likely to preclude discovery of all but a tiny fraction of any potential ore bodies. Furthermore, the mineral deposits most likely to be economic, which would be high concentrations of metals in ore bodies, tend to be localized features hidden by overburden or otherwise difficult to locate even under more hospitable conditions. In addition, since the onset of glaciation, enrichment processes related to near-surface weathering and water movement, such as occur in more temperate regions, would not have occurred in Antarctica. Despite these caveats, it is entirely possible that some mineral deposits might be found in Antarctica which could at some future time be of sufficient economic value that their extraction might be considered.

A great variety of mineral occurrences have been found in Antarctica, but no mineral occurs in sufficient concentration or grade to be commercially minable. The term ‘‘mineral occurrence’ is used to refer to small amounts of a mineral that in larger volumes in other parts of the world has been mined or is an indicator of a minable deposit. The term ''mineral deposit" is used to refer to a large amount of some mineral without reference to its economic value. The term ''mineral commodity' is used here to refer to the mineral itself or the refined product made from it. Other than ice, only two mineral commodities, a sedimentary iron ore formation in the Prince Charles Mountains of East Antarctica and coal beds in the Transantarctic Mountains, are known to be of sufficient size even to be classified as "deposits." Because of their inaccessibility in Antarctica and abundance elsewhere, neither is considered a commercial deposit.

Mineral deposits can be divided into several categories based on a combination of geologic and economic criteria according to a system developed jointly by the U.S. Geological Survey and the U.S. Bureau of Mines. [1] Known deposits are either demonstrated or inferred and can range from subeconomic resources to reserves (box 4-A). Reserves are identified mineral deposits that are economically recoverable with current technology. Subeconomic resources are those that have been identified but are not recoverable under current economic conditions and technology. In Antarctica, identified fresh water (ice), coal, and iron ore deposits would be classified as subeconomic. **Speculative resources are unknown or undiscovered deposits outside districts where economically extractable mineralization is known to have occurred. With few exceptions, the mineral resources of Antarctica would be classified as speculative at this time.**

While the classification of mineral resources will change with time, most experts would agree that classification of Antarctic minerals is not likely to change before the end of this century and probably not for several more decades. Any change would depend on what, if anything, is found, where it is found, and the supply and demand situation at the time of discovery. To be economically viable at current prices, a metallic mineral deposit in Antarctica would likely have to be world class in size or grade and have an ore value of $200 to $400 per ton depending on its location. For a gold deposit, this would be approximately 10 times the grade of deposits currently being developed in the western United States. In the case of petroleum, afield would have to contain several billion barrels of recoverable oil or about three orders of magnitude larger than would be economic onshore in the United States.

Photo credit. Am Hawthorne

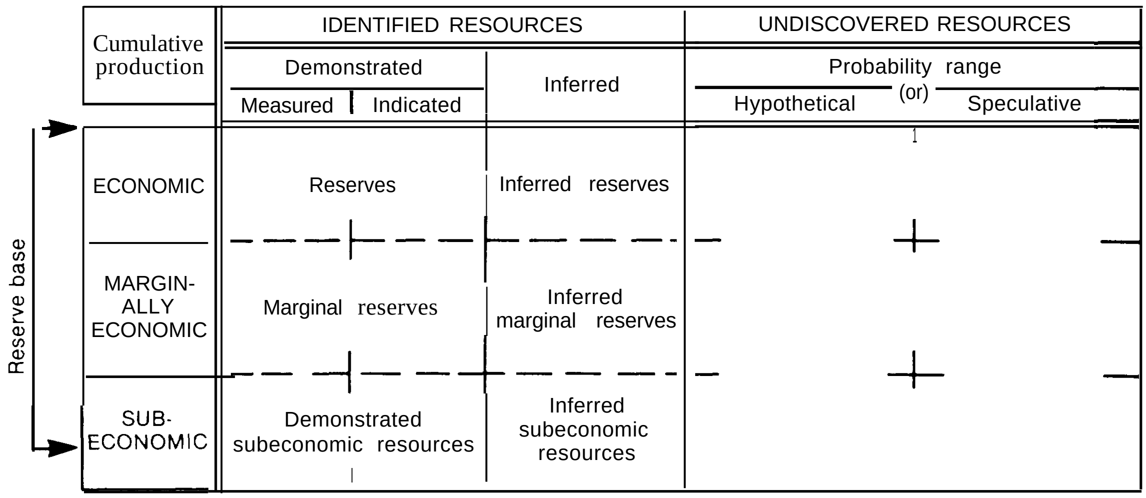
Transantarctic Mountains en route to the South Pole from McMurdo.

The following sections discuss the geological inferences regarding the formation and location of mineral deposits in Antarctica, assess the probabilities of discovering Antarctic mineral deposits, and offer some perspective on a selection of mineral commodities that might exist in Antarctica. The individual commodities discussed are not intended to represent all minerals likely to be found in Antarctica, but were chosen to provide a selection of

[1] ''Principles of a Resource/Reserve Classification for Minerals, from Geological Survey Circular 831, 1980, *Mineral Commodity Summaries 1988,* U.S. Bureau of Mines, pp. 184-187.

Box 4-A—Mineral Resources and Reserves

A general classification for describing the status of mineral occurrences was developed by the ***U.S.*** Geological Survey and the U.S. Bureau of Mines in 1976. The so-called ''McKelvey Box" named after the then-director of the USGS, Vincent McKelvey, further simplified the understanding of the of the economic relationships of the mineral-resource classification system:



The system is based on the judgmental determination of present or anticipated future value of the minerals in place according to the opinions of experts. Below are the economic definitions on which the resource-classification system is based:

- *Resource*: Naturally occurring mineral of a form and amount that economic extraction of a commodity is potentially feasible.
- *Identified Resource*: Resources whose location and characteristics are known or reliably estimated.
- *Demonstrated Resource*: Resources whose location and characteristics have been measured directly with some certainty (*measured*) or estimated with less certainty (*indicated*).
- *Inferred Resource*: Resources estimated from assumptions and evidence that minerals may occur beyond where resources have been measured or located.
- *Reserve Base*: Part of an *identified resource* that meets the economic, chemical and physical requirements that would allow it to be mined, including both measured and indicated resources.
- *Reserves*: Part of the *reserve base* that could be economically extracted at the time of determination.
- *Marginal Reserves*: Part of the *reserve base* that at the time of determination borders on being economically producible.
- *Undiscovered Resources*: Resources whose existence is only postulated.

plausibe examples covering a range of geological environments. Data on mineral occurrences in 'Antarctica in the following sections are largely taken from publications of the U.S. Geological Survey and other publications and papers in press by U.S. Geological Survey personnel. Data on world markets were abstracted from the U.S. Bureau of Mines, Mineral Commodity Summaries. Data on coal and uranium are from publications of the Energy Information Administration of the U.S. Department of Energy and the Organization for Economic Cooperation and Development's Nuclear Energy Agency.

The ratio of reserve base (see box 4-A) to current production was used in the sections devoted to specific mineral commodities to gain perspective on the future supply and market potential. These ratios are presented only for comparative purposes. Even in cases where the reserve base is large relative to current production (long term supply), this does not necessarily imply that if a high grade opportunity can be found in Antarctica, it would not attract interest. The reserve base rather than reserves was chosen because it includes not only reserves, which are currently economic, but also resources that are marginally economic and, to an undefined extent, some of the subeconomic resources. The reserve base is a broader term than reserves and, thus, for the purpose of defining future supplies, perhaps a better indicator. The broader category of "resources" could also have been used, resulting in a larger ratio. This might be more appropriate because, with few exceptions, the mineral resources of Antarctica would be classified no higher than speculative at this time. However, since for the purpose of projecting a future market it must be assumed that a deposit in Antarctica has been found, it would seem more realistic to project it in competition with known mineral resources reasonably likely to be developed in the future.

Current production is the other aspect of the reserve base to production ratio. Considering the variables in past minerals production, no attempt was made to project future production or to assess future needs based on changes in technology. Beyond short term fluctuations, decreases in annual production rates are generally less likely than increases. Obviously, higher annual production rates would reduce reserve base to production ratios, assuming there were no additions to the reserve base. Historical trends would suggest, however, that there will be additions to the reserve base. Projecting the extent to which this may offset increased future minerals production would depend, to some extent, on one's level of optimism.

Mineral development in Antarctica, if it were to occur, could also be driven by political or strategic concerns rather than by economic viability. Some believe that these concerns may become important. Therefore, strategic and critical materials concerns of the United States, if any, are also briefly summarized for the commodities discussed.

GEOLOGICAL ASSOCIATIONS

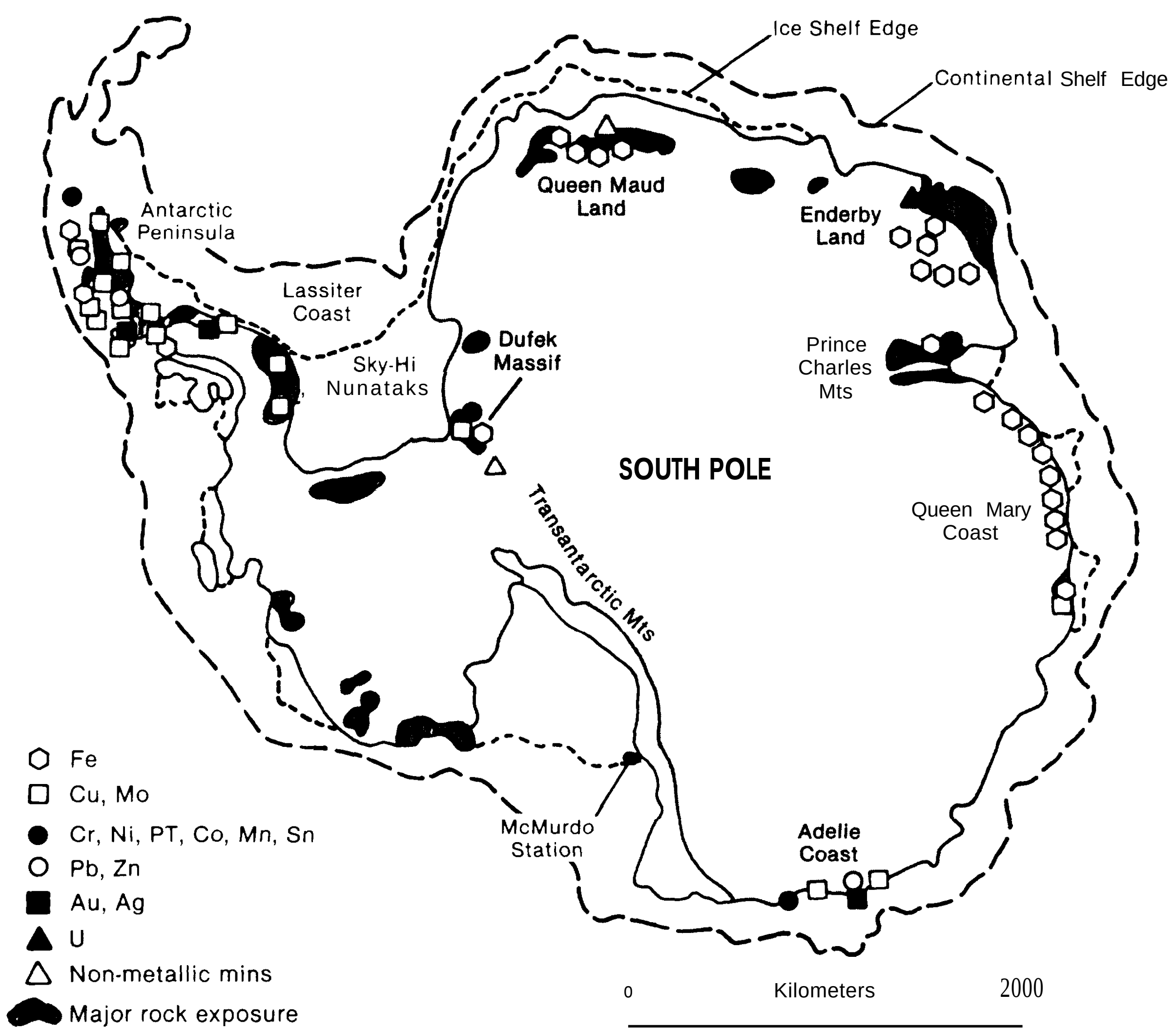
Antarctica can be divided into two parts on the basis of geology and topography, East Antarctica and West Antarctica. These areas are separated by the long mountain belt of the Transantarctic Mountains (figure 4-l). The line of division corresponds roughly to the division between the Eastern and Western Hemispheres or more closely to the 30°W. 150°E. meridian. East Antarctica is roughly twice as large as West Antarctica and is geologically older. It is a vast ice-covered plain with mountain peaks and ice-free areas only around the edges. Completely ice-covered mountain chains lie under the ice cap.

East Antarctica is mostly a **shield**[2] area consisting of very old (Precambrian) igneous, metamorphic, and deformed sedimentary rocks locally overlain by younger (Paleozoic through lower Mesozoic) sedimentary and igneous rocks of the Beacon Supergroup and their equivalents (box 4-B). The younger rocks are generally flat-lying and are especially widespread in the Transantarctic Mountains, which border the East Antarctic shield and provide a link to the younger sedimentary and volcanic rocks of West Antarctica. The geological picture, in general, is one of progressive addition through West Antarctica of younger belts of rock to the East Antarctic shield.

The rocks of East Antarctica are rarely exposed except along the coast and in the Transantarctic Mountains. In a few places near the coast, ice-free areas are found as ''dry valley s,' where receding glaciers and arid climate have left moraines and brackish lakes on the valley floor. The shield of East Antarctica contains a wide variety of mineral occurrences of a wide variety, as do shield areas of other continents. In contrast to the East Antarctic shield, relatively few mineral occurrences of interest have been found in the Transantarctic Mountains—

[2]Terms that appear in the glossary (app. G) are in bold the first time they appear.

Figure 4-l-Antarctic Mineral Occurrences



SOURCE. U.S. Geological Survey, 19SS,

with the exception of the Dufek Massif in the northern Pensacola Mountains near the Weddell Sea.[3] The Dufek intrusion is one of the world's largest layered mafic igneous complexes and is similar in certain respects to the mineral-rich Bushveld complex of South Africa.

Mineral deposits of moderate size and grade could be present in the Transantarctic Mountains. Among the most likely host rocks for ore mineralization would be:

- layered mafic intrusions such as the Dufek (platinum-group metals, chromium, cobalt, nickel);

[3] Peter D. Rowley, Paul L. Williams, and Douglas E. Pride, "Mineral Occurrences of Antarctica," *Petroleum and Mineral Resources of Antarctica*, John C. Behrendt (cd.), U.S. Geological Survey Circular 909, 1983, p. 27.

Box 4-B-Geologic Time Scale

Time interval	Major event	Began (millions of years ago)	Duration in millions of years
Cenozoic Era			
Quaternary Period			
Holocene Epoch	Man abundant	0.01	0.01
Pleistocene Epoch	Man appears	1,6	1.59
Tertiary Period			
Pliocene Epoch		5.3	3.7
Miocene Epoch	Mammals diversify Grasses spread	23.7	18,4
Oligocene Epoch		36.6	12.9
Eocene Epoch	Mammals develop rapidly	57.8	21,2
Paleocene Epoch		66.4	8.6
Mesozoic Era			
Cretaceus Period	Dinosaurs become extinct, Flowering plants appear	144	77.6
Jurassic Period	Birds appear	208	64
Triassic Period	Primative mammals appear, Dinosaurs appear	245	37
Paleozoic Era			
Permian Period	Reptiles appear	286	41
Pennsylvanian Period	Insects abundant	320	34
Mississippian Period		360	40
Devonian Period	Fish abundant	408	48
Silurian Period	Amphibians appear Land plants and animals appear	438	30
Ordovician Period	Fish appear	505	67
Cambrian Period	Marine invertebrates appear	570	65
Precambrian Era	Simple marine plants	3,800?	3,230?

SOURCE: Geological Society of America, 1983.

- sequences of marine sediments that incorporate substantial proportions of intermediate to **silicic volcanic** materials (copper, lead, zinc, silver); and
- porphyritic intrusions of intermediate t. sili. cic composition (copper, molybdenum, silver, gold).[4]

West Antarctica contains mountain ranges and isolated peaks, called nunataks, that extend through the ice and snow cover. Overall, the West Antarctic ice surface is much lower topographically than that of East Antarctica. If the present ice cover were removed, West Antarctica would appear as a series of scattered islands or group of islands surrounding the submerged Byrd Basin, which would connect with the Ross Sea, the Amundsen Sea, and the Weddell Sea.

The exposed rocks of West Antarctica in the Ellsworth orogen, between the Ross and Weddell Seas, are Paleozoic sediments and Mesozoic intrusions generally devoid of known metallic mineralization. The probability that significant mineral deposits are present in this zone appears to be poor. The thick sequences of sedimentary rocks like those exposed in the Ellsworth Mountains do not appear likely to host metallic ores, although the presence of

[4] N.A. Wright and p, L. Williams, *Mineral Resources of Antarctica*, U.S. Geological Survey Circular 705, 1974, p. 22.

Photo credit: Ann Hawthorne

Collecting samples on Mt. Oliver in Upper Wright Valley.

Mesozoic intrusive rocks in the Whitmore Mountains suggests somewhat more favorable conditions there.[5]

A substantial part of the Antarctic Peninsula consists of igneous intrusions of Mesozoic and Tertiary age that form a composite magmatic arc; arc-related volcanic and sedimentary rocks of similar age also occur. The volcanic and intrusive rocks of the Antarctic Peninsula belong to the **calc-alkaline** magmatic suite, rocks which in other parts of the world are associated with copper-lead-zinc ores. Consequently, the peninsula is a favorable geologic environment for copper, molybdenum, lead, zinc, tin, tungsten, silver, gold, and other mineral deposits.

Relationship to Adjacent Continents

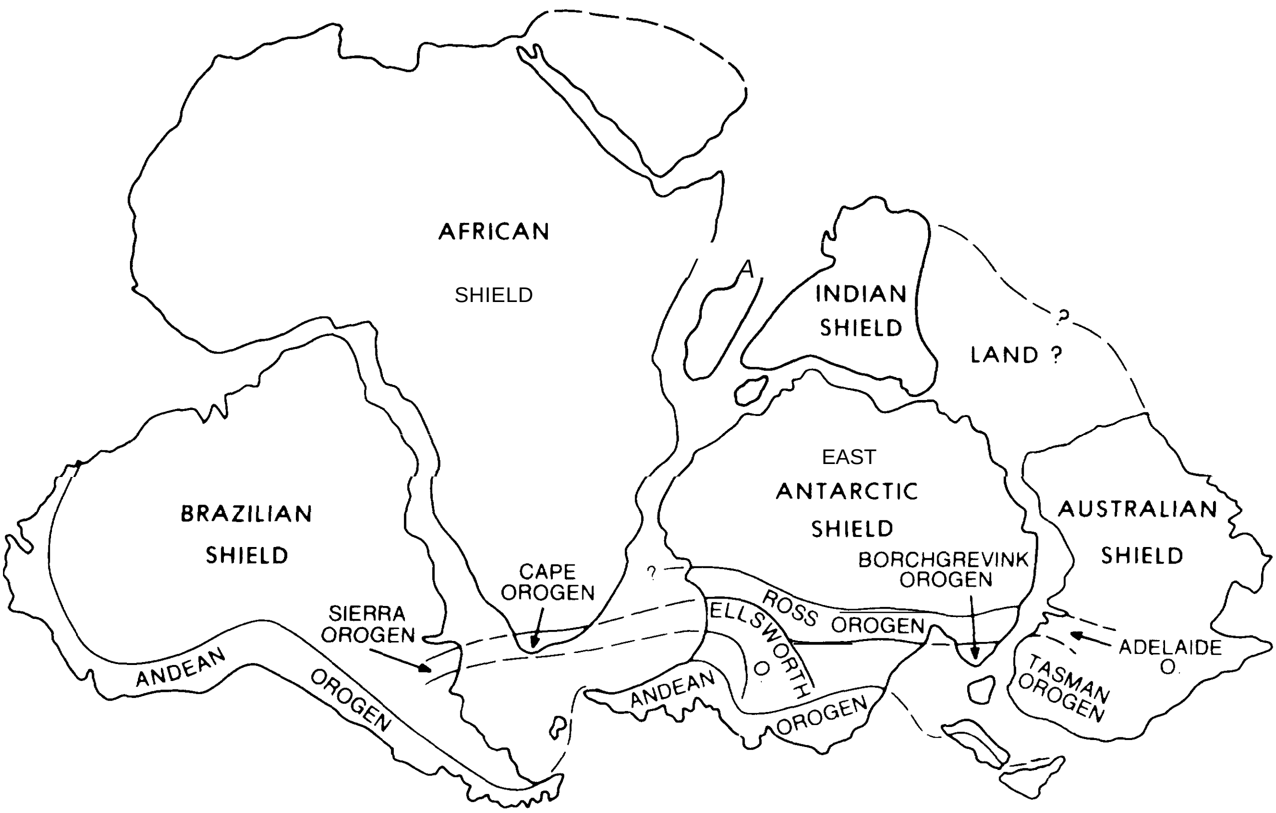
One way of assessing the mineral potential of Antarctica is by analogy with mineral deposits found in similar geologic settings on surrounding continents, Antarctica's relationship to the surrounding continents can be explained by the process of plate tectonics. According to the theory of plate tectonics, the Earth's rigid outer layer, called the **lithosphere, is** a mosaic of slablike plates that move with respect to one another at rates averaging a few centimeters per year. The plates ride on a hot, plastic layer of the Earth's mantle called the **asthenosphere.** Plate movements are thought to be driven by convection currents or density changes in the mantle and cause a seafloor-spreading process, in which molten material from the asthenosphere rises through the lithosphere to form new ocean crust at ridges on the ocean floor. Newly created oceanic crust moves outward from the mid-ocean ridge spreading centers. if the oceanic crust meets a continent on another plate, it may sink under the continent and be drawn down into the mantle in a process called subduction, (This process occurs along the Pacific coast of South America where Pacific crust plunges beneath the western margin of the continent.) Alternatively, if a continent is on the same plate as the new seafloor, it is carried along as though on a raft. (New ocean floor generated in the Atlantic Ocean carries the American continent westward toward the Pacific.) In general, the continents are carried passively by the lithospheric plates, which grow by seafloor spreading and occasionally collide to form mountain belts such as the Himalayas.

Reconstructing the former locations of continents based on the geologic record of plate movement indicates that approximately 200 million years ago the major land masses of the Southern Hemisphere, including what is now Antarctica. were joined together into a giant continent called **Gondwana** or Gondwanaland. In particular, the geological record shows that the western two-thirds of Australia, India, and part of southern Africa were close to East Antarctica at least during the Late Paleozoic and Early Mesozoic Eras.

The core areas of the continents are the old Precambrian shields. In the reconstruction of Gondwana, the Brazilian shield, African shield, Indian shield, Australian shield, and East Antarctic shield are all brought into close juxtaposition like pieces *of* a puzzle (figure 4-2). South America, though not

[5]Ibid., p. 23.

Figure 4-2--Geologic Provinces of Antarctica and Their Relationship to Adjacent Gondwana Continents



SOURCE: J.C. Behrendt, "Are There Petroleum Resources in Antarctica?" *Petroleum and Mineral Resources of Antarctica*, J.C. Behrendt (cd.), U.S. Geological Survey Circular 909, 1983, p 6.

contiguous with East Antarctica, was close to Africa.[6] Numerous mineral occurrences are found in the shield of East Antarctica. Many of these occurrences are similar to the mineralization of major economic deposits in comparable shield areas f the adjacent continents, These major deposits include **iron-formations** and bedded manganese in Australia, India, and Africa; conglomeratic **placer** gold-uranium deposits of the Witwatersrand *in* South Africa; chromite, nickel-copper, platinum, and magnetite-vanadium deposits of the **stratiform** Bushveld intrusion of South 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 pipes of South Africa, India, and Australia.[7] The Brazilian shield also contains important deposits of these types. Thus, since the shield areas of the adjacent continents in the Gondwana reconstruction have major mineral deposits similar to the types of mineralization found in the East Antarctic shield, it would seem reasonable to expect that similar deposits were formed in Antarctica,

Not only are the shield areas related, but analogs can also be found among the other geologic provinces of Antarctica. The Ross deformational belt of the Transantarctic Mountains extends into central Australia. The Flinders Ranges north of the city of

[6] Ibid., pp. 18-19.

[7] Peter D. Rowley, Paul L. Williams, and Douglas E. pride, ''Metallic and Nonmetallic Mineral Resources of Antarctica," *The Geology of Antarctica*, R.J. Tingey (ed.), Oxford University Ress (in press).

Adelaide lie within the Adelaide orogen and appear to correlate with parts of the Transantarctic Mountains. Numerous deposits of copper with associated gold, lead, zinc, silver, barium, manganese, antimony, and other metals are found in the Flinders Ranges in rocks of Late Precambrian and Early Paleozoic age. The deposit types include veins, stockworks, and replacement bodies generally related to Early Paleozoic igneous activity. Porphyry copper deposits and stratiform lead-zinc deposits are also found in the area. In the same general area is the recently discovered ore body at Roxby Downs, which is rich in copper, gold, silver, uranium, and rare-earth minerals. Further to the east, a belt referred to as the East Australian erogenic province (also called the Tasman orogen) consists of progressively younger sediments, volcanic rocks, and intrusions extending into the Early Mesozoic. This province, a portion of which geologically resembles part of north Victoria Land (the Borchgrevink orogen) in Antarctica, contains deposits of copper, lead, and zinc associated with submarine volcanism and tin, tungsten, molybdenum, bismuth, gold, and other metals apparently associated with subsequent **granitic** intrusions.

The extension of the Ross orogen toward Africa is less clear, but radiometric dating suggests that metamorphic activity occurred in eastern Africa at roughly the same time as the Ross orogeny, but no ore deposits have been found that can be associated with this event. The younger Cape orogeny of southernmost Africa strongly folded Late Paleozoic rocks but did not produce any metamorphism, intrusion, or ore mineralization. This event could be correlated with the Ellsworth orogen of Antarctica, which has also been found to be lacking significant mineral occurrences. In South America, the region comparable to the Ellsworth orogen lies between the shield and the Andes and has relatively few ore deposits, particularly in the Paleozoic to Lower Mesozoic stratigraphic section.

In general, it may be useful to think of the Transantarctic Mountains and West Antarctica as representing a set of Paleozoic to Early Mesozoic orogens that are progressively younger away from the East Antarctic shield toward the Pacific, Mineralization generally decreases in intensity eastward in Australia (this would be toward the Pacific Ocean in Antarctica; see figure 4-1) and is even weaker in

Photo credit: Ann Hawthorne

Helicopter leaving Mt. Feather after ferrying geology field part to site. Helicopters are indispensable in Antarctica.

New Zealand. Thus, by analogy, mineralization may decrease westward in West Antarctica exclusive of the younger Andean orogen. Consequently, the probability that significant mineral deposits are present in Antarctica in the zone between the Transantarctic Mountains and the Andean orogen would seem to be poor.

The youngest geologic province of Antarctica is the Andean orogen. The Andean magmatic and deformational belt extends northward from the Antarctic Peninsula through the Andes of South America, and in the opposite direction from Ellsworth Land and Marie Byrd Land through New Zealand to form the southern margin of the currently geologically active circum-Pacific volcanic belt. In the northern and central Andes, this belt is one of the richest metal-producing areas of the world. However, the southern Andes are not as rich in mineral deposits as the northern and central Andes. The geologic break seems to be where the Chile Ridge is subducted beneath South America at the boundary of the Nazca and Antarctic plates. Subduction of the oceanic plate is still active to the north but has slowed or stopped to the south where the Antarctic plate has moved at an acute angle to South America. Compared to the mineral-rich northern and central Andes, where ores tend to be localized near the tops of intrusive masses, the southern Andes and Antarctic Peninsula have a different geological history. In the peninsula, glaciation may have more deeply eroded the intrusive bodies, removing the tops where ore deposits may have been located.[8] The different geological history and environmental conditions suggest that the Antarctic Peninsula, Ellsworth Land, and Marie Byrd Land may be less richly mineralized than the north and central Andes. Nevertheless, by analogy with the Andes, the Antarctic Peninsula appears to be one of the more likely places in Antarctica for significant **base-metal** deposits and possible associated gold and silver.

Offshore Shelf Areas

Marine sedimentary basins are of primary interest to petroleum geologists. The fragmentation of Gondwana, which began about 175 million years ago, with the final split beginning about 28 million years ago, led to the deposition of thick sequences of Cretaceus and Tertiary sediments in mid-continent rift basins and on the newly created continental shelves where formerly the continents had been joined. Sediments of these ages also accumulated in basins that were later uplifted to become parts of the continents. Seismic surveys and exploratory drilling for petroleum have now been carried out on almost all the land and continental shelves of those areas that once touched Antarctica. Several relatively modest oil and gas fields have been discovered in southern South America, southern Africa, Australia, and New Zealand. Through the Gondwana reconstruction, these producing areas can be related to specific regions of Antarctica. However, this does not assure that petroleum will be found in the analogous areas in Antarctica due to differences in time of formation, sediment thickness, history of deformation, migration of any hydrocarbons, and other factors. For example, if oil producing sediments accumulated off Australia along time after the breakup of Gondwana, this would not necessarily be evidence of oil in an adjacent area of Antarctica.

Several petroleum producing areas on the adjacent continents may have analogs in Antarctica. The San Jorge and Magallanes Basins are petroleum producing regions in Argentina that can be related in a number of ways to the Larsen Basin of the Antarctic Peninsula (figure 4-3).[9] The San Jorge Basin contained proven reserves of 1.6 billion barrels in rocks of Jurassic or Early Cretaceus age. Sedimentary rocks of the same age are found in the Larsen Basin, but this in itself does not indicate hydrocarbon potential.

Mossel Bay off southern Africa is a minor petroleum producer. This basin bears a paleogeographic relationship to the Falkland Plateau, but may not be indicative of the hydrocarbon potential of the Weddell embayment.

Minor hydrocarbon accumulations have been found off the east coast of India in the Bay of Bengal and in Upper Cretaceus rocks in the Palk Bay area, which, through reconstruction, could correspond to the Prydz Bay area of Antarctica (Amery Basin) in which Cretaceus sediments have also been identified. The Prydz Bay area may also bear a relationship to the West Australian continental margin where producing fields are found near Perth.

The Cooper Basin in central Australia lies in a broad geologic province that possibly extended southward into Wilkes Land prior to their separation around 80 million years ago.[10] The Cooper Basin is an oil and gas producing province in Permian through Cretaceus rocks. No commercial petroleum discoveries have yet been made in the Great Australian Bight, Eucla, or Duntroon Basins (figure 4-3), which may, in part, be the conjugate margin to the Aurora Basin in the Wilkes Land region of Antarctica. The Otway and Bass Basins of Australia, which in the Gondwana reconstruction extend offshore toward Wilkes Land, are only minor producers.

The Gippsland Basin, in the Bass Strait between Tasmania and Victoria, is a major petroleum-producing province. However, the tectonism that formed the petroleum-bearing structures in this basin is not part of the southern Australian marginal rift system. Because Antarctica and Australia were already separated at the time of formation of the hydrocarbon-bearing structures in the Gippsland Basin, the basin has no analog on the Antarctic margin.[11]

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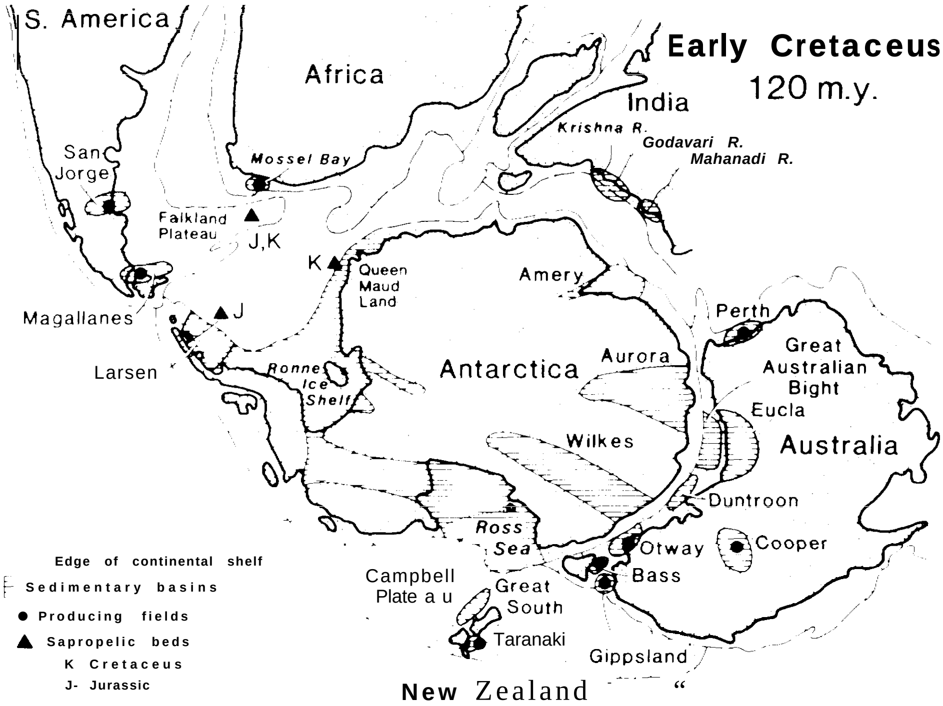
[8] Ibid.

[9] D.H. Elliot, "Antarctica: Is There Any Oil and Natural Gas'?" *Oceanus*, vol. 31, No. 2. Summer 1988, p. 38.

[10] Ibid.

[11] "Are There Petroleum Resources in Antarctica?' Petroleum *and Mineral Resources of Antarctica*, John C. Behrendt (cd.), U.S. Geological Survey Circular 909, 1983, p. 20.

Figure 4-3-Reconstruction of Gondwana in Early Cretaceus Time
(120 Million **Years Ago)**



The proximity of Antarctic sedimentary basins is shown in relation to basins in formerly adjacent continents and to producing 011 and gas fields.

SOURCE D H Elliot, "Antarctica. Is There Any 011 and Natural Gas?" *Oceanus*, VOl 31, No. 2, Summer 1988, p 37

The Campbell Plateau is the conjugate margin to the Ross Sea region, The Taranaki Basin off the North Island of New Zealand is primarily a gas-producing region and probably has no relationship to the Ross Sea continental shelf. Thus, **for the most part, the sedimentary basins on surrounding continents that have analogs in Antarctica are not major petroleum producing provinces.**

ANTARCTICA IN THE CONTEXT OF FUTURE MINERALS SUPPLY

The long-term availability of raw materials has been a recurring concern over much of the past century. This concern attained a new measure of public awareness in the 1970s when the price of oil and other commodities increased sharply. The public quickly realized that certain essential materials may be in finite supply and, hence, would become more costly and difficult to obtain. As a result of these concerns, exploration and exploitation of Antarctic minerals began to be seriously discussed.

Ore deposits form by relatively unusual combinations of natural processes, and, consequently, large, economic deposits are not common in the Earth's crust. For metallic minerals, these processes can be described as falling into three general classes, The two most important are **magmatic differentiation** and deposition from **hydrothermal solutions. Sur**face or near-surface enrichment is the third. Magmatic differentiation is the process whereby the various elements are distributed into the rocks formed during cooling and crystallization of a magma; locally concentrated deposits of certain minerals may be formed, Hydrothermal solutions or hot saline fluids pass through fractures or pore spaces *in rock,* dissolving or dislodging metals that are subsequently redeposited as sulfides, oxides, or even native metal, as the fluids cool or other conditions change. Surface or near-surface enrichment is simply the further concentration of metals by weathering or leaching by groundwater.

An ore deposit represents a special set of geologic circumstances and only becomes an economic proposition if a number of factors are favorable. 12 The first is discovery of the deposit itself. A vigorous exploration program does not automatically lead to the discovery of a new mineral deposit rich enough to mine. In Antarctica, a continent mostly covered by ice, the probability of discovery is greatly diminished.

Finding an ore deposit of sufficiently high grade is not enough. Accessibility is also very important. Deposits found near existing infrastructure will be mined before more remote deposits, other considerations being equal. In Antarctica, there is essentially no infrastructure.

A third factor controlling the development of mineral resources is the size of the deposit. Not only must the deposit be rich, but it must also be large enough to warrant the investment needed to develop it. In general, as the remoteness of the location increases, so must the size of the deposit necessary to offset the costs of the new infrastructure that will be required to develop it. Antarctica is the most remote continent in the world, Consequently, only large deposits, if any, will likely be developed. If first generation development were to occur and an infrastructure created, then costs of development of smaller deposits nearby, if any, may be lowered.

The largest deposits of a specific mineral or minerals are the easiest to find and tend to be discovered first. For any specific metallic resource, the few largest-tonnage deposits contain the majority of the total metal mined. For example, out of 165 porphyry copper deposits, the 16 largest deposits contain 64 percent of the metal content (past production plus resources), and the 82 largest deposits contain 94 percent of the metal. [13] For nickel, only 7 deposits account for more than 50 percent of the metal in a total of 156 nickel deposits; for tungsten, 3 deposits among 32 account for 59 percent of the tungsten; and for molybdenum, 3 of 34 porphyry molybdenum deposits account for 65 percent of the metal. Thus, based on past experience, **if a very large ore deposit were found in Antarctica, it would likely be found in the earlier stages of serious exploration and could, if developed, make a significant contribution to the world inventory of that mineral commodity.**

Much the same case can be made for large petroleum accumulations. A suitable environment had to have been present to have produced organic-rich source sediment. The source beds must have been buried and over time the temperature raised by the flux of geothermal heat (the internal heat of the Earth) to a degree sufficient to maturate the organic material and produce oil. The depth of this time-temperature range in which maximum oil generation occurs is known as the "oil window. ' The oil window generally occurs at depths between 2,500 and 16,000 feet and at temperatures between 150 and 300 "F. Natural gas is formed below the oil window. In areas of higher than normal geothermal heating, the oil window exists at shallower depths, is narrower, and encompasses younger sediments.

Petroleum must be retained in a **structural** or **stratigraphic trap** in order to produce a reservoir and prevent migration to the surface as probably occurred for much of the petroleum that has formed during the Earth's history. In Antarctica, not only must all of these conditions be met, but also **any reservoir will have to be located in an area where production is physically possible, and the field will likely have to be very large to be commercially viable.**

The same two principles that apply to ore bodies apply to world oil distribution as well. First, most oil is contained in a few large fields, but most fields are small. Second, in any region the large fields are usually discovered first. Since exploration for oil began in the early 1860s, some 40,000 oil fields have been discovered worldwide. The two largest classes of fields are the supergiants (fields larger than 5 billion barrels of recoverable oil) and the world-class giants (fields with 500 million to 5 billion barrels of recoverable oil). Only 38 supergiant oil fields have been found worldwide, and these few fields origi-

[12] See, for example, F.E. Trainer, "Potentially Recoverable Resources—How Recoverable'?" *Resources Policy,* March 1982, pp. 41-52.

[13] John H. DeYoung Jr, and Donald A. singer, "Physical Factors That Could Restrict Mineral Supply, ' *Economic Geology, 75th* Anniversary volume, 1981, pp. 942-943.

nally contained more than half of all of the oil discovered thus far. Twenty-six of these supergiants are in the Persian Gulf region, Three are in the Soviet Union; the United States, Mexico, and Libya each have two supergiants; and Algeria, Venezuela, and China have one each. The nearly 300 known world-class giant fields plus the 38 supergiants together account for about 80 percent of the world's discovered recoverable oil. Petroleum experts estimate that there are probably less than ten supergiants remaining to be discovered. **It is probable that nothing smaller than world-class giants or supergiants would be economic in the harsh Antarctic environment.**[14] Because large fields are usually found early (the biggest structures are more easily located and, therefore, are drilled first), it is likely that if any large fields exist in Antarctica, they will be discovered relatively early during exploration drilling.

In Antarctica, even a large field may not in itself be enough. The character of the reservoir is also important. For example, a reservoir will have to be relatively thick so that it can be drained by a minimum number of strategically placed wells. This is because the high cost of drilling and operating in polar regions limits the number of wells and production facilities that a field can support. Consequently, a large field with a relatively thin pay zone spread over a great area, may not be economically producible. Past experience has shown that a relatively small percentage change in world petroleum supply can have a substantially greater effect on the price of oil. Consequently, a relatively small shortage in available petroleum supply can have a magnifying effect on the price of oil and change the economics of field development.

Prospecting and Exploration in Antarctica

Prospecting and exploration in Antarctica would be extremely difficult. Mean air temperatures are much lower than those of any other large area of the Earth's surface, and winds generally are stronger and more constant than elsewhere. prospecting and exploration would likely be conducted only during the summer months. Transportation to most interior locations would likely be by air. This can be hazardous because weather forecasting is not highly developed in Antarctica and adverse weather conditions en route or at the destination may not be known when a flight begins. The logistics of transportation and supply commonly dominate decisions on where field work can be conducted, and areas that might deserve detailed study may not be accessible at times or have to be studied hastily,

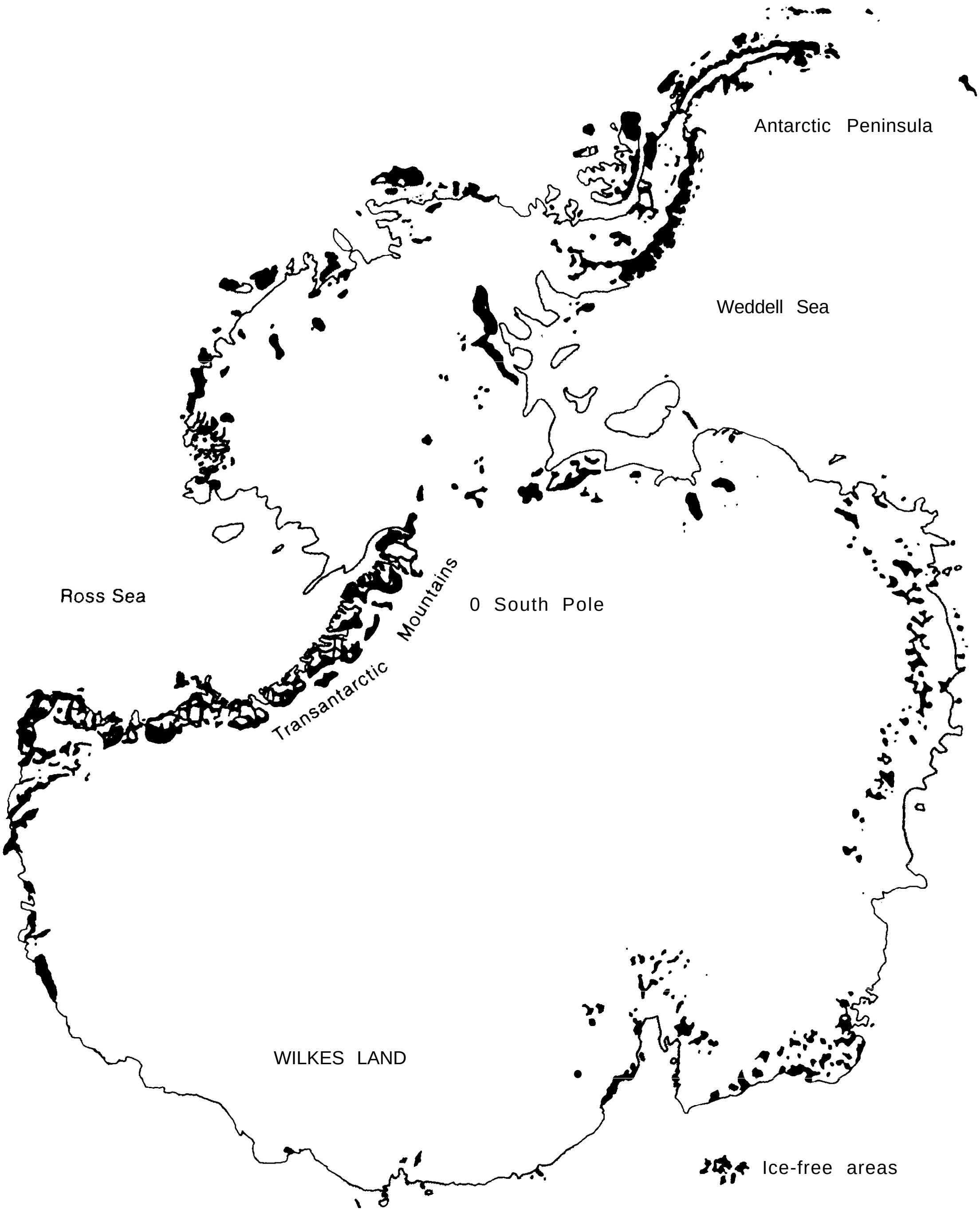
Most geologic investigations conducted thus far have been purely scientific and not designed to explore for and identify mineral deposits. No mineral occurrences have been explored by drilling. The geochemical patterns that result from alteration and mineralization in various areas of Antarctica are virtually unknown. In addition. glaciation could have removed near-surface deposits formed by weathering, and since the onset of glaciation, the ice cover has prevented enrichment processes related to near-surface weathering from occurring. Moreover, there has been little surface drainage during the past 30 million years, thus, the erosion and sorting necessary to form alluvial placer deposits would not have occurred. Older placer deposits, if any exist, would be in stream channels or basins now covered by ice.

Because nearly 98 percent of the continent is covered by ice, few mineral deposits are likely to be exposed (figures 4-4 and 4-5). The total area of exposed rock is comparable in size to the State of Colorado, but it is spread over an area larger than that of the United States and Mexico combined. Therefore, the logistics for any prospecting or exploration program are immense. Most of the exposed areas have been so little studied that they remain among the least geologically and geophysically explored areas of the world. Some large rock outcrops have never been visited.

Offshore, the situation is little better. Although over 54,000 nautical miles of marine multichannel seismic reflection survey lines have been collected around Antarctica since 1976, most of this information has not been published or otherwise made available (figure 4-6). The United States is the only country that has published and made freely available all of its seismic data as required under the Antarctic Treaty. This, however, represents less than 4 percent of the total collected by those conducting research in Antarctica. Very little is openly known about the

[14] "Are There Petroleum Resources in Antarctica? op. Cit., footnote 11, p. 3.

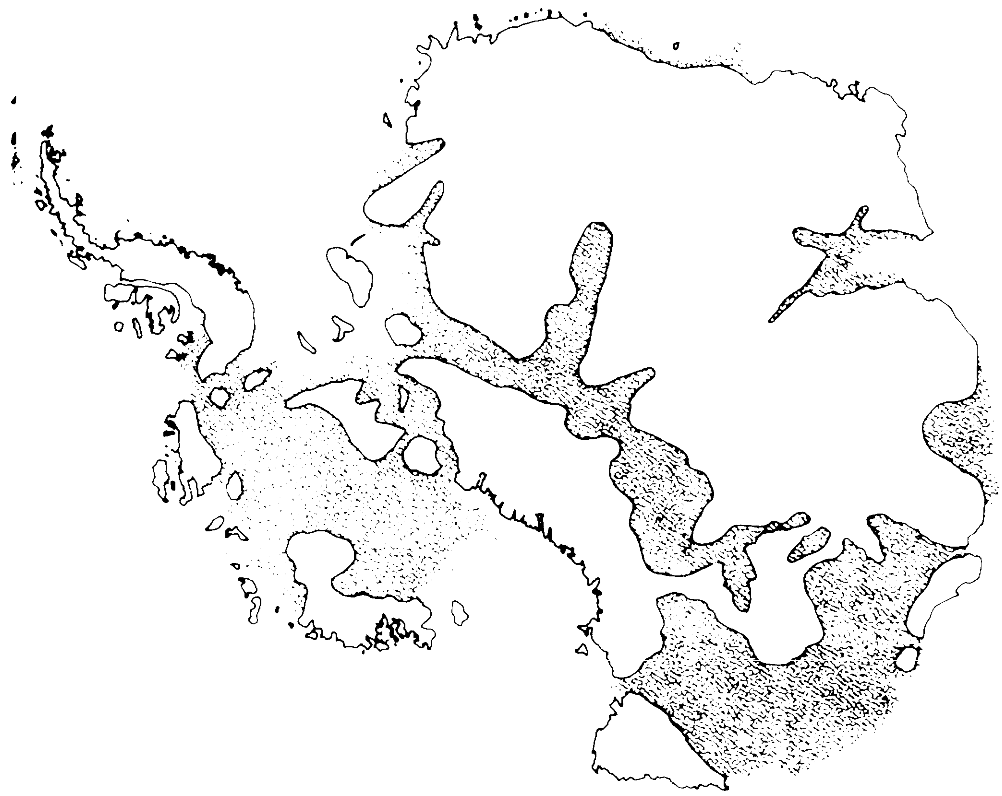
Figure 4-4-Exposed Rock Outcrop In Antarctica



Only *2* percent of Antarctica is exposed. Ninety-eight percent of the continent is covered by a thick ice sheet.

SOURCE: U.S. Gee@@ Survey, 1989

Figure 4-5-What Antarctica Would Look Like If the Ice Ware Removed



SOURCE. Generalized from U.S. Geological Survey, 1989

detailed subsurface structure and petroleum potential of the continental shelf areas. The failure to release data and the fact that many surveys have been run by groups owned in large part by oil companies has led to speculation that much of the offshore geophysical data gathered thus far has been focused on assessing petroleum resource potential rather than acquired for scientific purposes. In any event, the seismic lines run thus far are too widely spaced to be of more than reconnaissance value. Exploration for oil would be conducted on a much tighter grid. However, geological interpretations of the geophysical data can only be verified by drilling into the deeper sediments of each basin.

Five different types of reconnaissance surveys would be desirable to evaluate Antarctica's resource potential. The surveys described below would also provide additional data to supplement ongoing geologic and geophysical research. All the technology required to conduct these surveys is presently available.

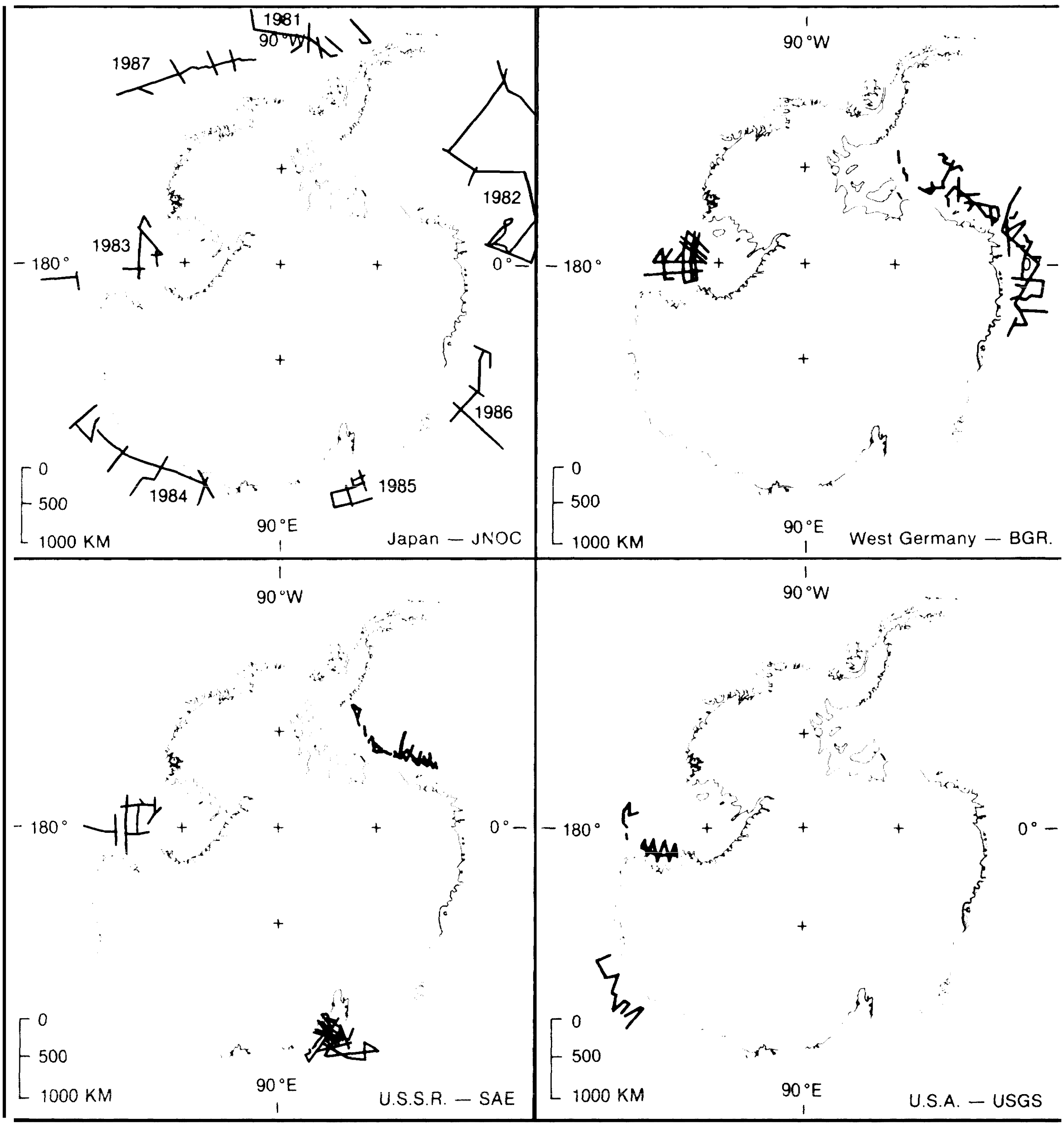
Offshore Geophysical Surveys

There are more than 20 major sedimentary basins and sub-basins on the continental margin around Antarctica. A typical offshore geophysical survey would involve collecting multichannel seismic-reflection data, high resolution seismic-reflection data, bathymetric data, magnetic data, gravity data, and sonobuoy wide-angle seismic data. To date, the small number of U.S. geophysical surveys have focused primarily on the Ross Sea.

Scientific Drilling

Until pre-glacial rock samples are collected from deep within some of the basins surrounding Antarctica, all estimates of hydrocarbon potential must be

Figure 4-6-Multichannel Seismic Data



SOURCE J C Behrendt, U S Geological Survey, 1989 viewed as highly speculative. According to the Minerals Convention, scientific drilling can be carried to any depth. Since 1972, the United States has been involved in 6 major scientific programs, which have drilled holes at more than 50 sites located in and around Antarctica. The greatest advances in our understanding of Antarctic geology over the next decade are likely to come from scientific drilling, if such projects are funded.

Offshore Geohazard Survey

Geohazard studies are critical to understanding geologic processes on the seafloor that could be a hazard to oil recovery structures. Such hazards might include faults, slumps, and significant topographic features. Geohazard surveys typically involve the collection of single channel seismic-reflection data, high resolution seismic-reflection data, precision bathymetric data, multibeam sonar data, seafloor cores and dredge material, and measurements of various sediment characteristics.

Onshore Aerosurveys

Aerosurveys in selected onshore areas of Antarctica have provided the principal information on ice thickness and sub-ice geologic structure. These surveys collect imagery data, such as photographs and radar information, and geophysical data such as magnetic, gravity, and radio echo sounding information. Logistics difficulties, poor navigation, and high costs have limited the quality of past aerosurveys.

Onshore Geophysical Transects

These transects would probably involve the collection of seismic reflection/refraction data and measurements of magnetism and gravity. Newly developed seismic equipment can be rapidly towed across the ice, thereby increasing the amount of data that can be collected over a given period of time.

If the United States decides to fund a comprehensive reconnaissance effort, the United States Geological Survey (USGS) estimates that it would cost about $250 million over a 10-year period (see table 4-1).[15] Some surveys would require all 10 seasons to complete; others only 3 to 5 seasons. Rather than surveying the entire continent, limited areas of the continent (e.g., only the ice-free areas) could be individually surveyed at a lower cost. However, the cumulative cost of many separate and smaller surveys conducted over a longer time period would likely be significantly higher than indicated in table 4-1,

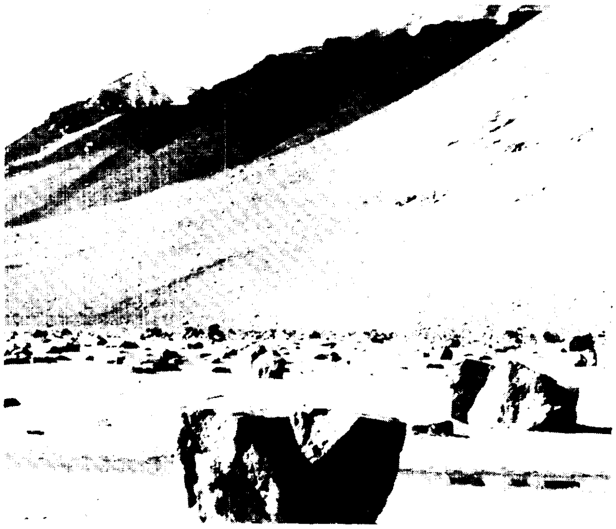


Photo credit: Bill Westermeyer

Don Juan Pond in Wright Valley, one of the "Dry Valleys" near McMurdo.

A similar comprehensive survey is being conducted within the U.S. Exclusive Economic Zone (EEZ), the offshore area within 200 nautical miles of the U.S. coastline. The EEZ was formally established by Presidential proclamation in 1983, thereby giving the United States resource jurisdiction over approximately 2.3 million square nautical miles of largely unexplored territory. This action led to a national effort-jointly conducted by the USGS and the National Oceanic and Atmospheric Administration (NOAA) with additional effort from academic institutions and private industry-to learn more about the geologic framework, seafloor processes, and nonliving resources of the EEZ.[16]

[15] Alan K. Cooper, *Evaluating Antarctica's Hydrocarbon (and Mineral) Potential—Geoscience Data Requirements and Costs,* U.S. Geological Survey, Menlo Park, CA. Special report for U.S. Congress, Office of Technology Assessment, Feb. 21, 1989 (unpublished).

[16] U.S. Congress, Office of Technology Assessment, Marine *Minerals Exploring Our New Ocean Frontier*, OTA-O-342 (Washington, DC: U.S. Government Printing Office, July 1987), p. 3.

Table 4-1-Desirable Research for Evaluating Resource Potential of Antarctica

Type of research	Relative importance for: Oil	Minerals	Estimated 10-yr cost (millions)
Offshore seismic surveys	High	Medium	$30
Onshore/offshore drilling	High	high	50
Offshore geohazards surveys	Medium	Low	20
Onshore aerosurveys	Medium	Medium	25
Onshore geophysical surveys	Low	Medium	25
Subtotal			150
Aircraft support			100
Total			$250

SOURCE: *A.* Cooper, U.S. Geological Survey, February 1989

There are important differences between the U.S. EEZ and Antarctica's offshore environment. First, the United States has exclusive rights to develop any resources in its EEZ, whereas U. S.-sponsored Operators would have to compete with others for resource rights in Antarctica. Second, the proximity of the EEZ to the United States simplifies its exploration. Antarctica is more than 10,000 miles from the United States. Finally, the exploitation of at least some of our EEZ resources (e.g., sand and gravel) is likely to be possible in the near future. Exploitation of Antarctica's resources will probably not be seriously considered for a few decades, if at all.

Consequently, **a major effort to undertake a detailed reconnaissance of our own EEZ is more easily justified than a similar effort for Antarctica. However, for the purpose of promoting potential, long-term U.S. commercial interests in Antarctica, a modest reconnaissance program in selected promising areas might be appropriate.** In fact, a fairly good indication of Antarctica's mineral potential could probably be obtained for about half the cost of the comprehensive survey described in table 4-1. Since activity in Antarctica is generally increasing, it may be even more important in the near-term to devote relatively more attention to acquiring baseline environmental data than resource assessment data. Before the recovery of any petroleum resources is attempted, research will be required to ensure that development can be conducted safely and efficiently with a minimum of environmental impacts. Several tens of millions of dollars would probably be required to address the research topics listed in table 4-2 adequately, although a rigorous cost evaluation was not conducted,

Table 4-2-Research Required To Ensure That Petroleum Resources Are Safely and Efficiently Recovered With Minimum Environmental impact

Basic research and information requirements:
- geotechnical studies of continental shelf sediments
- oil spill tracking and cleanup techniques
- improved techniques for forecasting weather, sea state, and pack ice conditions

Research requiring extended time-series measurements:
- circulation patterns and sea ice drift over the continental shelf
- iceberg size, frequency, movement, and scouring of the continental shelf
- adverse short-and long-term effects (e.g., toxicity) of oil dispersants on Antarctic phytoplankton, krill, seals, and benthic communities

SOURCE: Office of Technology Assessment, 1989,

Providing a firm scientific basis on which to estimate Antarctica's mineral resource potential will be a costly venture. These high costs could be reduced considerably through a cooperative international research program sponsored by all parties to the Minerals Convention. Alternatively, different parts of an agreed-upon research program could be conducted by different countries. Industry involvement, although potentially desirable, could complicate the situation somewhat. If such a program were instituted and paid for by private industry, its conduct would then fall under the purview of the Minerals Convention. Industry data could then be considered proprietary for at least 10 years.

Probabilities of Discovering Antarctic Mineral Deposits

A statistical exercise conducted by the U.S. Geological Survey in the early 1970s attempted to estimate the total number of mineral deposits likely to have formed in onshore areas of Antarctica and *the* number of those deposits likely to be discovered.

This exercise apparently has been the only attempt at such a projection.[17] It should be emphasized, however, that it is a paper exercise only and is not tied to an exploration effort.

The USGS began by reconstructing Gondwana and correlating Antarctica's major tectonic belts with the corresponding tectonic belts on the adjacent continents (refer to figure 4-2). Known mineral occurrences in each of the tectonic belts on Gondwana continents adjacent to Antarctica were divided into four categories: (1) **ferrous metals, (2)** base metals, (3) **precious metals,** and **(4)** other deposits (uranium, aluminum, tungsten, asbestos, rare earths, etc.). The density of each type of mineral occurrence in each tectonic belt was calculated. The results were extrapolated to Antarctica to estimate its resource potential in each of the continent's four major geologic provinces (Andean, Ellsworth, Ross, and Antarctic shield). The number of deposits expected in exposed areas in Antarctica was calculated based on the ratio of exposed area to total land area in each province. This number was then further reduced by an assumed success ratio in discovering deposits. These results (without reduction for success in discovery) are given in table 4-3.

Success in discovering mineral deposits in Antarctica is not only a function of the number of deposits expected to exist but also of the intensity of search. For example, the number of precious metal deposits estimated to exist in exposed areas of the Andean erogenic belt in Antarctica is 3.5. Assuming a one percent chance of discovery, the expected number of deposits found on any single exploration attempt would be **0.035** or about three chances in a hundred. Even this may be high for this region.

Again, this exercise is purely an abstract statistical approach and is not based on actual exploration efforts. In addition, what might constitute a commercial deposit elsewhere may not be economically viable in Antarctica. In any event, table 4-3 illustrates that, **other than in the Antarctic Peninsula (Andean Province), the chances of finding mineral deposits in exposed areas are small, and that base metal and precious metal deposits are the best prospects for discovery in the Antarctic Peninsula.**

SELECTED MINERAL RESOURCES

Oil and Gas

Prospects for Antarctica

Sedimentary basins are located on the continental margin of Antarctica and in the interior of West Antarctica. Sediments also probably occur inland of the East Antarctic ice margin (figure 4-7).[18] The major Antarctic basins of interest to petroleum exploration are in the Weddell embayment, Ross embayment, Prydz Bay, and Wilkes Land margin. Other sedimentary basins exist along the East Antarctic margin, the west coast of the Antarctic Peninsula, and probably on the broad continental shelves of the Amundsen and Bellingshausen Seas off West Antarctica. **Offshore sedimentary basins hold the best prospects for petroleum exploration because of the character and thickness of sediments and access for seismic exploration.**

Based on seismic evidence and the results of the Ocean Drilling Program's (ODP) Leg 113, the Weddell embayment contains possibly as much as 46,000 feet of sediment. Other than for the margin of the Larsen Basin and off Queen Maud Land, virtually nothing is known of the age and nature of the sediments. The older strata probably date back to the early stages of formation of the basin in the Late Jurassic period (around 150 million years ago), and consist of terrestrial and marine sediments. These deposits might have contained organic material that could have provided potential hydrocarbon source rocks. These beds are overlain by as much as 10,000 feet of glacially derived sediment, laid down over the last 30 million years, with no source rock potential. The thermal history is unknown, but the oil window has been estimated to lie within the deeper parts of the basins. The Larsen Basin, in particular. on the western side of the Weddell embayment, is estimated to have a moderate potential for hydrocarbon formation. To the east, off Queen Maud Land, the oil window is estimated to lie below the organic-rich beds on the continental shelf.

[17] Wright and Williams, op. cit., footnote 4, pp. 24-27.

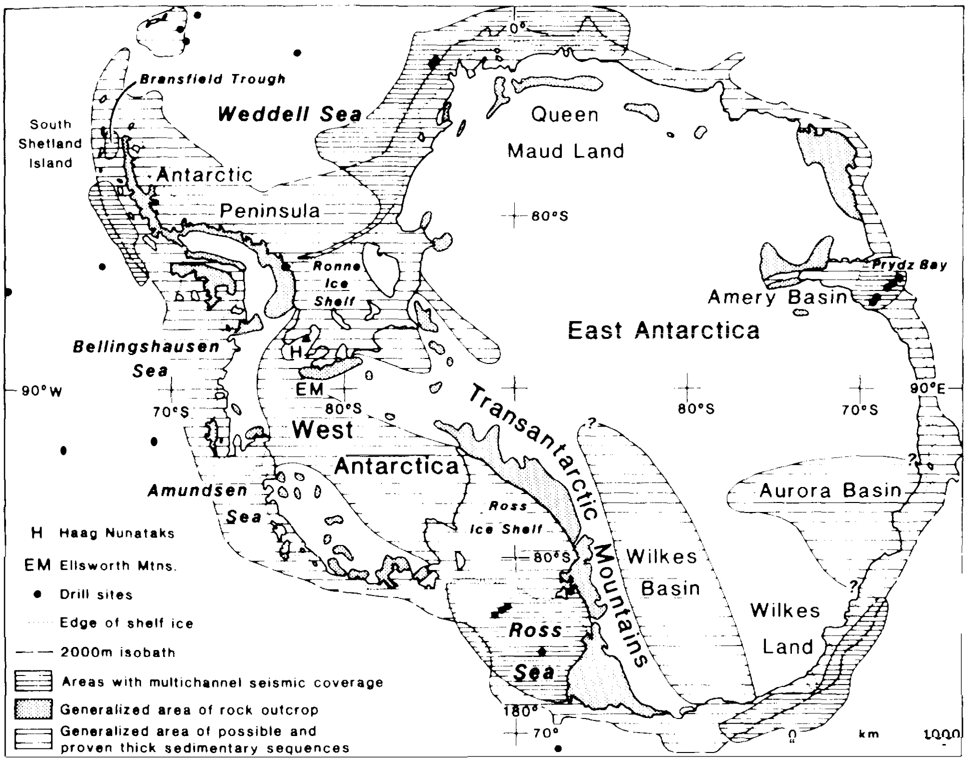
[18] Elliot, op. cit., footnote 9, p. 33.

Table 4-3-Estimated Number of Major Mineral Deposits in Antarctica

	Type of deposit			
Geologic province	Base metal	Ferrous	Precious	Other
Andean:				
Total	175	60	82	63
In exposed areas	7.5	2.5	3.5	2.5
Ellsworth:				
Total	56	90	8	16
In exposed areas	0.7	1.0	0.1	0.2
Ross:				
Total	10	10	5	8
In exposed areas	0.6	0.6	0.3	0.5
Shield:				
Total	69	138	66	73
In exposed areas	0.1	0.3	0.1	0.1

SOURCE: N.A. Wright and P.L. Williams, "Mineral Resources of Antarctica," US. Geological Survey Circular 705, 1974, pp. 24-27.

Figure 4-7-Sedimentary Basins in Antarctica



The major Antarctic basins of interest to petroleum exploration are in the Weddell embayment, Ross embayment, Prydz Bay, and Wilkes Land margin.

SOURCE: D.H. Elliot, "Antarctica: is There Any 011 and Natural Gas?" *Oceanus,* VOI 31, No. 2, Summer 1988, p. 33.

If this is the case, there would be little potential for petroleum formation in the Queen Maud Land margin.

The Ross embayment contains three identified basins of which the Victoria Land Basin off Ross Island would appear to have the best prospects for petroleum formation. This basin contains as much as 46,000 feet of sediment in a rift zone that has relatively high heat flow. Heavy hydrocarbon residues were recovered from a scientific drill site on the western margin of the Victoria Land Basin in 1986. The asphaltic residue indicates that hydrocarbons formed in the area but have migrated, possibly millions of years ago. Of the other two basins, the Central Trough and Eastern Basin off Marie Byrd Land, only the deepest portions would lie within the oil window. Drill cores from both of these basins have shown traces of gaseous hydrocarbons, but these are from glacial marine sediments and most likely represent local decomposition of organic material not related to the formation of petroleum.

Another rift zone in Prydz Bay, called the Amery Basin, also contains as much as 46,000 feet of sedimentary rock. Cores taken in this area have likewise shown traces of gas. Of more significance geologically is the recovery of Cretaceus sediment, indicating a long history of deposition in preglacial times and, consequently, the possibility of suitable source rock.

The Wilkes Basin is a marine basin extending inland under the ice and offshore onto the continental shelf. This basin contains as much as 20,000 feet of sediment on the shelf including organic-rich material of Early Cretaceus age with source rock potential.

The other sedimentary basins are less prospective for hydrocarbon accumulation. This includes the Brartsfield Trough off the western tip of the Antarctic Peninsula, where hydrocarbons were found in relatively shallow cores from a young (2 million years) and thin sedimentary sequence. While the thermal gradient is sufficiently high in this area to maturate organic material at shallow depth, the thin sedimentary section argues against the likelihood of significant hydrocarbon accumulations. Consequently, it might be presumed that the hydrocarbons being formed in this basin are probably seeping onto the sea floor where they are being degraded by natural processes.

World Resources

Current annual world crude oil production is around 21 billion barrels and has been fairly stable at about that amount for several years. Oil is produced by many countries. The three largest producers, the Soviet Union, the United States, and Saudi Arabia, account for nearly half of annual world production. Until 1987 world proven recoverable reserves were calculated at about 657 billion barrels. Since then, revised estimates, largely of Middle East reserves, have raised this figure to 956 billion barrels.[19] Based on the 956 billion barrel figure the average world reserves to production ratio is 46. Undiscovered recoverable reserves of conventional crude oil are estimated at around 400 billion barrels.

If the remaining recoverable, conventional oil in the world were distributed evenly and exploration and development proceeded at past rates, world oil production could be sustained for nearly 50 years before being constrained by a declining resource base. A steep drop in world oil production of more than 50 percent in 10 years would then be likely.[20] At that time, if not before for other reasons (and demand were still high), oil prices could be expected to rise sharply. If a commercial oil field is discovered in Antarctica in the future, OTA's analysis (app. A) indicates that it will only be developed profitably if oil prices are much higher than today. However, higher oil prices tend to decrease demand and to encourage additional conservation and the use of alternative fuels, Environmental concerns about the burning of fossil fuels, such as ozone depletion and climate change, may also reduce petroleum consumption and hold prices lower.

Discussion of declining conventional petroleum reserves invariably raises the question of the potential for developing unconventional sources of crude oil, namely by developing heavy oil, tar sands, and shale oil, and by using enhanced oil recovery techniques. While some unconventional deposits are being produced today, the annual amount of petroleum derived from them is currently relatively insignificant compared to world consumption: high

[19] Since proved reserves are part of the equation used by OPEC in determining production quotas (a contentious matter), there is some question as to the technical basis for some of the new estimates.

[20] Joseph P. Riva Jr., *The World's Conventional Oil Production Capability Projected Into the Future by Country*, Congressional Research Service, Report for Congress, No. 87-414 SPR, May 1987, p.15.

rates of production cannot yet be achieved. In addition, current production from unconventional sources is largely from sites with the most favorable characteristics, as would be expected. Projecting significantly greater production from unconventional sources through future technological developments is much easier to envision than accomplish. Consequently, **as long as the world is dependent on petroleum there will be an incentive to locate and produce conventional deposits.**

A decision to develop a promising Antarctic discovery could be made even if development would not be profitable. In particular, it is sometimes suggested that energy-poor countries, such as Japan, may wish to undertake unprofitable development to obtain an assured source of supply. OTA does not think that this motivation is as strong as the profit motive, in part because energy-poor countries have less expensive or less technologically challenging alternatives available to them (e.g., Brazil's sugar cane to ethanol program), and these alternatives are likely to become more diverse and more available in the future as the price of oil rises. Also, Antarctica would not likely be the most secure source of supply in times of emergency.

Energy security is of sufficient concern to the United States that the Strategic Petroleum Reserve (SPR) was created to provide an emergency supply of petroleum in the event of a disruption in imports. At present the SPR contains about 550 million barrels of oil held in caverns leached from salt domes in the Gulf Coast.

As for the possibility that an Antarctic claimant country might try to develop an unprofitable oil field to solidify a claim, neither the Antarctic Treaty nor the Minerals Convention would support this. Even if these agreements were disregarded, a claimant could undertake other, less expensive activities to have the same practical effect.

Although petroleum development in Antarctica is considered unlikely in the near term, OTA has developed a hypothetical scenario for oil field development there. This scenario (found in app. A) explores technology capabilities and needs, addresses economic considerations, and presents several alternative approaches to development.

Coal

Prospects for Antarctica

Coal is found principally in Permian and Triassic rocks around the perimeter of East Antarctica. Thick beds are most notably in the Beacon Supergroup of the Transantarctic Mountains and in the Beaver Lake area of the Prince Charles Mountains. The deposits all seem to have formed on flood plains in shallow swamps that were rapidly being filled with sandy material. Most of the coal deposits are in a Permian sandstone sequence that is more than 1,600 feet thick and found in both the Prince Charles and Transantarctic Mountains. Although individual coal beds as much as 20 feet thick have been reported, most of the beds are less than 12 feet thick and tend to be lens shaped and have a limited horizontal extent. While some coal seams have been traced over a considerable distance, the horizontal extent of most of the individual beds that have been reported is less than half a mile,

The coal is commonly of a high rank, ranging from medium-volatile bituminous to anthracite and generally having a high ash and low sulfur content. Most of the coal occurs in mountainous areas at a considerable distance from the coast. None of the known deposits are economically minable. Deposits near coastal areas would have the greatest potential for export. The conventional wisdom has generally been that while Antarctic coal may not be economic to export, it could possibly be used for local heating or power production. However, even the Soviet station at Beaver Lake, adjacent to exposed coal in the Prince Charles Mountains, finds it more economical to meet energy needs with imported oil.

World Resources

World hard coal (anthracite and bituminous) production in 1987 was nearly 3,6 billion short tons. Although coal is mined in a large number of countries, the three largest producers are China, the United States, and the Soviet Union. Recoverable reserves total 719 billion short tons. The reserves to production ratio is 200. In addition, there are 300 billion tons of recoverable reserves of lignite. **It is highly unlikely that an export market for Antarctic coal would develop in the foreseeable future.**

Uranium

Prospects for Antarctica

Uranium occurs in many geologic settings. Among the more important categories are quartz-pebble conglomerate deposits, deposits related to erosional surfaces in Precambrian rocks, disseminated and contact deposits in igneous and metamorphic rocks, vein deposits, and sandstone deposits of various ages. Again, some insight can be gained by comparing Antarctica with the surrounding Gondwana continents. South Africa contains an abundance of uranium and is a major uranium producer. However, most of the uranium produced in South Africa is a byproduct of gold mining, principally from the Precambrian quartz-pebble gold conglomerates of the Witwatersrand region. Australia is also a major uranium producer. In Australia, most of the known uranium resources are contained in deposits spatially related to erosional surfaces in Precambrian rocks. The South African and Australian deposits suggest that uranium might be present in the Precambrian rocks of East Antarctica.

Uranium minerals, or anomalous levels of radioactivity, have been found in several locations in Antarctica, particularly in Enderby Land, the Adelie Coast, and the Transantarctic Mountains of Victoria Land in East Antarctica. No **known occurrences of radioactive minerals in Antarctica contain commercial quantities.** However, larger deposits might be present in sedimentary basins that existed prior to the break up of Gondwana.

World Resources

Reported world uranium production in 1986 totaled 40,900 short tons. Reactor requirements were 43,200 short tons with the difference being made up from stocks. Exclusive of China, Eastern Europe, and the Soviet Union for which data are not available, the four largest producers were Canada, the United States, South Africa, and Australia followed by Namibia, Niger, and France. Total known resources, which include the reasonably assured resources and the estimated additional resources based on direct geological evidence, total 3.9 million tons. The ratio of known resources to reactor requirements currently stands at 91 or nearly a century of supply. In addition, undiscovered resources are estimated at over 1.8 million tons. **Even with the projected moderate growth in nuclear power production, supplies of uranium should be adequate for the foreseeable future.** In the long term, advances in nuclear power generation and enrichment technologies are expected to reduce the requirements for natural uranium. Even though the cost of uranium in current prices may be higher in the long term, the cost of finding and producing uranium from Antarctica would likely be much higher still.

Chromium

Prospects for Antarctica

Of the many minerals that contain chromium, the only ore mineral is chromite, an oxide of chromium and iron. Primary chromite deposits occur as stratiform or **podiform** bodies in certain types of **ultramafic** rocks composed primarily of olivine and pyroxene minerals, or rocks derived from them. Chromite is also found in placer deposits derived from the weathering of primary deposits. Stratiform chromite deposits are found in layers of up to several feet thick of fairly uniform composition extending over large areas. The Bushveld Complex in the Republic of South Africa and the Stillwater Complex in Montana are deposits of this type. Most of the world's identified chromium resources are in stratiform deposits. Podiform deposits are generally smaller and, as implied by the name. the ore is in irregular pods or lenses within the host rock.

The Dufek intrusion in the northern Pensacola Mountains of the Transantarctic Mountain chain is a very large stratiform body with a composition similar to that of the Bushveld and Stillwater Complexes. While concentrations of minerals containing chromium have not been found in the Dufek, anomalous trace amounts of chromium, nickel, and cobalt have been reported in some of the rock analyses. Consequently, there is speculation based on geochemical comparisons and interpretation that the Dufek intrusion may contain significant amounts of chromium, nickel, and platinum-group metals in the lower unexposed portions. Chromite has also been found disseminated and in thin layers in a small ultramafic intrusion on Gibbs Island in the South Shetland Islands. In addition to chromium, the intrusion may also contain nickel and cobalt minerals, However, the chromite occurrence does not appear to have commercial potential.[21]

World Resources

Chromium has important uses in the metallurgical industry to enhance such properties as hardenability, impact strength, and resistance to corrosion, oxidation, and wear. Ferrous alloy production, mainly stainless steels, accounts for most of the chromium consumed. Chromium also has uses in refractory materials and chemical products. Chromium is considered a strategic and critical material for National Defense Stockpile purposes; several forms of chromium-bearing materials are contained within the stockpile.

World mine production of chromite in 1988 was 12.4 million short tons. The Republic of South Africa and the Soviet Union each produced nearly one-third of the total. The world reserve base of chromite is 7.5 billion tons of which 84 percent is in South Africa and 11 percent is in Zimbabwe. The reserve base to production ratio is 658. World resources total about 36 billion tons of chromite, of which over 99 percent is in southern Africa. In summary, there is enough chromium in known deposits to last for centuries, although the fact that most of it is concentrated in one region may be of concern. **At current prices in South Africa of about $56 per ton, it would hardly be economic to develop a chromite deposit anywhere except under special circumstances.** However, if the circumstances included a complete cut off in supply from South Africa over a long term, the economics of the world market would certainly change. The economics of a chromite mining operation in Antarctica could also improve if there were associated coproducts of higher value such as platinum or cobalt. In addition, a strategic rather than an economic incentive could drive interest in prospecting for chromium in Antarctica.

The difficulties of hard rock mining in Antarctica are discussed in appendix B with regard to both an inland location such as the Dufek Mass if and at a more accessible coastal location. Because the ore, type, and location of any hypothetical mine site are so completely speculative, and because there are too many other variables, at present, it was not considered possible to develop a specific scenario for hard rock mining that would provide any additional insight. However, by comparison with selected hard minerals mines in the Arctic, some speculative estimates can be made of technological problems and ore values needed for a commercial Antarctic mine.

Copper

Prospects for Antarctica

Although copper is found in several types of deposits including porphyry, sedimentary, and volcanic, porphyry copper deposits include the largest known deposits and make up 52 percent of the world resources of the metal. Many of the more important porphyry copper deposits also contain commercially important quantities of molybdenum, while others contain gold and silver. Most copper occurrences in Antarctica have been found in the Antarctic Peninsula and on islands off the coast of the Peninsula. The most promising copper occurrences are on islands off the west coast of the Peninsula and are associated with the youngest intrusions of the Andean belt. Economically promising deposits, if any are found in this region, would likely be of the type found in porphyritic igneous rock and may be associated with possible vein deposits. Veins containing a variety of metals are found throughout the Antarctic Peninsula.

Extensive products of mineralization on King George Island, including pyrite, hydrothermally altered rock, and large veins have led some investigators to speculate that there maybe a porphyry-type copper deposit at depth on King George Island. The hydrothermally altered rocks containing mineralization are interpreted as representing the upper or near-surface portion of a large intrusive body. In addition, the pyrite contains anomalously high copper and cobalt values, suggesting that the intrusive body may be rich in copper. Others, however, do not find the evidence for an underlying porphyry copper deposit compelling, and they suggest that the observed minerals represent normal separation during solidification of an intrusive body of this sort.

[21]Rowley et al., op. cit., footnote 3, p. 40

Other copper occurrences have been reported in the South Shetland Islands. Two localities on Livingston Island contain copper associated with igneous intrusive bodies. In one place, the copper minerals may represent the remains of a deeply eroded copper-molybdenum porphyry deposit, Vein and porphyry-type alteration and mineralization took place on a number of other islands and coastal locations throughout the region. Copper occurrences are found in about 30 places along the east coast of the Antarctic Peninsula. Low grade porphyry copper and vein deposits also are found in the southern part of the Peninsula. Three locations, in particular, contain porphyry copper mineralization. One is a low grade copper-molybdenum deposit in the Copper Nunataks of the central Lassiter Coast. Another is in the Sky-Hi Nunataks, and the third is in the Merrick Mountains of eastern Ellsworth Land. Minor amounts of copper minerals have also been found in some of the metamorphic and intrusive rocks of East Antarctica and the Transantarctic Mountains. Sedimentary rock units of the Transantarctic Mountains could also be prospective hosts for stratiform copper deposits.

World Resources

Copper has been one of the more important materials in the advance of industry, technology, and the arts. The largest use of copper is in electrical applications such as motors, generators, power distribution facilities, industrial controls, communications equipment, and wiring. The U.S. Government Stockpile goal for copper is 1 million tons, whereas the inventory is 22,000 tons.

World mine production of copper in 1988 totaled 9.4 million short tons of recoverable copper metal. Chile and the United States were the two major producing countries, with other major producers including Canada, the Soviet Union, Zaire, Zambia, Poland, and Peru. The world reserve base of copper is about 620 million short tons of recoverable copper, of which Chile and the United States together have nearly 40 percent. The ratio of world reserve base to production is 66. Land-based world resources are estimated at 1.8 billion tons of copper, and resources in deep sea nodules are estimated at 0.8 billion tons, **In view of the relative abundance of copper resources, there would appear to be little economic incentive to extract copper from Antarctica, given the added costs of operating in such an environment, unless it were an exceedingly rich and accessible deposit.** Porphyry copper deposits are typically low grade, high volume ore bodies. Any associated coproducts such as precious metals (gold, silver, and platinum), molybdenum or other base metals (lead and zinc), or cobalt could improve the economics.

Gold

Prospects for Antarctica

Gold is found as a trace mineral in certain course sediments, and in a series of deposits of deep-seated origin that are somewhat difficult to classify. Gold occurs widely in gravels as a placer deposit. Typically, these are fluviatile deposits near the headwaters of fast-flowing rivers where gold particles are trapped between pebbles or in bedrock irregularities. In Antarctica, placer deposits could only have occurred before the onset of glaciation and would now probably be buried under ice. The gold deposits of the Witwatersrand in South Africa occur in Precambrian conglomerate. This may suggest that similar deposits could exist in the Precambrian shield of East Antarctica, although they would probably need to be of higher grade to be economic in Antarctica.

Other types of gold deposits are associated with magmatic, hydrothermal, or metamorphic activity. For example, gold is commonly found in quartz veins and related deposits cutting through a variety of host rocks. In continental tectonic belts, gold deposits are found that are broadly related to the hydrothermal phases of calc-alkaline and **alkaline** igneous rocks. In hydrothermal deposits, metallic minerals are precipitated from high-temperature aqueous solutions, either by changes in temperature and pressure or by evaporation of the liquid. Minerals are deposited in the cavities, cracks, or interstices of the host rock. Many porphyry copper deposits contain important amounts of gold, and many have an alluvial dispersion of gold around their outcrops. While gold could occur throughout many regions of Antarctica, perhaps the most promising region for its discovery and possible development might be the Antarctic extension of the Andean magmatic and reformational belt. This region includes the Antarctic Peninsula and the coastal regions of Ellsworth and Marie Byrd Land. Although the Antarctic Peninsula may be less metal rich, this belt in the northern and central Andes is one of the richest metal-producing areas in the world. The volcanic and intrusive rocks of the Antarctic Peninsula belong to the calc-alkaline magmatic suite with which many of the world's copper-lead-zinc and similar ores, often containing silver and gold, are associated. In addition, the Antarctic Peninsula and nearby islands are the most ice-free and accessible region in Antarctica, thus, making both mineral discovery and potential development more feasible.

No significant concentrations of gold have been recorded in Antarctica. Minor gold and silver have been reported in assays of sulfide minerals from several locations in the Antarctic Peninsula region, Traces of gold and silver have also been found in the Cape Denisen area of the Adelie Coast and in Victoria Land,

World Resources

In 1988, world mine production of gold reached 55 million troy ounces valued at about $24 billion. About 35 percent of this production came from the Republic of South Africa. The next largest producers in decreasing order were the Soviet Union, the United States, Australia, and Canada. The world reserve base is over 1.5 billion ounces of which more than half is in the Republic of South Africa. The reserve base to production ratio is over 28. The world's gold stocks, excluding gold in industrial usage, total about 2.7 billion ounces, of which 1.23 billion ounces are official monetary stocks and 1.44 billion ounces are privately held as coin, bullion, or jewelry. Total world resources of gold are estimated at 2.4 billion ounces, of which 15 to 20 percent are byproduct resources. The Republic of South Africa has about one-half of the world resources, and the Soviet Union, Brazil, and the United States about 12 percent each. **At current world market prices, if a rich gold deposit were discovered in Antarctica, particularly in the region of the Antarctic Peninsula, there would likely be economic interest in considering its extraction.**

Iron

Prospects for Antarctica

Iron is the fourth most abundant rock-forming element, chemically making up about 5 percent of the Earth's crust. The largest concentrations of iron are found in banded sedimentary iron formations of Precambrian age. These formations supply most of the world's iron ore and comprise the bulk of the world's iron resources. The most extensive iron deposits in Antarctica are in East Antarctica, where a Precambrian banded iron-formation (jaspilite), similar to the Lake Superior-type ores, is found. The largest of these deposits is in the Prince Charles Mountains, notably at Mount Rucker, where individual jaspilite beds up to 230 feet thick alternate with slate, siltstone, ferruginous quartzite, schist, and metamorphosed igneous rocks. In addition, although not exposed in outcrop, large magnetic anomalies, some extending for over 100 miles under the ice, almost certainly indicate additional iron deposits. In general, scattered exposures of bedrock and glacially transported boulders indicate that iron formations occur between western Wilkes Land and western Enderby Land, covering a large area of East Antarctica.

Based on their limited exposure, the Mount Rucker deposits appear to be of lesser grade than commercial banded iron-formation elsewhere in the world, except for deposits near industrialized areas. The average iron content is 34 percent whereas, for example, the Hammersley Basin deposits of northwestern Australia contain huge reserves averaging around 55 percent iron. For this reason and because the Mount Rucker deposits are nearly 400 miles from the coast, it is highly unlikely that they will become economically developed.

An iron oxide vein subprovince occurs in western and central Queen Maud Land where quartz-magnetite and garnet-magnetite veins from 2 to 15 feet wide are found in gneissic country rock at the contacts with mafic intrusions. Numerous iron occurrences are found throughout the region in veins and stockworks of various ages, some associated with copper and other metals.[22]

[22] P.D. Rowley, A.B. Ford, P.L. Williams, and D.E. Pride, "Metatlogenic provinces of Antarctica," *Antarctic Earth Science*, R.L. Oliver, P.R. James, and J.B. Jago (eds.) (Cambridge, MA: Cambridge University Press, 1983), p. 416.

World Resources

World mine production of iron ore in 1988 was 918 million long tons. The two countries producing the largest amount were Brazil and the Soviet Union. The world reserve base of iron ore is estimated at213 billion long tons, of which approximately one-fourth is located in the Soviet Union and one-fifth in Australia. Large amounts are also found in Brazil, Canada, India, South Africa, and the United States. The reserve base to production ratio is 245. Consequently, at the current annual rate of production, the reserve base would last nearly two and one-half centuries. Furthermore, world resources are estimated to exceed 800 billion long tons. Thus, **it is reasonable to conclude that there will be no market for Antarctic iron ore in the foreseeable future.**

Molybdenum

Prospects for Antarctica

Most molybdenum deposits are of three major types:

- porphyry or disseminated deposits, including stockworks and breccia pipes, in which metallic sulfides are dispersed through relatively large volumes of altered and fractured rock,
- contact-metamorphic zones and bodies of silicified limestone adjacent to intrusive granitic rocks, and
- quartz veins.

All three of these types are hydrothermal in origin and represent nearly all of the molybdenum mined in the world. In addition to the porphyry deposits in which molybdenum occurs as the principal metal sulfide, many porphyry copper deposits contain smaller amounts of molybdenum as an important byproduct. In Antarctica, molybdenum is found associated with copper mineralization in the Antarctic Peninsula region. In addition, molybdenum minerals are widespread in dikes and pegmatites in Wilkes Land in East Antarctica and at a number of localities along the Adelie Coast. None of these occurrences is of economic significance. The best prospect for locating a significant molybdenum deposit in Antarctica would likely be in association with a copper porphyry in the Antarctic Peninsula region.

World Resources

Molybdenum is a refractory metallic element used primarily as an alloying agent in steels, cast irons, and superalloys to enhance hardenability, strength, toughness, and resistance to wear and corrosion. Mine production was 189 million pounds of recoverable molybdenum metal in 1988 of which the United States produced over 39 percent. Other major producers were Chile, Canada, Mexico, and Peru. The reserve base to production ratio for molybdenum is 145 or enough to maintain production at current levels well into the 22nd century. Over 45 percent of the world's reserve base is located in the United States. Identified resources amount to about 46 billion pounds worldwide. Molybdenum resources are adequate to supply world needs for the foreseeable future. It **is difficult to envision a situation wherein a molybdenum mining operation in Antarctica could compete in the world market for quite some time without additional revenues from associated coproducts.**

Platinum-Group Metals

Prospects for Antarctica

The platinum-group metals are geochemically associated with mafic or ultramafic rocks and occur as segregations in layers or pods, Because of their relatively high specific gravity, platinum-group metals also are found in placer deposits sometimes associated with gold. The world's premier platinum deposit is the layered lode deposit in the Merensky Reef of the Bushveld complex in the Republic of South Africa. Although much younger than the Bushveld complex, the Dufek intrusion in the northern Pensacola Mountains of Antarctica is a similar layered mafic igneous complex of considerable extent. It approaches the Bushveld complex in size and is an order of magnitude larger than any other known body of this type. The great size of the Dufek intrusion and its similarity to other mafic igneous intrusions, nearly all major examples of which contain economically significant resources of one or more metals, has prompted considerable speculation regarding its mineral potential.[23]

Comparison to the Bushveld and other similar intrusions suggests that if the Dufek contains significant quantities of platinum-group metals, they

[23] Maarten de Wit, *Minerals and Mining in Antarctica* (Oxford: Clarendon Pros, 1985).

likely would be within the unexposed basal parts. To date, no platinum-group minerals have been identified in the Dufek intrusion, although some rock analyses have shown trace amounts of these elements. The extent to which age is a factor in assessing the mineral potential of the Dufek intrusion is unknown. Most other stratiform mafic intrusions containing economically significant resources are Precambrian in age, whereas the Dufek intrusion is Jurassic. Another consideration that would affect the economics of developing a mineral deposit in the Dufek intrusion is the fact that the exposed portions, which represent only a few percent of the intrusion, are more than 300 miles from the ocean. Based on geophysical evidence, the intrusion itself is believed to extend out under the Filchner and Ronne Ice Shelves.

World Resources

The uses of the platinum-group metals are related to their chemical inertness over wide temperature ranges, excellent catalytic qualities, and high melting points. Three of the group, platinum, palladium, and iridium, are considered strategic and critical for purposes of the National Defense Stockpile. The stockpile inventory of each, however, is less than half the desired goal.

World mine production of platinum, palladium, iridium, osmium, rhodium, and ruthenium together totalled over 8.9 million troy ounces in 1988. The major producer countries are the Republic of South Africa and the Soviet Union. The world reserve base of platinum-group metals is estimated to be 2.14 billion troy ounces of which 1.9 billion ounces (89 percent) are in South Africa. The ratio of world reserve base to production is 268 or enough to last over two and one-half centuries at current production rates. World resources of platinum-group metals are estimated to be 3.3 billion ounces of which the United States holds about 300 million ounces. **Considering the difficulties of mining in the interior of Antarctica, unless there were a major disruption of supplies from South Africa there would probably be little economic incentive to develop a platinum deposit in Antarctica if one were found. The** deposit would have to be exceedingly rich to provide an economic incentive.

Strategic and critical mineral concerns could provide sufficient incentive to develop a platinum-group metals deposit in Antarctica, even if it were not commercially viable. On the other hand, new developments in catalysts that could replace platinum-group metals could reduce critical mineral concerns.[24]

Rare-Earth Metals

Prospects for Antarctica

The rare-earth elements, sometimes called the lanthnides, are a group of 15 chemically similar elements with atomic numbers 57 through 71, inclusive. Although not a lanthanide, yttrium, atomic number 39, is often included with the rare-earth metals because it commonly occurs with them in nature, having similar chemical properties. Some members of the rare-earth group of metals are relatively abundant in the Earth's crust, such as cerium, neodymium, lanthanum, and yttrium, whereas others are considered rare. The rare-earth elements and yttrium are minor constituents in over 100 minerals, but in only a few are they sufficiently concentrated to be considered ore minerals. The two minerals that are the primary sources of rare-earth elements are bastnasite and monazite of which bastnasite is the major source. These minerals generally occur in granitic rocks more commonly than in basic rocks, Monazite is general1y recovered from beach sand deposits as a byproduct of other heavy minerals recovery such as ilmenite, rutile, zircon, and gold. Xenotime is a yttrium phosphate mineral found in the same environment as monazite, and is a major source of yttrium.

In Antarctica, airborne radiometric surveys have found radioactivity anomalies that have been shown, on field inspection, to be related to thorium- and uranium-bearing minerals as well as to rare-earth and tin-bearing minerals within sandstone of the basal (Devonian) parts of the Beacon Supergroup in the Darwin Glacier area of the Transantarctic Mountains.[25] Upper Permian or Triassic nepheline syenite plutons in western Queen Maud Land of East Antarctica contain zirconium and the rare-earth elements, lanthanum and cerium,

[24]Recently Ford Motor Co. announced that it has discovered a potential substitute for platinum used in catalytic converters.

[25]Rowley et al., op. cit, footnote 7.

Box 4-C—Icebergs (Fresh Water)

Although, technically, ice is a mineral resource there was agreement among the Consultative Parties that the definition of mineral resources in article 1 (6) of the Convention (defined as nonliving, natural, nonrenewable resources) does not include ice. During the negotiation of the Minerals Convention, there was a specific decision to exclude ice from coverage of the minerals regime. The Final Act of the Special Consultative Meeting notes that harvesting ice from the coastal region of Antarctica, particularly if land-based facilities were required, could raise some of the environmental and other issues addressed in the Convention. Consequently, representatives at the meeting agreed that the question of harvesting Antarctic ice should be further considered by the Consultative Parties at the next regular meeting.

It is estimated that Antarctica contains over 90 percent of the world's fresh water in the form of ice and snow that accumulated over millions of years.[1] Precipitation in most of Antarctica is very light. Annual snowfall at the South Pole is less than an inch water equivalent, making it drier than some desert areas elsewhere in the world. Although difficult to estimate, the overall water budget of the continent is thought to be roughly in balance with most of the gain from annual precipitation offset by the loss to the sea in the form of icebergs and melting glaciers. If all the ice should melt, the oceans would rise between 200 and 300 feet.

The possibility that fresh water from Antarctica might become available in the form of captured icebergs towed to areas of need is of recurring interest to arid or drought-stricken coastal areas of the world. The volume of ice annually entering the oceans from Antarctica is estimated at 1.5 trillion short tons, of which 900 billion tons is from ice shelves, 500 billion tons is from glaciers and ice streams, and 50 billion tons is from the edges of ice sheets. Because a great amount of energy is required to move icebergs, it is not economically feasible at present. Snow and ice are converted to potable water for local use in Antarctica. Desalination is also used in coastal locations including the U.S. stations, McMurdo and Palmer.

Photo credit: Ann *Hawthorne*

Seaward edge of the Ross Ice Shelf, source of numerous tabular icebergs, the shelf is 80 feet above the water at this point.

[1]OTA finds that penguins walk the way the do because they walk on a lot of ice

World Resources

The unusual properties of the rare-earth elements are responsible for their important uses in catalysts (especially for petroleum refining), as iron and steel alloying agents, glass and ceramics additives, permanent magnets, and phosphors for television and lighting. Although 504 short tons of rare-earth oxides remain within the National Defense Stockpile, they are no longer classified as strategic and critical for the purposes of the stockpile, and the goal has been reduced to zero, There is also no stockpile goal for yttrium.

World mine production of the rare-earth metals in 1988 was over 55,000 short tons of rare-earth oxide, of which the United States and China each produced nearly one-third of the total. Other major producing countries are Australia, Malaysia, India, and Brazil in order of output. The world reserve base is 52 million tons, of which over 75 per cent is contained in a huge bastnasite deposit in China; most of the rest of the reserve base is in the United States. The ratio of reserve base to production is over 1,340. Total world resources are believed to be very large relative to expected demand. With prices for high purity oxides ranging from $9 per pound for lanthanum to over $2,200 per pound for lutetium, there is some likelihood that if a high grade deposit of bastnasite were found in an accessible area of Antarctica, it might well be economic to develop. However, **in terms of strategic or resource scarcity concerns, there would be little incentive to develop a rare-earth deposit in Antarctica.**

Diamonds

Prospects for Antarctica

Diamonds have not been found in Antarctica, but ultramafic rocks similar to the diamond-bearing rocks of Africa and Australia have been mapped in the Prince Charles Mountains and other locations in East Antarctica. In comparing Antarctica with the surrounding continents in the Gondwana reconstruction, the rich diamond deposits of southern Africa and Australia suggest that Antarctica may also contain such deposits. Many of the diamond-bearing pipes of Africa are Cretaceus in age; hence, if diamond-bearing pipes of the same age are present in Antarctica they most likely would be intrusions in areas of older rock. Thus, based on age, prospective areas would include exposed rocks in the Transantarctic Mountains and other parts of East Antarctica rather than in geologically younger areas of West Antarctica. However, individual pipes have cross sections of only a few tens or hundreds of meters, and only a small percentage of the pipes contain diamonds in economic quantities.

Most of the diamonds initially discovered in Africa and more recently in Australia were located in alluvium (placer deposits). Placers are still major sources of diamonds in Australia, Angola, Namibia, South Africa, and Zaire. Because of extensive ice cover and consequent lack of water transport and sorting, placer deposits would be extremely rare in Antarctica. Any placer deposits that may have formed prior to the extensive glaciation would likely be in former stream channels or basins now buried under ice cover. The best available places to prospect would be beaches and shallow shelf areas of East Antarctica.

In Africa and western Australia, diamond placers were traced to the lode sources in kimberlite pipes. Kimberlite is an altered, dark-green basic rock of igneous origin and is the main source of primary diamonds. Although approximately 1,000 occurrences of kimberlite have been reported throughout the world, diamond has not been observed in most of them. The odds against finding a diamond-bearing pipe in Antarctica, essentially by blind drilling, would be astronomical. Detecting a valuable mineral in which the ratio is from 15 to 30 million parts of waste to 1 part of value, as is the case for diamonds, is exceedingly difficult even in areas where bedrock is accessible. Massive kimberlite may be detected by magnetic means.

World Resources

Diamonds that are unsuitable as gem stones are used for industrial purposes, such as cutting, grinding, and drilling, and are considered strategic and critical materials for the National Defense Stockpile. The inventory of industrial stones is currently in excess of the stockpile goal.

World mine production of gem and industrial diamonds was approximately 86 million carats in 1988. The major producing countries are Australia, Botswana, Zaire, South Africa, and the Soviet Union. The world reserve base of industrial diamonds is 1.9 billion carats. World gem diamond reserves are estimated to be about 300 million carats, including near-gem grade, and the reserve base is substantially larger but difficult to estimate because of changing economic evaluations. Most of the reserves are in southern Africa, the Soviet Union (Siberia), and western Australia. The reserve base to production ratio for industrial diamonds is 35 and the ratio is either comparable or lower for gem diamonds. **If good gem quality diamonds were discovered in Antarctica, they would likely find a world market. Although, as stated above, the odds of discovering such a deposit are small.**