U.S. GEOLOGICAL SURVEY CIRCULAR 930–F

International Strategic Minerals Inventory Summary Report—Cobalt

Prepared as a cooperative effort among earth-science and mineral-resource agencies of Australia, Canada, the Federal Republic of Germany, the Republic of South Africa, the United Kingdom, and the United States of America

Major geologic age units

Age			Million years before present
Holocene	QUATERNARY	CENOZOIC	
			0.01
Pleistocene	QUATERNARY	CENOZOIC	
			2
Pliocene	TERTIARY	CENOZOIC	
			5
Miocene	TERTIARY	CENOZOIC	
			24
Oligocene	TERTIARY	CENOZOIC	
			38
Eocene	TERTIARY	CENOZOIC	
			55
Paleocene	TERTIARY	CENOZOIC	
			63
Late Cretaceous	Cretaceous	MESOZOIC	
			96
Early Cretaceous	Cretaceous	MESOZOIC	
			138
Jurassic		MESOZOIC	
			205
Triassic		MESOZOIC	
			~240
Permian		PALEOZOIC	
			290
Pennsylvanian	Carboniferous	PALEOZOIC	
			~330
Mississippian	Carboniferous	PALEOZOIC	
			360
Devonian		PALEOZOIC	
			410
Silurian		PALEOZOIC	
			435
Ordovician		PALEOZOIC	
			500
Cambrian		PALEOZOIC	
			~570
PRECAMBRIAN	Late Proterozoic	PROTEROZOIC	
			900
PRECAMBRIAN	Middle Proterozoic	PROTEROZOIC	
			1600
PRECAMBRIAN	Early Proterozoic	PROTEROZOIC	
			2500
PRECAMBRIAN		ARCHEAN	

ADDENDA FOR CIRCULAR 930–F, "International Strategic Minerals Inventory Summary Report—Cobalt"

The sentence on page 9, column 1, line 16, should appear as follows:

"Western Mining Corporation, owner of Kwinana, has processed concentrates and matte derived from its own mines and those of other companies having mines in Western Australia. Statistics relating to cobalt products from Kwinana cannnot be traced to specific mines in Western Australia."

Western Mining Corporation does not process concentrates on a toll basis at Kwinana, and all feed for the refinery has come from mines in Western Australia.

The first entry in table 15, on page 46, should be deleted.

Kwinana should not be included here, because similar plants elsewhere have not been included in this table. The Kwinana nickel refinery in Australia produces a nickel-cobalt sulfide byproduct.

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By Richard N. Crockett, Gregory R. Chapman, and Michael D. Forrest

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FOREWORD

Earth-science and mineral-resource agencies from several countries started the International Strategic Minerals Inventory in order to gather cooperatively information about major sources of strategic mineral raw materials. This circular summarizes inventory information about major deposits of cobalt, one of the mineral commodities selected for the inventory.

The report was prepared by Richard N. Crockett, Gregory R. Chapman, and Michael D. Forrest of the British Geological Survey of the Natural Environment Research Council and edited by David M. Sutphin of the U.S. Geological Survey (USGS). The cobalt inventory was compiled by the authors (Richard N. Crockett, chief compiler); O. Roger Eckstrand, W. David Sinclair, and Ralph I. Thorpe, Canadian Department of Energy, Mines and Resources (EMR), Geological Survey of Canada; Valerie A. Fell, EMR, Mineral Policy Sector (MPS); Gabriele I.C. Schneider, South African Department of Mineral and Energy Affairs (MEA), Geological Survey; Brian G. Elliott, Australian Bureau of Mineral Resources, Geology and Geophysics; and Michael P. Foose, USGS. Additional contributions to the report were made by Antony B.T. Werner and Jan Zwartendyk, EMR, MPS; Donald I. Bleiwas and William S. Kirk, U.S. Bureau of Mines; Erik C.I. Hammerbeck, MEA, Geological Survey, and Ian Goldberg, MEA, Minerals Bureau.

Director

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INTERNATIONAL STRATEGIC MINERALS INVENTORY SUMMARY REPORT

COBALT

By Richard N. Crockett, Gregory R. Chapman, and Michael D. Forrest[1]

ABSTRACT

Major world resources of cobalt are described in this summary report of information in the International Strategic Minerals Inventory (ISMI). ISMI is a cooperative data-collection effort of earth-science and mineral-resource agencies in Australia, Canada, the Federal Republic of Germany, the Republic of South Africa, the United Kingdom, and the United States of America. This report, designed to be of benefit to policy analysts and geologists, contains two parts. Part I presents an overview of the resources and potential supply of cobalt on the basis of inventory information which covers only discovered deposits. Part II contains tables of some of the geologic information and mineral-resource and production data that were collected by ISMI participants.

PART I—OVERVIEW

INTRODUCTION

The reliability of future supplies of so-called strategic minerals is of concern to many nations. This widespread concern has led to duplication of effort in the gathering of information on the world's major sources of strategic mineral materials. With the aim of pooling such information, a cooperative program named International Strategic Minerals Inventory (ISMI) was started in 1981 by officials of the governments of the United States, Canada, and the Federal Republic of Germany. It was subsequently joined by the Republic of South Africa, Australia, and the United Kingdom.

The objective of ISMI reports is to make publicly available, in convenient form, nonproprietary data and characteristics of major deposits of strategic mineral commodities for policy considerations in regard to short-term, medium-term, and long-term world supply. This report provides a summary statement of the data compiled and an overview of the supply aspects of cobalt in a format designed to be of benefit to policy analysts and geologists. Knowledge of the geologic aspects of mineral resources is essential in order to discover and develop mineral deposits. However, technical, financial, and political decisions must be made, and often transportation and marketing systems must be constructed before ore can be mined and processed and the products transported to the consumer; the technical, financial, and political aspects of mineral-resource development are not specifically addressed in this report. The report addresses the primary stages in the supply process for cobalt and includes some considerations of cobalt demand.

The term "strategic minerals" is imprecise. It generally refers to mineral ore and derivative products that come largely or entirely from foreign sources, that are difficult to replace, and that are important to a nation's economy, in particular to its defense industry. Usually, the term implies a nation's perception of vulnerability to supply disruptions, and of a need to safeguard its industries from the repercussions of a loss of supplies.

Because a mineral that is strategic to one country may not be strategic to another, no one list of strategic minerals can be prepared. The ISMI Working Group decided to commence with chromium, manganese, nickel, and phosphate. All of these studies, plus the

[1]Authors are with the British Geological Survey (Natural Environment Research Council).

study of platinum-group metals, have now been published. Additional studies on cobalt (this report), vanadium, graphite, titanium, tungsten, tin, lithium, and zirconium have been subsequently undertaken.

The data in the ISMI cobalt inventory were collected in the early months of 1985. The report was submitted for review and publication in June 1986. The information used was the best available in various agencies of the participating countries that contributed to the preparation of this report. Those agencies were the Bureau of Mines and the Geological Survey of the U.S. Department of the Interior; the Geological Survey and the Mineral Policy Sector of the Canadian Department of Energy, Mines and Resources; the Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany; the Geological Survey and the Minerals Bureau of the Department of Mineral and Energy Affairs of South Africa; the Bureau of Mineral Resources, Geology and Geophysics of the Australian Department of Resources and Energy; and the British Geological Survey, a component institute of the Natural Environment Research Council.

No geologic definition of a deposit (or district) is used for compiling records for this report. Deposits (or districts) are selected for the inventory on the basis of their present or expected future contribution to world supply. Records of all deposits compiled by ISMI participants meet this general "major deposit" criterion and are included in the inventory.[2] For some areas, such as the Sudbury district (Canada) or the Bushveld Complex (South Africa), inventory records have been compiled on a deposit-by-deposit basis, although production and resources of cobalt cannot be distinguished by individual deposits. In several cases production and resources can only be evaluated on a district or even national basis, and this problem receives some attention in this report. Because the assignment of a specific number of records to the cobalt resources of a district or even of a nation was not done with the same detail by all compilers, comparisons among numbers of cobalt records in different geographic areas or among numbers of cobalt records and those records of other commodities reported on in this series are not meaningful.

The ISMI record collection and this report on cobalt have adopted the international classification system for mineral resources recommended by the United Nations Group of Experts on Definitions and Terminology for Mineral Resources (United Nations Economic and Social Council, 1979; Schanz, 1980). The terms, definitions, and resource categories of this system were established in 1979 to facilitate international exchange of mineral-resource data; the Group of Experts sought a system that would be compatible with the several systems already in use in several countries. Figure 1 shows the U.N. resource classification in this report. The term "reserves," which many would consider to be equivalent to r1E or R1E, has been interpreted inconsistently and thus has been deliberately avoided in the U.N. classification. Category R3, undiscovered deposits, is not dealt with in this report.

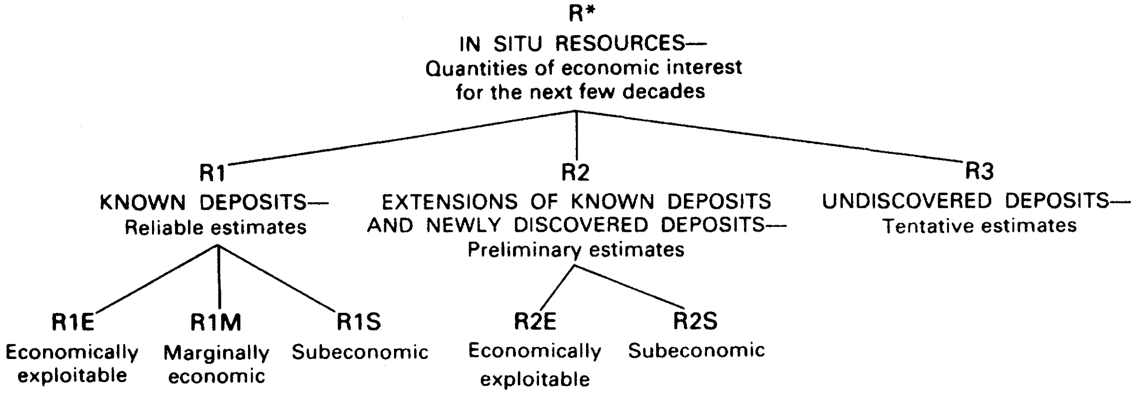
The reporting of resource data that relate to cobalt presents special hazards. The problem is dealt with more fully at a later stage, but essentially it arises from the byproduct status of much of the world output of cobalt. Only a minority of companies or countries report ores of cobalt on a conventional grade and tonnage basis. Some of the larger producers, for example those of New Caledonia or the Sudbury district (Canada), have made little effort to evaluate resources of individual mines that may contribute to collective corporate or national cobalt output. In the absence of reliable figures for in-place resources, estimates of mining recovery with respect to cobalt are also likely to be unrealistic.

The World Bank economic classification of countries (World Bank, 1985, p. 174–175), which is based primarily upon GNP per capita, has been used in modified form in this report to illustrate distribution of resources and production according to economic groupings of countries. This classification was chosen because it relies primarily on objective economic criteria, although the groupings were altered to include the Council for Mutual Economic Assistance (COMECON) country grouping. This change was made to account for the close relationship of the Soviet Union and Cuba.

SUMMARY OF USES

Cobalt is a silvery white metal, atomic number 27, atomic weight 58.93, having a specific gravity of 8.9, and a melting point of 1,495 °C. The average concentration of cobalt in rocks constituting the terrestrial crust is estimated as being about 23 parts per million, perhaps one quarter of the concentration for nickel (Taylor, 1964). It occupies a position in the periodic table of the elements that confers chemical properties that are akin to those of nickel. In metallic form,

[2]No information is provided on deposits that were once significant but whose resources are now considered to be depleted.



*The capital "R" denotes resources *in situ*; a lower case "r" expresses the corresponding *recoverable* resources for each category and subcategory. Thus, r1E is the recoverable equivalent of R1E. This report deals only with R1 and R2, not with R3.

Figure 1.—United Nations resource categories used in this report (modified from Schanz, 1980, p. 313).

usually as the component of an alloy, cobalt lends qualities of heat and corrosion resistance coupled with high strength. Where used on hard-facing surfaces, such alloys are also exceptionally resistant to abrasion. The ferromagnetic properties of cobalt metal are also utilized in various special alloys made for the manufacture of permanent magnets. In addition to its use as a metal, usually alloyed, about 25 percent of total cobalt consumption is in the form of nonmetallic compounds.

Reliable estimates of cobalt end use on a worldwide basis are not available, but for 1985 the U.S. Bureau of Mines (Kirk, 1987, p. 297) reports the following information regarding U.S. cobalt consumption: superalloys, mainly for industrial and aircraft gas turbine engines, 47 percent of reported consumption; magnetic materials for various electrical applications, 11 percent; catalysts, 9 percent; driers, 8 percent; metal cutting and mining tool bits, 8 percent; and other uses, 17 percent.

Cobalt in steel.—Cobalt is added to steel for various hot-work applications, particularly where good heat resistance or the ability to work at high speeds is required. Some stainless and "maraging" steel specifications demand the addition of cobalt. The latter are a class of ultrahigh-strength, low-carbon steel alloys that contain 18 to 25 percent nickel.

Nonferrous alloys.—Cobalt is widely used in various alloys that are characterized by their resistance to abrasion and corrosion, their hardness, and their ability to take a high polish. Such qualities make these alloys of value in the construction of chemical plants and for other purposes where freedom from oxidation and distortion at high temperatures is required.

The nomenclature of nonferrous alloys of cobalt is confused. The term "stellite" was originally applied to alloys consisting essentially of chromium, tungsten, and cobalt and, sometimes, molybdenum, iron, and nickel as well. In 1975, the Stellite Division of the Cabot Corporation, the leading producer of such alloys, proposed that the general term "high-performance alloys" should be applied to all iron-, nickel-, and cobalt-based alloys capable of withstanding extreme conditions of heat, wear, and corrosion. Cabot proposed that subdivisions should be recognized that include superalloys, corrosion-resistant alloys, and wear-resistant alloys. Cobalt is used in superalloys because it imparts strength at high temperatures and is resistant to corrosion. Superalloys are designed for service above 800 °C where extreme mechanical stresses are encountered and resistance to oxidation is required. Corrosion-resistant alloys contain large percentages of chromium or molybdenum. Wear-resistant alloys contain tungsten, chromium, and more than 1 percent of carbide particles dispersed in the matrix. There is considerable overlap in the properties and applications of the three categories of high-performance alloys. However, the term "superalloy" is frequently used to embrace them all and, therefore, has to be used with caution.

Metallic cobalt and cemented carbides ("hard metal").—The main use of cobalt as pure metal, as opposed to being one component of an alloy, is as a binding material in the manufacture of specialist hard-metal tools. Cemented carbides were first developed in the early decades of this century when ways were being sought to make use of the extreme hardness of tungsten carbide which, in the pure state, is too brittle and porous for direct use. If, however, tungsten carbide particles are set in a matrix of cobalt, a material is obtained that is capable of machining cast iron and nonferrous metals. Hard metals capable of machining steels were later developed by the use of other metal carbides, notably those of titanium, tantalum, vanadium, and niobium. Although other binder metals are used for special applications, cobalt best fills the requirement that the binder material must become a liquid at a significantly lower temperature than the carbide and also that it must wet the carbide particles completely. In consequence, tungsten carbide and cobalt-based hard metals still satisfy the bulk of the demand of the machine tool industry. Cobalt is also used as a binder for diamond or diamond dust in cutting tools.

Magnets.—Among the relatively few metallic elements displaying ferromagnetic properties, cobalt possesses unique qualities that make it especially suitable for permanent magnets. Its highly anisotropic crystal structure imparts a high coercivity; that is, its magnetism is relatively difficult to neutralize. Cobalt also has a high Curie temperature that ensures that it retains its induced magnetism at temperatures that would cause rapid demagnetization in other materials. Cobalt has a lower electrical resistivity than that of iron and is therefore able to raise the saturation magnetization of the latter when mixed with it. Iron-based magnets are generally "soft"; that is, they are easily demagnetized (with a low coercivity) and are therefore primarily used as electromagnets. Iron-cobalt alloys, however, offer few distinct advantages and are not in wide demand. Most cobalt-based magnets are therefore "hard" in nature, contain relatively little or no iron, and are used in "hard" or permanent applications. The most important hard magnetic materials are Alnico alloys, hard ferrites, and rare earth-cobalt magnets. The Alnico alloys were developed before World War II and typically have compositions in the range of 5 to 35 percent cobalt, 14 to 30 percent nickel, 6 to 12 percent aluminum, and the remainder iron. Alnico alloys, although still widely used, do have some disadvantages. Those that are made by casting tend to be excessively brittle. Greater physical strength can be obtained with sintered Alnicos produced by powder metallurgy, but these are magnetically weaker. The move toward ferrites and alloys with rare-earth metals has, therefore, been a response to these disadvantages of Alnico. The most important high-performance magnets utilizing rare earths are based on alloys of cobalt and samarium which combine weight advantage with high coercivity.

Catalysis.—Various compounds of cobalt are used as catalysts. The most common class of chemical reaction in which such catalysts are used is hydrogenation, but processes involving hydration, desulfurization, oxidation, and reduction can also be catalyzed. Such chemical reactions are important stages in a number of commercial processes including petroleum refining, synthetic fuel production, and certain stages in the manufacture of plastics and lubricants.

Paints and related products.—Cobalt oxides and salts are used in paints, ceramics, and allied products as decolorizers, dyes, dryers, pigments, and oxidizers. Cobalt also promotes the adherence of enamel to steel.

There are other uses of cobalt in which amounts consumed are very small but which are, nonetheless, of some importance in the manufacture of certain glasses and ceramics. For example, the addition of cobalt compounds will neutralize the yellowish color given by iron and, if used in greater quantities, impart a blue coloration. Cobalt in small quantities is essential to the healthy development of animal tissue since in vivo it is incorporated into vitamin B_{12}. In pastures where there is a soil deficiency of cobalt, yields from grazing animals may be dramatically improved by the administration of cobalt compounds either directly or in the form of an oxide pellet which is carried in the animal's rumen through its lifetime.

RECENT ASPECTS OF SUPPLY AND DEMAND

From the viewpoint of many industrialized countries, notably Japan and countries in North America and in western Europe, the supply of cobalt is strategic in the sense that a high proportion of cobalt supplies, which are essential to the prosperity of those countries, must be imported. The United States, for example, must rely on foreign suppliers for about 95 percent of its cobalt requirement. Two factors in recent years have caused additional attention to be focused upon cobalt as a strategic mineral prone to supply difficulties. The first of these factors is that high-grade cobalt deposits are located in only a very few countries, at least one of which, Zaire, has shown a recent history of political instability. The second factor is that most cobalt is produced as a byproduct of either nickel or copper production, thus increasing the threat of restricted cobalt supply if there is a downturn in the market for either of the other two commodities.

Attention can be drawn to several aspects of the recent history of cobalt supply and demand:

- In the middle and latter parts of the 1970's, African supplies of cobalt were subject to a number of uncertainties linked to the regional political situation. Following the collapse of Portuguese rule in Angola in 1975, civil war in that country disrupted the vital railroad link to the port of Lobito over which much of Zairean output of copper and cobalt, as well as a significant proportion of that of Zambia, had previously passed. Two alternative land routes (to Dar es Salaam in Tanzania and to Capetown in South Africa) and an airlift were able to carry most of the output for export. Therefore, supply interruptions from this cause did not prove to be as serious as feared. However, the outbreak of civil war in the Shaba Province of Zaire itself in May 1978, followed by Belgian and French military intervention, focused world attention upon the dependence of industrialized market economy countries upon African cobalt. In the conflict, damage to processing plants and equipment in the areas affected by fighting was not as great as had been expected, and mining activity was again at a significant level by early 1979.
- Despite fears at the time of the Shaba rebellion that shortages in world supplies of cobalt would develop, the industry as a whole proved remarkably resilient, and the tonnage of cobalt-in-ore produced in the years immediately following this event showed no downturn. In contrast, producer prices for refined metal jumped threefold between 1977 and 1978.
- Table 1 summarizes cobalt production for recent years and confirms the existence of a rising trend uninterrupted by the African troubles of 1978. At the end of 1980, however, a steep fall in production commenced and continued through 1983. Preliminary data indicated that this decline had been reversed by 1984, but world production levels have yet to reach the record levels of 1980. The fall in cobalt production recorded in the early 1980's (irrespective of whether this is recorded as mine output of cobalt-in-ore or as refined metal) probably disguises an even steeper decline in consumer demand. Most cobalt is produced as a byproduct of copper or nickel production, and variations in the levels of cobalt production are as much a response to the vagaries of demand for these metals as to the market for cobalt itself. Additional costs incurred by the conversion of cobalt concentrates to metal are not high relative to total costs, and even in times of poor market demand it is likely to be convenient to refiners to stock metal rather than bulky concentrates.
- Political events in the late 1970's were, however, the direct cause of a period of price instability contrasting with an era of static cobalt prices persisting since at least 1919, the earliest year for which data are available (Kirk, 1985). For over half a century until the early 1970's, cobalt prices had rarely exceeded $2.50 per pound and, after adjustment for inflation, had actually declined during the period. This decline was a function, evidently, of increasing efficiency of mining and metallurgical practice. Although prices tended to rise after 1972, they had only reached $6.85 per pound by February 1978 immediately before the outbreak of the troubles in Zaire. In the aftermath of those events, consumer apprehensions of impending shortage were reflected by a surge in orders. Although the shortage failed to materialize, such apprehensions were reflected in the cobalt producer price which rose to $25.00 per pound by February 1979. Thereafter, producer prices remained at this level through 1980. By the beginning of 1981, a fall in consumption and increasing substitution stimulated a progressive decline in the producer price. The last universally recognized producer price of $12.50 per pound was set in February 1982, although by this time the producer price system had effectively collapsed.
- The period of turmoil in cobalt prices from the late 1970's on also saw a decoupling of the previously close relationship between producer-posted prices and the levels of prices achieved by cobalt on the free market. In the uncertain few months following the African troubles, spot-price transactions approaching $50.00 per pound were recorded, far in excess of producer prices, themselves at an all-time high. By early 1981, spot prices were falling below those posted by the producers, encouraging a decline in the latter. A temporary convergence was recorded in early 1982 when the last producer price of $12.50 per pound was set. The peak in spot prices proved very short lived, and in December 1982, metal was trading at $4.75 per pound, making the official producer price largely irrelevant. A resumption of more orderly conditions became evident in early

TABLE 1.—*World cobalt mine production, 1977–83*

[Source: British Geological Survey (1985); figures are in thousand metric tons of contained cobalt]

Year	1977	1978	1979	1980	1981	1982	1983
Mine production	27.1	29.3	31.8	33.7	28.3	21.1	19.6

1984 with increasing demand and an upward movement of spot prices. By March 1984, a credible producer price was set at $11.70 per pound by Zaire and supported by other major producers. For much of 1985, this price held with a negligible divergence of spot prices. However, by the beginning of 1986, a rapid expansion in Zambian production and sales from the French strategic stockpile had again thwarted defense of the $11.70-per-pound level set by Zaire.

- Since 1980, the proportion of cobalt originating from African sources, where it is mostly a byproduct of the copper industry, has declined from about one-half of total world output to nearer one-third. Cobalt from non-African sources is mostly produced along with nickel. However, there is no evidence that the nickel industry has benefited substantially from this shift. The period of exceptionally high demand and realistic posted prices for cobalt at the beginning of the decade was too fleeting to offer any salvation to the industry already affected by an equally profound collapse in demand for nickel.
- The steep climb in cobalt prices recorded at the beginning of the decade also had a marked effect on the pattern of consumption. For many applications, particularly in the field of audio engineering and telecommunications, Alnico magnets were replaced by alloys with less cobalt, by ferrite, or by manganese-aluminum-carbon alloys. In Japan, for example, substitution for Alnico magnets was responsible for a decline in cobalt consumption of 57 percent between 1978 and 1981. Substitution has now slowed; indeed for most uses, for example in DC motors and in moving coil meters, certain Alnico alloys are considered to be essential.
- Prospects for increased strength in the cobalt market in the late 1980's and into the next decade are considered to be linked to a growing demand for superalloys by the aviation industry, which is faced with the need to replace civilian fleets of obsolete wide-bodied aircraft.

THE GEOLOGY OF COBALT

Cobalt is an important component of a number of distinct mineral species. Naturally occurring cobalt minerals include various sulfides and arsenides and certain oxides and hydrates. Sulfides include linnaeite (Co_3S_4) and others, such as carrolite ($CuS{\cdot}Co_2S_3$) which have closely related crystal structures. Arsenides form part of a continuous crystal series that embraces such forms as skutterudite ($(Co_3Ni)As_{3-x}$; where $x=0$ to 0.5) and smaltite ($(Co_2Ni)As_{3-x}$; where $x=0.5$ to 1). A third series of minerals, in which cobalt is combined with both sulfur and arsenic, includes as its most important member cobaltite ($(Co_2Fe)AsS$). Oxides and hydrates containing a high proportion of cobalt generally occur in zones where other cobalt minerals have been subjected to weathering or other secondary alteration processes. Erythrite, or cobalt bloom, is a hydrated cobalt arsenate with a formula corresponding to $Co_3As_2O_8{\cdot}8H_2O$, but asbolite (cobalt wad), a mixture of cobalt and manganese oxides, and heterogenite, hydrated copper oxides, are amorphous colloidal materials with indeterminate chemical formulae. Cobalt may also partially substitute for metal ions in certain minerals, such as for magnesium in olivine or notably for nickel and iron in sulfides like pentlandite ($(Fe,Ni)_9S_8$) and pyrrhotite ($Fe_{1-x}S$; where $x=0$ to 0.2 and constitutes a balance mainly made up of nickel). Pentlandite and pyrrhotite are thus important sources of cobalt where such substitution has taken place.

In general terms, ore deposits containing cobalt minerals of sufficient concentration to be of economic interest occur in four distinct environments in terrestrial rocks (table 2) and also in certain deep-sea deposits.

Magmatic deposits.—Cobalt mineralization is associated with sulfide segregation in a number of igneous environments. In such cases, cobalt is likely to be associated with nickel and iron and will be present in minerals like pentlandite and pyrrhotite. Sulfide segregations may be associated with ultramafic lava flows (such as the Yilgarn block, Western Australia, and the Thompson Nickel Belt, Canada) or with hypabyssal sills associated with flood basalts (Noril'sk, Soviet Union). Of particular importance as a source or potential source of cobalt are sulfide segregations associated with large plutonic complexes of mafic or ultramafic rock. The Sudbury district of Ontario, Canada, and the Duluth Complex (Kawishiwi province) southeast of

TABLE 2.—*Geologic deposit types represented by deposits in the ISMI cobalt inventory*

Geologic deposit type[1]	Subclassifications
Magmatic..........	Ultramafic, gabbroic (mafic), volcanic peridotite.
Hydrothermal......	Volcanic exhalative, vein/replacement, skarn.
Laterite...........	Silicate laterite, oxide laterite.
Sediment-hosted ...	Carbonate-hosted, sandstone/shale-hosted.

[1] Other geologic deposit types such as ocean-floor nodules and cobalt-rich crusts are known but thus far have not been economically exploited and are not included in the ISMI cobalt inventory.

Ely, Minn., in the United States, are examples of this kind of magmatic deposit. The Sudbury district may not, however, be typical in that an exogenetic origin has been proposed resulting from an ancient meteorite impact (Dietz, 1964). The Bushveld Igneous Complex in South Africa with its pronounced layered structure is also the source of a small output of cobalt, although in this case the cobalt is produced along with platinum-group metals rather than as a byproduct of nickel production. Magmatic deposit subclasses in the inventory are ultramafic, gabbroic (mafic), and volcanic peridotite (komatiite).

Hydrothermal deposits.—Cobalt is one among several metallic elements that may be transported in hot aqueous solutions as complex ions and eventually be deposited in fissures and veins. Sulfides and arsenides, like cobaltite, skutterudite, and smaltite, are characteristic minerals of hydrothermal deposits, representative examples of which occur at Timiskaming district, Ontario, and Bou Azzer, Morocco. Hydrothermal deposits in the inventory can be classified as volcanic exhalative, vein replacement, or skarn deposits. Although true hydrothermal deposits are relatively insignificant in terms of world resources, the classification of certain deposits presents some difficulty since some may have originally been formed as magmatic segregations (for example, ancient "greenstone belts" of Finland and Botswana) or as sediment-hosted types (Blackbird mine, Idaho) and subsequently much modified by hydrothermal activity. Because of their complex history, the classification of such deposits is somewhat arbitrary.

Laterite deposits.—Cobalt is one among a number of metals that may be concentrated in the zone where primary sulfide and silicate ore minerals are subjected to chemical and physical changes associated with atmospheric weathering that produces silicate or oxide laterite. The secondary minerals resulting include various complex carbonates, oxides, and hydroxides within which the concentration of cobalt may be markedly enhanced with respect to the primary mineralization from which they derive. Of special importance are highly aluminous and ferruginous laterites that arise from the particularly intense alteration of bedrock under hot and humid tropical weathering conditions. Where laterites have developed over a substratum of mafic or ultramafic igneous rocks, nickel, sometimes accompanied by cobalt, is frequently concentrated in the weathering zone. Because of the surface-related nature of the processes that give rise to nickel laterites, such deposits are particularly well developed in association with large bodies of igneous rock in regions that fall within contemporary tropical latitudes, for example, Cuba, the Philippines, and New Caledonia. Old deposits that may have been formed at a time when tropical conditions were prevalent at other latitudes are more likely to have been removed by subsequent denudation. Fossil laterites do, however, survive and are of economic importance in Greece, Yugoslavia, the Soviet Union, and the United States. Laterite deposits are an important source of nickel and, as with magmatic deposits, any cobalt recovered is subsidiary to nickel production.

Sediment-hosted deposits.—Cobalt occurrences of this type, although providing a substantial proportion of world production, are virtually confined to adjacent regions of Zaire and Zambia in central Africa. There they are associated with particular copper-rich strata of sedimentary origin and are affected to some extent by later metamorphism. The controversy regarding the syngenetic or epigenetic origin of these ores has continued over many years and is not yet fully resolved. Distinctive cobalt-bearing minerals that occur in this environment include linnaeite and carrolite and secondary minerals like heterogenite and erythrite.

Ocean-floor deposits.—Large submarine resources of cobalt are associated with concentrations of metal-rich nodules present in vast fields on the deep ocean floor in several regions. Typical analyses of such nodules are as follows: manganese, 24 percent; nickel, 1 percent; copper, 1 percent; and cobalt, 0.35 percent (Sibley, 1980). Although these deposits are rich in metallic mineralization, thus far ocean-floor deposits have not been mined, and there are no firm plans for mining these deposits in the near future. For this reason, the ISMI cobalt inventory does not include ocean-floor deposits of the nodule type or of cobalt resources that may exist in environments such as crusts developed on the flanks of seamounts.

TECHNOLOGICAL AND STATISTICAL ASPECTS OF COBALT PRODUCTION

Cobalt, by virtue of its byproduct status, originates from several different kinds of ore. Thus there is no standard metallurgical flowsheet for the conversion of cobalt-bearing ore to refined cobalt products. Rarely is there a simple correlation between the locations where cobalt-bearing ore is mined and where refining is undertaken. Indeed, much of the world refining capacity is situated in countries remote from the sources of ore. Cobalt may be traded and shipped as unprocessed ore or in a number of partially processed forms such as metallurgical concentrates, mixed-metal mattes or sulfides, and oxide sinter. A satisfactory definition of cobalt production is therefore difficult to achieve with respect to the countries from which the ore originates. For cobalt mine-production figures to be useful, they must be heavily qualified. Such figures may refer to the cobalt content of the ore mined or to the cobalt actually recovered—generally quite distinct entities. In some cases, cobalt production figures for individual mines cannot easily be determined. At Sudbury, Ontario, for example, mine production of cobalt is totally subsumed within the infrastructure of nickel production. Much cobalt originating from Sudbury eventually emerges from refineries in Norway, but it would be impossible to partition this output between individual mines in Sudbury Basin. Further complexity is added by refiners processing a mixture of feedstocks. Therefore refinery output recorded for individual countries may embrace mine production from several. Hale (1983, p. 9) supports the view that mine-production figures for cobalt should refer to ore destined to be processed by a route appropriate to cobalt recovery. He points out that rather than assaying for cobalt content of ore shipped to the processor, many mines simply use refinery statements of cobalt recovery from their feedstock as a basis for reporting mine production. It is doubtful, however, whether either approach would be of much use in considering cobalt-ore production from Sudbury where the evaluation and selection of ore for mining takes little account of cobalt content.

Ores that contain cobalt are mined by conventional methods, both underground and open pit, depending upon geologic circumstances. Beneficiation of sulfide and arsenide ores to provide concentrates is also performed by conventional methods. Concentrates and certain ores that are not amenable to beneficiation, principally those derived from laterites, are then subjected to various metallurgical procedures, the choice of which is determined by the mineralogy of the original ore.

Concentrates derived from magmatic-stratiform and hydrothermal ores are likely to consist mainly of copper and iron sulfides containing some cobalt and lesser quantities of distinct cobalt sulfides and arsenides. In general, such concentrates are treated by hydrometallurgical processes which enable cobalt hydroxide to be precipitated from pregnant aqueous solution. It is also possible to smelt the concentrate directly to an impure alloy of cobalt with copper, iron, and silicon from which cobalt can be leached or precipitated as hydroxide or carbonate. Concentrates of Zairean origin formerly treated by this method are now treated by the purely hydrometallurgical route.

The beneficiation of magmatic nickel ores yields a concentrate consisting of a high proportion of a mixed sulfide of nickel and iron and lesser quantities of iron sulfides. In each of these there may be traces of cobalt. The concentrate can be subjected to pyrometallurgical techniques designed to promote the oxidation of iron and its separation, in the form of an iron-silicate slag, from the molten sulfides of the other metals. The remaining sulfides are allowed to cool to a matte, the composition of which might be 48 percent nickel, 27 percent copper, 22 percent sulfur, and much smaller percentages of cobalt, residual iron, and precious metals. Nickel and copper mattes are separated from each other by flotation, the cobalt being carried with the nickel. The next stage is to convert the nickel matte to oxide by roasting, followed by reduction of the oxide to pure metal with coke as the reductant. Separation of the cobalt and nickel is then effected by electrolysis. Impure nickel, having been previously cast into anodes, is dissolved and redeposited on a pure nickel cathode. The electrolyte, in which cobalt accumulates, is periodically changed and the cobalt and other metallic impurities are precipitated with suitable reagents.

The mineralogical nature of laterite ores precludes an intermediate stage of processing to a concentrate as is the case with sulfide or arsenide ores. In some cases, however, preconcentration is possible by passing the ore through rotating trommels which break and pass weathered rock, rich in nickel and cobalt, and discharge broken unweathered rock at the end. In most localities, beneficiation is confined to crushing and drying. Since laterite ores may contain 16 to 27 percent moisture (Mishra and others, 1985), the cost of drying can be an expensive proportion of the overall cost of nickel and cobalt recovery.

The recovery of nickel and cobalt from laterites poses a variety of problems relating to the complex mineralogy of these ores. Both pyrometallurgical and hydrometallurgical processes are used. Since nickel recovery is the primary objective of such techniques, performance in terms of cobalt recovery is variable. Table 3 summarizes the four main recovery processes and their performance in relation to cobalt production. All four processes for the treatment of laterite ores have major drawbacks. Hydrometallurgical flowsheets have to be designed for specific feed compositions, and pyrometallurgical processes are heavy consumers of energy. In any case for laterite ores that are generally directed to ferronickel production, the pyrometallurgi-

TABLE 3.—*Comparison of four main processes for cobalt recovery from nickel laterites*
[After Mishra and others, 1985]

Process	Ore type	Cobalt recovery[1] (percent)
Pyrometallurgical		
Smelting to matte----------	Blended limonite and garnierite.	20–25
Reduction to ferronickel--	------do.-------------	[2]0
Hydrometallurgical		
Reduction roast ammonia leach------------------------	Limonite	40–50
Sulfuric acid leach----------	------do.-------------	85–90

[1] Impure cobalt compounds obtained by any of the processing routes have to be further refined to obtain material of desirable quality. This may be done again electrolytically or, alternatively, by fire-refining techniques. The end product, if in metallic form, will be cathodes, granules, or shot of better than 99.8 percent cobalt. Some refineries may not produce metal at all, but instead convert precipitated cobalt hydroxide directly to pure oxide or other compounds.

[2] No cobalt is recovered as a separate product.

cal treatment is not usually appropriate for the recovery of byproduct cobalt.

Also relevant to the production of cobalt is the modern improvement in nickel-refining technology embodied in the Sherritt Gordon process which has the advantage of being able to operate on feedstocks of lateritic or magmatic nickel ore, converter mattes, or any combination of these. The feedstock is subjected to a continuous leaching operation in which compressed air and ammonia are applied. Nickel, cobalt, and copper can be separated in a series of essentially hydrometallurgical steps.

The introduction of Sherritt Gordon technology for nickel production at Kwinana in Western Australia reinforces further the difficulty of associating refinery output of cobalt with specific mining operations. Western Mining Corporation, owner of Kwinana, processes material there derived from its mines in Australia, some of the matte from the company smelter at Kalgoorlie, and concentrates processed on a toll basis for other companies. Western Australian statistics relating to pure-cobalt products would not necessarily relate to local sources of ore. Tracing such production back to specific mines in Western Australia or elsewhere would be impossible.

COBALT RESOURCES

In Part II of this report, tables 13 and 14 identify 103 discrete mines and deposits from which varying amounts of cobalt may be recovered. In the previous section, it was explained that the byproduct status of most cobalt recovered and the nature of the recovery and of individual refining procedures determined the impossibility of relating much of world production of refined cobalt to specific mines. For related reasons, it is also difficult to quantify cobalt resources for individual mines. In most cases, the development planning during the lifetime of a mine will depend upon the location of ores with optimum quantities of copper or nickel. Revenues generated from cobalt have historically tended to be treated as a bonus added to the return on capital invested in mines whose primary product was one of the major metals.

The resources of the mine properties that are listed in Part II are often reported as a tonnage of a polymetallic ore with no indication of cobalt grade. Therefore, aggregation of cobalt resources on the basis of individual mine data is not possible. For the purpose of comparing the distribution of cobalt resources with the various geologic deposit types listed in table 2, a different procedure has to be adopted. The only regularly published estimates of cobalt resources are produced by the U.S. Bureau of Mines (for example, 1985) and relate only to individual countries. It is not possible to disaggregate these national data to the level of 100 different mines. Instead, in table 4 an attempt is made at partial disaggregation by estimating cobalt resources within 40 provinces, each assigned to one of four major geologic deposit types. For example, the Sudbury area of Canada is treated as one resource province characterized by magmatic ore, although it actually comprises 22 distinct mines that contribute to the cobalt output of the region in unknown proportions relative to each other. Figures 2 and 3 show the location of these somewhat arbitrarily defined resource provinces.

The U.S. Bureau of Mines reports resource data using the term *reserve base* which includes demonstrated resources that are currently economic, marginally economic, and some that are subeconomic (U.S. Bureau of Mines and U.S. Geological Survey, 1980, p. 2). It is not the precise equivalent of the combined R1 and R2 categories in the U.N. classification used in ISMI (fig. 1). Given the uncertainties in the estimation of cobalt resources, however, reserve base figures reported by the U.S. Bureau of Mines are used directly as R1 and R2 in table 4 and elsewhere in the text.

The cobalt-resource data in table 4 are grouped by geologic deposit type in table 5 and figure 4 in order to illustrate the relative abundance of recognized cobalt resources in terms of their geology. Cobalt resources within each of the four primary deposit types have

TABLE 4.—*Summary of cobalt-resource provinces*

[Resource provinces are shown on figure 2; figures are in metric tons of contained cobalt and may not add to totals shown due to rounding; N.a., not applicable]

Country	U.S. Bureau of Mines (1985) estimate of national R1 and R2[1] resources	Name of resource province	Geologic deposit type	Suggested partition of R1 and R2[1] resources among resource provinces
Australia	91,000	West Australian Shield	Magmatic	79,000
		Queensland	Laterite	12,000
Canada	260,000	Sudbury (Ontario)	Magmatic	180,000
		Thunder Bay (Ontario)	do.	
		The Pas (Manitoba)	Magmatic	Negligible
		New Quebec (Quebec)	do.	2,000
		Timiskaming (Ontario)	Hydrothermal	Negligible
		Cassiar (British Columbia)	do.	82,000
China	Not reported	Jinchuan	Magmatic	2,000
Cuba	1,800,000	Cuban	Laterite	1,800,000
Finland	34,000	Fennoscandian	Hydrothermal/ magmatic	34,000
New Caledonia	860,000	New Caledonian	Laterite	860,000
Philippines	400,000	Surigao	do.	400,000
Soviet Union	230,000	Khuvo-Aksinsk (Tura)	Hydrothermal	100,000
		Noril'sk (Siberia)	Magmatic	No information;
		Pechenga (Kola)	do.	partitioned thus:
		Central Ural	Laterite	65,000 magmatic,
		South Ural	do.	65,000 laterite.
United States	860,000	Blackbird (Idaho)	Sediment-hosted	310,000
		Fredericktown (Missouri)	Hydrothermal	220,000
		Riddle (Oregon)	Laterite	260,000
		Gasquet Mountain (California)	do.	
		Kawishiwi (Minnesota)	Magmatic	84,000
Yugoslavia	Not reported	Serbia/Macedonia	Laterite	19,000
Zaire	2,100,000	Shaba	Sediment-hosted	2,100,000
Zambia	540,000	Copperbelt	do.	540,000
Other market economy countries[2]	1,200,000	N.a.	Various	
Partition of R1 and R2 resources for other market economy countries				
Burma		Bawdwin	Hydrothermal	15,000
Morocco		Bou Azzer	do.	120,000
Peru		Marcona	do.	120,000
Botswana		Selebi-Pikwe	Magmatic	26,000
South Africa		Bushveld	do.	>352,500
Zimbabwe		Zimbabwean	do.	17,000
Uganda		Kilembe	Sediment-hosted	8,000
Brazil		Tocantins	Laterite	19,000
Burundi		Buhinda	do.	150,000
Dominican Republic		Dominican	do.	35,000
Greece		Grecian	do.	120,000
Guatemala		EXMIBAL	do.	25,000
India		Sukhinda	do.	32,000
Indonesia		Gag Island	do.	140,000

[1] R1 and R2 are data reported as *reserve base* by the U.S. Bureau of Mines. (See text, p. 9.)

[2] A term used by the U.S. Bureau of Mines to combine statistics for several countries without listing them individually. This category should not be confused with economic categories of the World Bank.

markedly different global distributions. Despite the considerable concentration of resources in sediment-hosted deposits, the only major deposits of this type are confined to a single region straddling the frontier between Zaire and Zambia. It is possible that the absence of other copper-cobalt resource provinces akin to that of central Africa may reflect a lack of adequate exploration in similar areas of Proterozoic rocks subjected to low grades of metamorphism. Nonetheless, it appears highly improbable that provinces of comparable size and geology remain to be discovered.

Cobalt resources falling within the magmatic deposit type show a wider distribution on a worldwide scale than is the case with the sediment-hosted deposits. In this case, however, prospects for substantial additions to the world resource inventory are con-

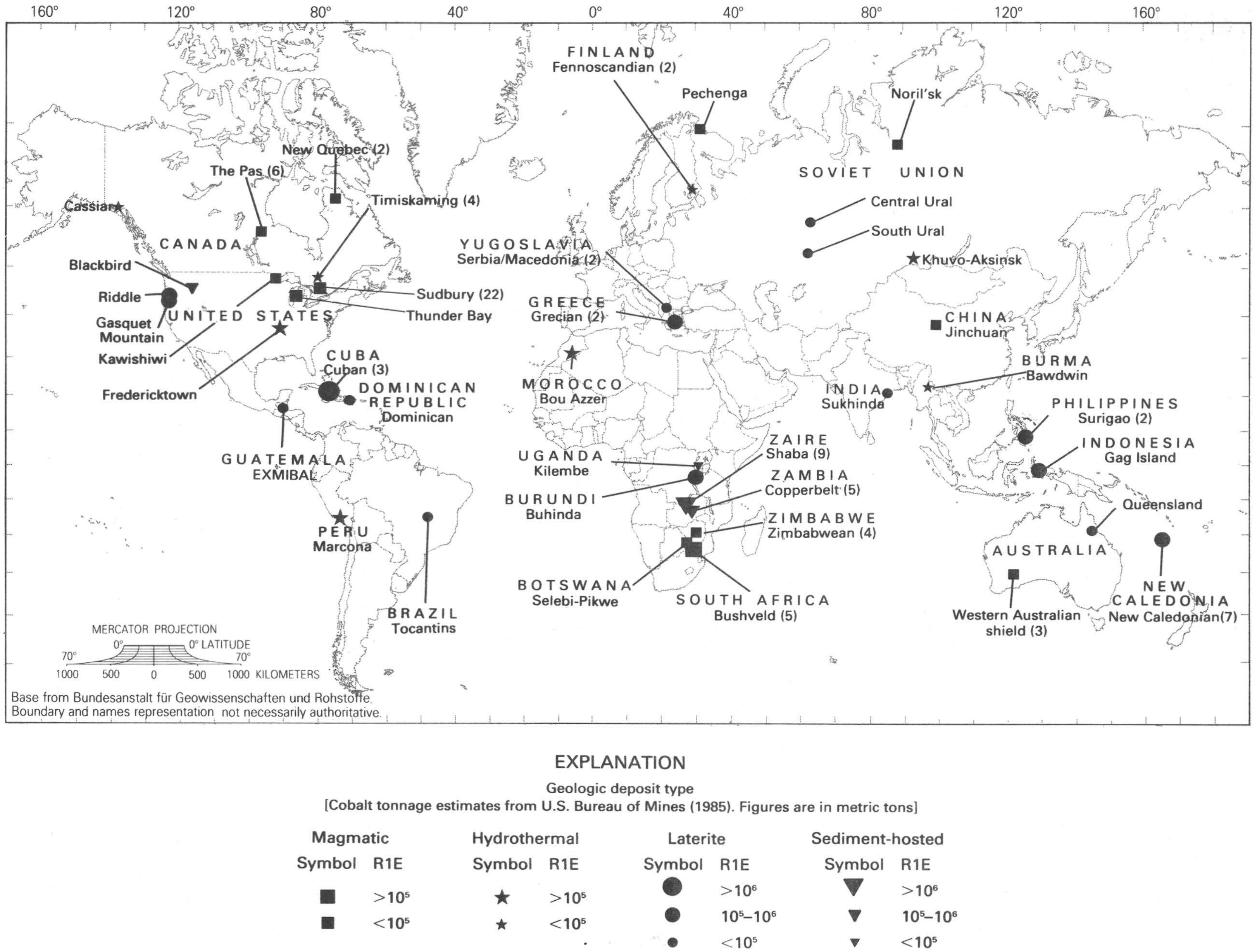


Figure 2.—Location, deposit type, and estimated resources of cobalt-resource provinces in the world. Numbers in parentheses indicate the number of records (mines and deposits) for each province. Location names are from the tables in Part II.

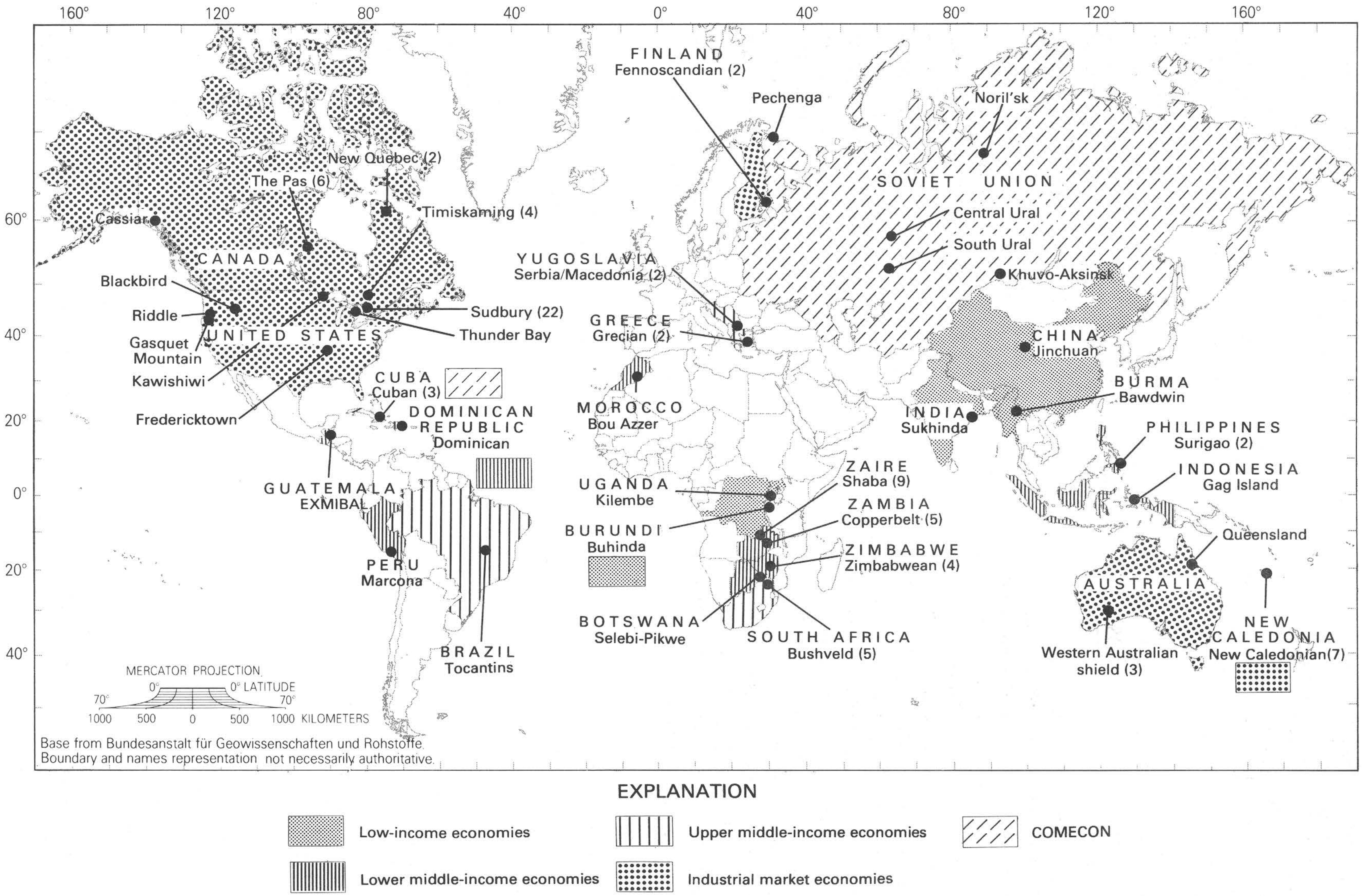


Figure 3.—Economic classification modified from the World Bank (1985, p. 174–175) for countries where the world's cobalt-resource provinces occur. The Council for Mutual Economic Assistance (COMECON) coordinates the economics of Soviet-bloc countries. Numbers in parentheses indicate the number of records (mines and deposits) for each province. Location names are from the tables in Part II.

TABLE 5.—*Resources from the world's major cobalt-resource provinces by geologic deposit type*

[Resource figures are in million metric tons of contained cobalt metal; figures may not add to totals shown due to rounding]

Geologic deposit type	Number of records	Number of provinces	Resources R1+R2	Percent
Magmatic......	48	12	0.80	9.6
Hydrothermal..	12	8	.70	8.3
Laterite........	27	16	3.92	46.8
Sediment-hosted.......	16	4	2.96	35.3
Total....	103	40	8.38	100

strained for geologic reasons peculiar to this deposit type. About 30 percent of the world's identified resources of cobalt within the U.S. Bureau of Mines estimates that are classified as magmatic are in scattered deposits within weakly to strongly metamorphosed Precambrian shield areas such as those of Canada, Western Australia, Botswana, and Zimbabwe. Future discoveries of metamorphosed mafic or ultramafic igneous rocks in such shield areas are very likely, but their contribution to the world inventory of magmatic-type cobalt resources may be limited.

Other magmatic-type resources, including those in large intrusions, may also be discovered. The larger intrusions, such as the layered Bushveld Igneous Complex of South Africa and other types like Sudbury in Canada, are rare and apparently were formed as a result of singular crustal conditions perhaps only applicable to Precambrian times.

Further discovery and development in the foreseeable future of complexes comparable in size to the Sudbury or Bushveld complexes is unlikely, but the prospects for future extensions to known deposits are favorable. This is particularly true in the Bushveld Igneous Complex of South Africa which, despite a long history of production of several metals, has never been systematically evaluated. The estimate of 352,500 metric tons for South African R1 + R2 resources in table 4 must certainly be regarded as a gross understatement of the real position.

Hydrothermal deposits such as those of the United States, Finland, Morocco, and Burma have historically provided a significant contribution to world output of cobalt, but none of these deposits are important in terms of future cobalt production. New discoveries of hydrothermal deposits in Canada, the Soviet Union, and other countries suggest that the identified economic resources in such deposits are comparable in size to those of magmatic deposits. However, the prospects for future discovery of deposits of this type are difficult to assess since hydrothermal deposits occur in a wide variety of geologic environments.

During the past 20 years or so, the discovery rate of new cobalt resources has been particularly high due

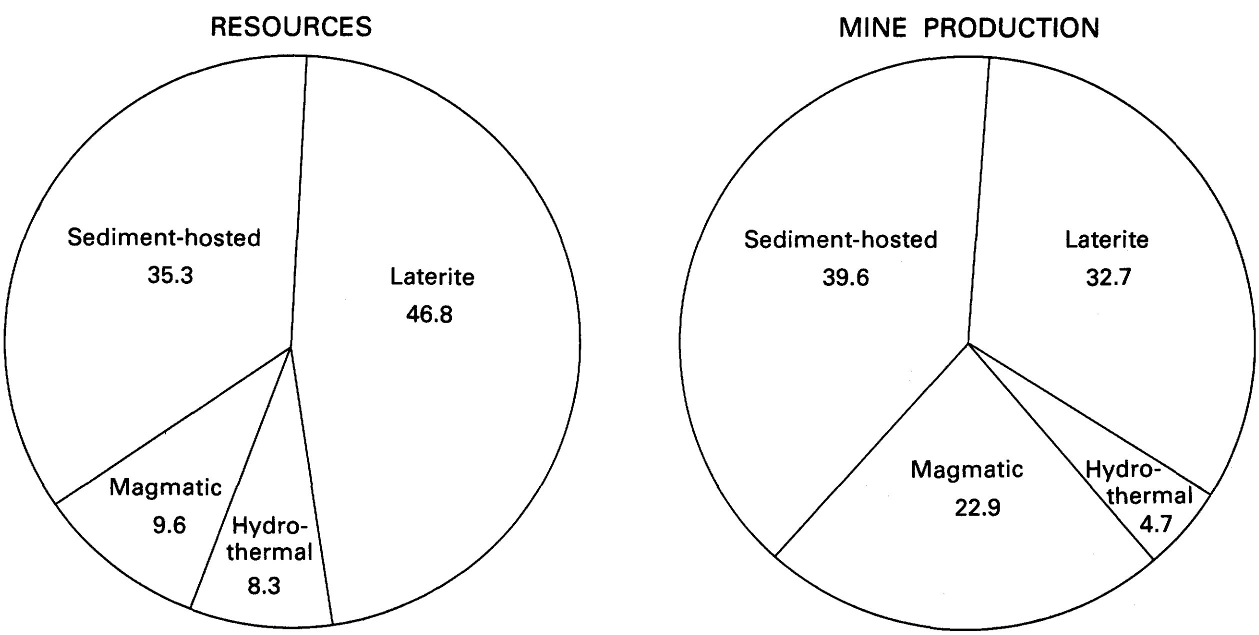


Figure 4.—Distribution of cobalt resources and mine production by geologic deposit type. Other geologic deposit types such as ocean-floor nodules and cobalt-rich crusts are known but thus far have not been economically exploited and are not included in the ISMI cobalt inventory.

TABLE 6.—*Resources from the world's major cobalt-resource provinces by economic class of country*

[Resource figures are in million metric tons of contained cobalt metal; figures may not add to totals shown due to rounding]

Economic class[1]	Number of records	Number of provinces	Resources	Percent
Low-income...	14	6	2.31	27.5
Lower middle-income......	17	9	1.43	17.0
Upper middle-income......	10	4	.51	6.0
Industrial market......	54	15	2.11	25.2
COMECON...	8	6	2.03	24.2
Total...	103	40	8.38	100

[1] Modified from World Bank (1985, p. 174–175) classification, which is based principally on GNP per capita and other distinguishing economic characteristics. Countries in which cobalt-resource provinces occur are, by class: low-income economies—Burma, Burundi, China, India, Uganda, Zaire; lower middle-income economies—Botswana, Dominican Republic, Guatemala, Indonesia, Morocco, Peru, Philippines, Zambia, Zimbabwe; upper middle-income economies— Brazil, Greece, South Africa, Yugoslavia; industrial market economies—Australia, Canada, Finland, New Caledonia, the United States; and COMECON (Council for Mutual Economic Assistance)—Cuba, the Soviet Union. A sixth economic class, high-income oil exporters, is not listed because those countries do not have identified major cobalt resources.

to resources in laterite deposits. Cuba and New Caledonia have long been significant cobalt producers, but new discoveries in several tropical and subtropical regions have greatly extended the inventory of laterite resources. Table 5 indicates that laterites currently account for nearly half of the world's cobalt resources. This proportion may increase because reported resource data for laterite deposits usually account for only a limited area of a deposit and not for additional prospective terrain around the discovery.

Data contained in table 4 can also be analyzed with respect to the political and economic affiliation of the countries concerned. (See table 6 and fig. 5.) In general, the World Bank (1985) economic classification for countries is followed, except with regard to the Soviet Union and Cuba, which are more conveniently combined into Council for Mutual Economic Assistance (CMEA, or COMECON) nations because of their strong economic link.

The approximately one-quarter share of resources from industrial market economies includes those of New Caledonia, a territory of France. New Caledonia falls within this category by virtue of its relatively low population and its correspondingly high per capita GNP which is based upon wealth in minerals rather than on an intrinsically high level of industrial development. Otherwise, the largest resources of cobalt directly under the control of industrial market economy nations are located in Australia, Canada, and the United States, although of these only Australia and Canada presently contribute raw material toward production of metal.

The classification of Brazil and South Africa as upper middle-income countries rather than as industrial market economy countries results from the dilution of their GNP by relatively high population. Without the potential Brazilian and South African contribution, the Western industrial market economy countries appear to occupy a roughly equal position in comparison to resources within the COMECON sphere. With the addition of the largely unevaluated resources of the South African Bushveld Igneous Complex and Brazilian laterites, Western industrial market economy countries might be expected to occupy a predominant position in terms of cobalt resources.

Approximately 40 percent of world cobalt resources are located in countries that profess no alignment either to COMECON or to Western industrial groups such as the Organization for Economic Cooperation and Development (OECD). Within this nonaligned category, the central African resources of Zaire and Zambia are most prominent, although the potential of future discoveries of laterite deposits in countries like Indonesia and the Philippines is considerable. Zaire and Zambia have a more pivotal role as suppliers of cobalt to the West than the crude resource figures would suggest. Prolonged interruption of such supplies might be expected to result in a shift of investment toward unexploited resources in Western countries or perhaps toward unexploited laterite resources in other tropical countries.

COBALT PRODUCTION

Statistics published by the British Geological Survey (1985, p. 55) report 11 countries where ore is raised from which cobalt metal is ultimately extracted. These data show considerable difference from the list of countries that produce refined cobalt metal. The two lists are set out in table 7 for comparative purposes.

For analysis of production with respect to geologic deposit types and the economic classification of producing countries, it is appropriate to use the mine production of cobalt data summarized in the first part of table 7.

For 1983, it is estimated that mine production of cobalt amounted to nearly 19,600 metric tons. To break down this figure into cobalt originating from different geologic deposit types, it is assumed that in certain countries, like Australia and the Soviet Union, cobalt originates from the different deposit types in roughly equal proportions. Given these assumptions,

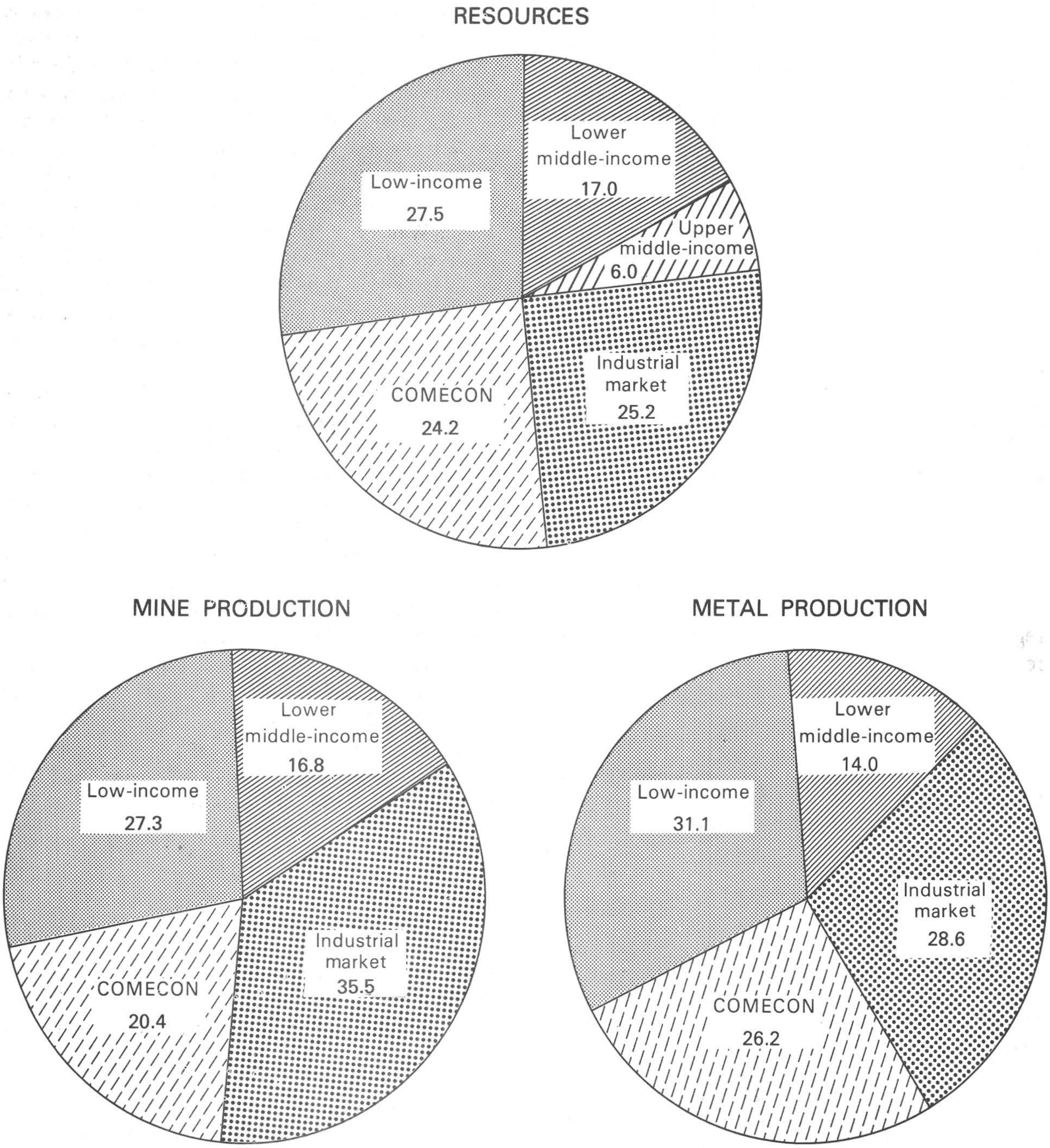


Figure 5.—Distribution of cobalt resources and mine and metal production by economic class of country. Economic classes of countries are modified from World Bank (1985, p. 174–175) classification, which is based principally on GNP per capita and other distinguishing economic characteristics. Countries in which cobalt-resource provinces occur are, by class: low-income economies—Burma, Burundi, China, India, Uganda, Zaire; lower middle-income economies—Botswana, Dominican Republic, Guatemala, Indonesia, Morocco, Peru, Philippines, Zambia, Zimbabwe; upper middle-income economies—Brazil, Greece, South Africa, Yugoslavia; industrial market economies—Australia, Canada, Finland, New Caledonia, the United States; and COMECON—Cuba, the Soviet Union. A sixth economic class, high-income oil exporters, is not listed because those countries do not have identified major cobalt resources. (See table 12 for list of metal-producing countries.)

TABLE 7.—*World production of cobalt contained in ore and concentrate in 1983*

[Modified after British Geological Survey, 1985, p. 55; figures are in metric tons. N.r. = None reported; figures may not add to totals shown due to rounding]

Country	Mine production[1]	Cobalt metal[2]
Australia	2,804	N.r.
Belgium	N.r.	(3)
Botswana	223	N.r.
Canada	1,584	849
Cuba	1,600	N.r.
Czechoslovakia	N.r.	(4)
Finland	930	1,550
France	N.r.	(5)
Germany, Federal Republic of	N.r.	[6]150
Japan	N.r.	1,371
New Caledonia	1,630	N.r.
Norway	N.r.	903
Philippines	578	N.r.
Soviet Union	[6]2,400	[6]4,500
United States	N.r.	93
Zaire	[7]5,349	5,349
Zambia	[7]2,407	2,407
Zimbabwe	74	N.r.
World total	19,600	17,200

[1] There is frequently disparity between cobalt content of ore raised and cobalt actually recovered. Figures in this column relate where possible to cobalt recovered. Exceptions are Australia and New Caledonia, the figures for which relate to cobalt-in-ore raised.

[2] In addition to production listed above, several countries, including France, the Federal Republic of Germany, the United Kingdom, and the United States are known to produce substantial amounts of cobalt compounds that are not necessarily in pure form.

[3] Production not reported. Much metal reported under Zaire is believed to be processed further in Belgium.

[4] Believed to recover cobalt from material of Cuban origin.

[5] Metal produced until 1982 from material of Moroccan origin.

[6] British Geological Survey estimate.

[7] Figures for cobalt-in-ore raised for these countries substantially exceed cobalt recovered.

TABLE 8.—*Mine production of cobalt in 1983 by geologic deposit type*

[Production figures are in metric tons of contained cobalt metal; figures may not add to totals shown due to rounding]

Geologic deposit type	Production	Percent
Magmatic	4,480	22.9
Hydrothermal	930	4.7
Laterite	6,410	32.7
Sediment-hosted	7,760	39.6
Total	19,600	100

the data given in table 8 and figure 4 can serve as a guide to the distribution of resources and production in 1983.

Production from hydrothermal ores is currently unimportant on a world scale and is virtually confined to Finland. The other three major geologic deposit types all make a major contribution to world output. Magmatic and lateritic ores are widely distributed, whereas sediment-hosted ores are concentrated in central Africa. Because of economic and political instabilities in central Africa, however, it is appropriate to examine the significance of sediment-hosted ores in relation to world cobalt demand on an historical basis. Table 9 examines the relative contribution of major producers within each of the four main geological categories over a period of 85 years. The data in table 9 do not give a complete picture, as minor production from several countries in earlier decades is difficult to assign to specific geologic deposit types. There are also ambiguities that arise from the steep growth of world output of cobalt since 1898. It is necessary to examine table 9 in conjunction with table 10 which deals with individual countries, in order to better understand the contributions from different types of ore decade-by-decade.

Table 9 illustrates the steady contribution provided by magmatic ores throughout the period under review, and table 10 suggests that for most of this period Canada was the principal source. Nonetheless, as overall world production has expanded, production of cobalt from magmatic sources has relatively declined. In contrast, since exploitation of central African ores commenced in the 1920's, the contribution of sediment-hosted ores has consistently out-performed the magmatic contribution for several decades. However, the latest available figures (table 9) suggest something of a renaissance for magmatic ores, and this may be connected with political and economic troubles in Africa since 1978.

The very high proportion of cobalt derived from lateritic sources in the earliest years of the 20th century is merely an artifact of low overall world production. It was not until about 1960, when Cuban production began and was followed by a great increase in output from New Caledonia, that the contribution of laterites became really significant.

By analogy with the previous section dealing with resources, mine production of cobalt of the 11 producer nations detailed in table 7 is related to economic status in table 11 and figure 5. In table 11, an index of the extent to which mine production of cobalt within each economic class of nations is supported by resources under the direct control of those nations is suggested by the ratio between the production percentage for each economic class and the corresponding resource percentage given earlier in table 6.

The COMECON group of nations, with mine production of cobalt from the Soviet Union and Cuba, is fortunate in having an even larger share of world resources than they do of production. This favorable position is dependent upon very large Cuban resources. Any weakening of political links between Cuba and the

TABLE 9.—*Contributions by geologic deposit type to total world production of cobalt-in-ore, 1898–1982*

[N.r. = None reported; based on various British Geological Survey publications]

Geologic deposit type	1898 to 1907	1908 to 1917	1918 to 1927	1928 to 1937	1938 to 1947	1948 to 1957	1958 to 1967	1968 to 1977	1978 to 1982
				Percent					
Laterite	67.8	2.8	([1])	N.r.	N.r.	N.r.	2.7	16.7	23.7
Magmatic	28.5	97.2	62.3	31.9	4.1	8.9	9.4	8.8	14.3
Sediment-hosted	N.r.	N.r.	22.6	55.7	66.8	76.5	63.4	61.5	50.0
Hydrothermal	N.r.	N.r.	N.r.	11.9	8.4	5.8	9.0	4.7	3.2
Other[2]	3.7	N.r.	15.1	.5	20.7	8.8	15.5	8.3	8.8
				Thousand metric tons					
Estimated total world production	3.8	7.1	5.1	14.4	35.8	99.0	159.1	289.2	144.2

[1] Negligible.

[2] Includes minor production from several countries, generally unclassifiable by geologic deposit type.

TABLE 10.—*National contributions to total world production of cobalt-in-ore, 1898–1982*

[Figures may not add to 100 percent due to rounding; N.r. = None reported; based on various British Geological Survey publications]

Country	1898 to 1907	1908 to 1917	1918 to 1927	1928 to 1937	1938 to 1947	1948 to 1957	1958 to 1967	1968 to 1977	1978 to 1982
				Percent					
Canada	28.4	97.2	62.3	20.8	4.1	8.9	9.4	5.6	6.0
United States	N.r.	N.r.	N.r.	N.r.	6.5	8.1	N.r.	N.r.	N.r.
Zaire	N.r.	N.r.	22.6	38.9	52.1	68.7	53.8	50.8	40.3
Zambia	N.r.	N.r.	N.r.	16.8	24.7	7.8	9.5	11.5	9.5
Finland	N.r.	N.r.	N.r.	N.r.	2.2	N.r.	2.4	1.6	4.1
Morocco	N.r.	N.r.	N.r.	11.9	8.0	5.8	9.0	4.7	3.2
Burma	N.r.	N.r.	N.r.	11.1	1.9	N.r.	N.r.	N.r.	N.r.
Australia	1.1	N.r.	13.9	.4	.3	.1	.2	4.7	11.4
Philippines	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	.6	3.8
New Caledonia	67.8	2.8	.4	N.r.	N.r.	N.r.	.2	8.1	7.8
Soviet Union	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	4.7	7.5
Cuba	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	2.7	5.2	5.1
Others	2.7	N.r.	.8	N.r.	.2	.6	[1]12.8	2.4	1.3
				Thousand metric tons					
Estimated total of world production	3.8	7.1	5.1	14.4	35.8	99.0	159.1	289.2	144.2

[1] Including a significant but uncertain production from the Soviet Union and approximately 0.7 percent from Uganda.

remaining COMECON nations may radically change the outlook for this economic community.

In contrast, the group of industrial market economy countries, which can be expected to be the main consumers of cobalt products outside COMECON, have a ratio of percentage production to percentage resources that is greater than 1. This ratio emphasizes the importance of resources located within their own sphere in Finland, Canada, Australia, and New Caledonia.

The position of countries within the low-income and lower middle-income groups is radically different. The production performance of these two groups is a closer reflection of their overall endowment in resources. The low-income category controls, for example, about 28 percent of world resources (located principally in Zaire; table 6) and contributes almost exactly the same proportion (again from Zaire) of world mine production (table 11). None of the numerous countries that can be classified as low-income or lower middle-income economies are significant consumers of cobalt products, and output of cobalt from countries within these groups is therefore destined for export. There is no evidence that COMECON is a major consumer of cobalt originating from the two lowest income categories. It is therefore apparent that Western industrial market economy nations, despite extensive use of indigenous deposits, are still dependent to a large degree upon supplies imported from nonmarket economy countries. Such dependence does,

TABLE 11.—*Mine production of cobalt in 1983 by economic class of country*

[Production figures are in metric tons of contained cobalt metal content; figures may not add to totals shown due to rounding]

Economic class[1]	Production[2]	Percent	Ratio of production percentage/ resource-percentage[3]
Low-income	5,349	27.3	0.99
Lower middle-income	3,282	16.8	.98
Upper middle-income	Negligible	.0	.0
Industrial market	6,948	35.5	1.41
COMECON	4,000	20.4	.84
Total	19,600	100	

[1] Modified from World Bank (1985) classification which is based principally on GNP per capita and on other distinguishing economic characteristics.

[2] Figures for countries having mine production in 1983 are shown in table 7.

[3] Resource percentages are shown in table 6.

however, seem to be lessening. Table 11 indicates, for example, that low-income and lower middle-income economy nations collectively support a 44-percent share of world mine production, most of which will find its way to Western markets. In 1978, however, the share supplied by low-income and lower middle-income economy nations was much higher—in the region of 61 percent.

Because of the flow of partially processed cobalt materials across national boundaries, lists of countries producing refined cobalt metal and compounds often do not correspond to lists of countries having mine production of cobalt. The second part of table 7 gives a listing for national production of cobalt metal. Fuller details of individual refineries are given in table 15 in Part II of this report.

A breakdown of refined metal production with respect to geologic category would be meaningless, but it is of interest to compare metal production by economic class (see table 12) with the corresponding data for mine production (table 11; see also fig. 5).

Although the lists in table 7 that refer to mine production of cobalt and production of metal for various countries show considerable differences in detail, the aggregation into economic classes displayed by tables 11 and 12 suggests that broadly the same balance is maintained, with low-income and lower middle-income economy countries commanding about 45 percent of world metal production—almost an identical proportion to their share of mine production. However, this similarity may be more apparent than real. In the case of Zaire, for example, much metal produced in that country is further processed in Belgium. Therefore, it is a matter of opinion whether this metal should be regarded as Zairean, and hence as belonging to the low-income economy class, or as Belgian and therefore to be transferred to the industrial market economy class.

TABLE 12.—*Cobalt metal production in 1983 by economic class of country*

[Production figures are in metric tons of cobalt metal; figures may not add to totals shown due to rounding]

Economic class[1]	Production[2]	Percent
Low-income	5,350	31.1
Lower middle-income	2,410	14.0
Upper middle-income	Negligible	.0
Industrial market	4,920	28.6
COMECON	4,500	26.2
Total	17,200	100

[1] Modified from World Bank (1985, p. 174–175) classification, which is based principally on GNP per capita and other distinguishing economic characteristics.

[2] Figures for countries having cobalt metal production in 1983 are show in table 7.

CONCLUSIONS

The attitude shared by most industrialized countries that cobalt is strategic is partly based upon the relatively large demand for the metal for special alloys designed to give optimum resistance to heat, abrasion, and chemical attack. Historically, permanent magnets have been an area where the possibilities of substitution for cobalt are limited, even though the gross consumption of cobalt in permanent magnets is not large.

The strategic nature of cobalt resulted in a scramble for supplies and a consequent rapid escalation of prices following political upheavals in central Africa in the late 1970's. The fear of a prolonged interruption of supply did not prove well-founded, however, and world output of cobalt declined in the early 1980's for reasons more related to economic downturn than to political factors. Until at least the end of the century, future shortfalls of supply from African sediment-hosted ores resulting from political infrastructure problems in that area might be replaced by increased production from magmatic ores in countries such as Canada or Australia. The position is complicated, because cobalt of central African origin is a byproduct of copper production rather than of nickel production, as in other countries. Future supplies of cobalt are therefore conditioned by the level of demand for nickel. Apart from some hydrothermal deposits limited in number and size, high-grade ores of cobalt are unknown, and it is doubtful whether cobalt production in any region could be maintained upon the basis of revenue from this metal alone. The largest unexploited resource of cobalt probably exists in laterites—many of which have been barely examined. However, since nickel production from such laterites has to compete with nickel production from metallurgically more amenable sulfide ores, the prospects for a substantial increase in the proportion of cobalt from laterite do not appear especially promising. The outlook for the next few decades therefore suggests further episodes of price volatility and, where increased demand for cobalt is out of phase with the cyclical demand for nickel, possible shortages as well.

PART II—SELECTED INVENTORY INFORMATION FOR COBALT DEPOSITS AND DISTRICTS

Tables 13 and 14 contain information from the International Strategic Minerals Inventory record forms for cobalt deposits and districts. Only selected items of information about the location and geology (table 13) and mineral production and resources (table 14) of the deposits are listed here; some of this information has been abbreviated. Table 15 lists cobalt production from primary resources to contrast the location of the original source of the raw material to where it may be processed.

Summary descriptions and data are presented in tables 13 and 14 essentially as they were reported in the inventory records. For instance, significant digits for amounts of production or resources have been maintained as reported. Data that were reported in units other than metric tons have been converted to metric tons for comparability. Some of the data in the tables are more aggregated than in the inventory records, such as cumulative production totals that for some mines have been reported by year or by groups of years. Some of the abbreviations used in the inventory record forms have been used in these tables; they are explained in the headnotes.

Age abbreviations and prefixes:

Quaternary........QUAT
Tertiary..........TERT
Cenozoic..........CEN
Pleistocene........PLEIS
Pliocene..........PLIO
Miocene..........MIO
Cretaceous........CRET
Jurassic..........JUR
Triassic...........TRI
Hercynian.........HERC
Permian..........PERM
Devonian.........DEV
Cambrian.........CAMB
Precambrian.......PREC
Proterozoic........PROT
Archean..........ARCH
Early.............E
Middle...........M
Late.............L

Other abbreviations:

Ma, Million years
Ga, Thousand million years
—, Not reported on the ISMI record form

Site name	Latitude/ longitude	Deposit type	Host rock	Age of mineralization
		Australia		
Agnew mine (Western Australia).	27° 49′S. 120° 42′E.	Magmatic (stratiform, sulfide).	Serpentinized dunite	ARCH (2.9—2.7 Ga)
Kambalda-St. Ives district (Western Australia).	31° 12′S. 121° 39′E.	------do.----------------	Serpentinized peridotite.	------do.--------------------
Windarra district (Western Australia).	28° 29′S. 122° 14′E.	------do.----------------	------do.----------------	------do.--------------------
Greenvale mine (Queensland).	18° 55′S. 144° 59′E.	Laterite	------do.----------------	DEV; TERT
		Botswana		
Selebi-Pikwe district	22° 05′S. 27° 52′E.	Magmatic (stratiform, massive and disseminated).	Amphibolite	ARCH
		Brazil		
Tocantins mine	14° 33′S. 48° 23′W.	Laterite	Peridotite	TERT
		Burma		
Bawdwin mine	23° 07′N. 97° 18′E.	Hydrothermal (stratabound).	Volcanoclastic sediments.	TRI (210 Ma)
		Burundi		
Buhinda district	03° 45′S. 30° 15′E.	Laterite	Peridotite and gabbro.	MIO
		Canada		
SUDBURY BASIN, ONTARIO—FALCONBRIDGE LTD.:				
East mine, Falconbridge.	46° 35′N. 80° 47′W.	Magmatic, gabbroic	Gabbro, norite	EPROT (1.85 Ga)
Falconbridge mine	46° 35′N. 80° 48′W.	------do.----------------	------do.----------------	------do.--------------------
Fecunis North mine	46° 39′N. 81° 21′W.	------do.----------------	Granite breccia	------do.--------------------
Fraser mine	46° 40′N. 81° 21′W.	------do.----------------	------do.----------------	------do.--------------------

Abbreviations for mineral names (after Longe and others, 1978, p. 63–66 and some additions):

Antigorite	ANGR	Cooperite	COOP	Magnetite	MGNT	Psilomelane	PLML
Atokite	ATOK	Digenite	DGNT	Malachite	MLCT	Pyrite	PYRT
Bismutite	BMTT	Enstatite	ENST	Martite	MRTT	Pyrrhotite	PYTT
Bornite	BRNT	Galena	GLEN	Millerite	MLRT	Safflorite	SFLR
Braggite	BRAG	Garnierite	GRNR	Montmorillonite	MMRL	Serpentine	SRPN
Carrolite	CRLT	Goethite	GTHT	Niccolite	NCLT	Skutterudite	SKRC
Chalcocite	CLCC	Halloysite	HALL	Olivine	OLVN	Smaltite	SMLT
Chalcopyrite	CLCP	Hematite	HMTT	Orthopyroxene	ORPX	Sperrylite	SPRL
Chloanthite	CLNT	Heterogenite	HETE	Pentlandite	PNLD	Sphalerite	SPLR
Chromite	CRMT	Illite	ILLT	Plagioclase	PLGC	Tetrahedrite	TRDR
Clay	CLAY	Laurite	LART	Platinum	PLNM	Violarite	VOLR
Cobaltite	CBLT	Limonite	LMON	Polydymite	PLDM		

Tectonic setting	Local environment	Principal mineral assemblages	Reference
	Australia—continued		
Greenstone belt	Massive sulfides at base of serpentinite body in metabasalts and metasediments.	PYTT, PNLD, CLCP, PYRT, MGNT.	Marston and others (1981).
------do.-------------------------	Embayment at base of ultramafic lava flow.	PYTT, PNLD, PYRT, CLCP, MGNT, CRMT.	Gresham and Loftus-Hills (1981).
------do.-------------------------	------do.-------------------------	PYTT, PNLD, PYRT, CLCP, MGNT.	Roberts (1975).
---	Weathered serpentinized ultrabasic rocks.	LMON, Ni and Co silicates	Fletcher and Couper (1975).
	Botswana—continued		
Limpopo belt	---	PYTT, PNLD, CLCP, PYRT.	Wakefield (1976).
	Brazil—continued		
---	Tropical weathering	GRNR, CLAY	Pecora (1944).
	Burma—continued		
Subduction-related marine volcanic activity.	---	GLEN, SPLR, PYRT, CBLT, BMTT, TRDR.	Brinckmann and Hinze (1981).
	Burundi—continued		
Rift system	Tropical weathering	LMON, Ni silicates	---
	Canada—continued		
Intracratonic intrusion triggered by meteoritic impact.	Penecontemporaneous faulting.	PYTT, PNLD, CLCP	Thomson (1959).
------do.-------------------------	------do.-------------------------	PYTT, PNLD, CLCP	Do.
------do.-------------------------	Footwall breccia	PYTT, PNLD, CLCP	---
------do.-------------------------	---	CLCP	---

Site name	Latitude/ longitude	Deposit type	Host rock	Age of mineralization
		Canada—continued		
Lockerby mine	46° 26′N. 81° 20′W.	Magmatic, gabbroic	Gabbro, norite	EPROT (1.85 Ga)
Onaping-Craig mine	46° 38′N. 81° 23′W.	------do.----------------	------do.----------------	------do.--------------------
Strathcona mine	46° 40′N. 81° 20′W.	------do.----------------	------do.----------------	------do.--------------------
SUDBURY BASIN, ONTARIO—INCO LTD.:				
Clarabelle pit	46° 31′N. 81° 03′W.	------do.----------------	------do.----------------	------do.--------------------
Coleman mine	46° 41′N. 81° 20′W.	------do.----------------	Leucocratic breccia	------do.--------------------
Copper Cliff North mine.	46° 30′N. 81° 04′W.	------do.----------------	Quartz diorite	------do.--------------------
Copper Cliff South mine.	46° 28′N. 81° 04′W.	------do.----------------	------do.----------------	------do.--------------------
Crean Hill mine	46° 25′N. 81° 21′W.	------do.----------------	Greenstone breccia	------do.--------------------
Creighton mine	46° 28′N. 81° 11′W.	------do.----------------	Gabbro, norite	------do.--------------------
Frood mine	46° 39′N. 81° 00′W.	------do.----------------	Quartz diorite	------do.--------------------
Garson mine	46° 34′N. 81° 52′W.	------do.----------------	Gabbro, norite	------do.--------------------
Levack mine	46° 39′N. 81° 23′W.	------do.----------------	Leucocratic breccia	------do.--------------------
Levack East mine	46° 39′N. 81° 22′W.	------do.----------------	------do.----------------	------do.--------------------
Little Stobie mine	46° 33′N. 81° 00′W.	------do.----------------	Gabbro, norite	------do.--------------------
McCreedy West mine.	46° 38′N. 81° 24′W.	------do.----------------	Leucocratic breccia	------do.--------------------
Murray mine	46° 31′N. 81° 04′W.	------do.----------------	Gabbro, norite	------do.--------------------
Stobie mine	46° 32′N. 81° 00′W.	------do.----------------	Quartz diorite	------do.--------------------
Totten mine	46° 23′N. 81° 27′W.	------do.----------------	------do.----------------	------do.--------------------
THUNDER BAY DISTRICT, ONTARIO—INCO LTD.:				
Shebandowan mine	48° 36′N. 90° 15′W.	Magmatic, ultramafic	Serpentinized peridotite.	EPROT

Tectonic setting	Local environment	Principal mineral assemblages	Reference
	Canada—continued		
Intracratonic intrusion triggered by meteoritic impact.	---	PYTT, PNLD, CLCP	---
------do.------------------------	---	PYTT, PNLD, CLCP	---
------do.------------------------	Sudbury sublayer	PYTT, PNLD	Abel and others (1979).
------do.------------------------	Sublayer intrusion at base of irruptive sequence.	PYTT, PNLD, CLCP	Souch and others (1969).
------do.------------------------	------do.------------------------	PYTT, PNLD, CLCP	---
------do.------------------------	Penecontemporaneous faulting.	PYTT, PNLD, CLCP	Pattison (1979).
------do.------------------------	------do.------------------------	PYTT, PNLD, CLCP	Souch and others (1969).
------do.------------------------	------do.------------------------	PYTT, PNLD, CLCP	Card (1968).
------do.------------------------	------do.------------------------	PYTT, PNLD, CLCP	Souch and others (1969).
------do.------------------------	------do.------------------------	PYTT, PNLD, CLCP, PLNM, Ni arsenides.	Zurbrigg and others (1957).
------do.------------------------	Faulting associated with basal contact intrusion.	PYTT, PNLD, CLCP	Souch and others (1969).
------do.------------------------	Sublayer intrusion at base of irruptive sequence.	PYTT, PNLD, CLCP	Do.
------do.------------------------	------do.------------------------	PYTT, PNLD, CLCP	---
------do.------------------------	------do.------------------------	PYTT, PNLD, CLCP	Hoffman and others (1979).
------do.------------------------	Footwall breccia and veins below intrusion.	PYTT, PNLD, CLCP, MLRT.	Do.
------do.------------------------	Sublayer intrusion at base of irruptive sequence.	PYTT, PNLD, CLCP	Souch and others (1969).
------do.------------------------	------do.------------------------	PYTT, PNLD, CLCP	---
------do.------------------------	Penecontemporaneous faulting.	---	---
Greenstone belt	Sheared peridotite	PYTT, PYRT, PNLD, CLCP.	Morin (1973).

TABLE 13.—*Selected geologic and location information from*

Site name	Latitude/ longitude	Deposit type	Host rock	Age of mineralization
		Canada—continued		
THOMPSON NICKEL BELT, THE PAS MINING DISTRICT, MANITOBA:				
Birchtree mine	55° 42′N. 97° 55′W.	Magmatic, ultramafic (stratiform).	Biotite schist	EPROT (2.32 Ga)
Moak mine	55° 57′N. 97° 35′W.	Magmatic, ultramafic	Serpentinized peridotite.	EPROT (1.8-1.7 Ga)
Pipe No. 1 mine	55° 29′N. 98° 09′W.	Magmatic, ultramafic (stratiform).	------do.----------------	------do.--------------------
Pipe No. 2 open pit	55° 30′N. 98° 09′W.	Magmatic (stratiform, disseminated).	------do.----------------	EPROT
Soab North and South mines.	55° 13′N. 98° 25′W.	Magmatic (stratiform).	Serpentinized peridotite and biotite schist.	EPROT (2.32 Ga)
Thompson mine	55° 43′N. 97° 51′W.	Magmatic (stratiform, disseminated).	Biotite schist	------do.--------------------
NEW QUEBEC DISTRICT, QUEBEC:				
Donaldson deposit	61° 40′N. 73° 18′W.	Magmatic, ultramafic	Peridotite	EPROT
Katiniq deposit	61° 41′N. 73° 40′W.	------do.----------------	------do.----------------	------do.--------------------
TIMISKAMING MINING DISTRICT, ONTARIO:				
Beaver-Temiskaming mine.	47° 21′N. 79° 38′W.	Hydrothermal, vein	Volcanic rock	EPROT (2.2 Ga)
Castle-Trethewey mine.	47° 45′N. 80° 44′W.	------do.----------------	Clastic sedimentary rock.	------do.--------------------
Coniagas mine	49° 23′N. 79° 41′W.	------do.----------------	------do.----------------	------do.--------------------
Langis mine	47° 23′N. 79° 34′W.	------do.----------------	------do.----------------	------do.--------------------
CASSIAR MINING DISTRICT, BRITISH COLUMBIA:				
Windy Craggy deposit.	59° 43′N. 137° 44′W.	Hydrothermal, volcanic exhalative.	Siltstone	LTRI
		China		
Jinchuan mine (Gansu Province).	Approx 39°N. 100°E.	Magmatic, gabbroic, stratiform; massive and disseminated.	Ultramafic rocks	EPROT
		Cuba		
Moa Bay district	20° 37′N. 74° 58′W.	Laterite	Peridotite	CEN
Nicaro district	20° 35′N. 75° 33′W.	------do.----------------	Serpentinized peridotite.	------do.--------------------

Tectonic setting	Local environment	Principal mineral assemblages	Reference
Canada—continued			
Supracrustal Proterozoic rocks near margin of Archean craton.	Ultramafic sill in metasedimentary sequence.	PYTT, PYRT, PNLD, CLCP, Ni arsenides.	Theyer (1980).
------do.------------------------	------do.------------------------	Sulfides	Patterson (1963).
------do.------------------------	---	---	---
------do.------------------------	Ultramafic sill in metasedimentary sequence.	PYTT, PYRT, PNLD, VOLR.	Coats and others (1972).
------do.------------------------	---	PYTT, PYRT, PNLD, CLCP.	Do.
------do.------------------------	Ultramafic sill in metasedimentary sequence.	PYTT, PYRT, PNLD, CLCP.	Do.
Circumcratonic volcanic fold belt.	Mafic volcanic flow	PYTT, PNLD, CLCP, SRPN.	---
------do.------------------------	------do.------------------------	PYTT, PYRT, PNLD, CLCP, SRPN.	Barnes (1979).
Archean inlier in Proterozoic.	Veins in fracture	Fe, Ni, Co sulfides and arsenides.	Sergiades (1968).
Proterozoic blanket rocks above Archean unconformity.	------do.------------------------	------do.------------------------	Do.
Archean inlier in Proterozoic.	------do.------------------------	------do.------------------------	Do.
------do.------------------------	------do.------------------------	------do.------------------------	Do.
Spreading center	Sedimentary trough	PYTT, CLCP, PYRT	MacIntyre (1984).
China—continued			
---	---	---	Brady (1981).
Cuba—continued			
Obducted ophiolite	Tropical weathering	GTHT, HALL, Ni and Co colloids.	Linchenat and Shirokova (1964).
------do.------------------------	------do.------------------------	GTHT, LMON, MGNT, CRMT, GRNR.	Case (1980).

TABLE 13.—*Selected geologic and location information from*

Site name	Latitude/ longitude	Deposit type	Host rock	Age of mineralization
		Cuba—continued		
Punta Gorda district	20° 35′N. 74° 51′W.	Laterite	Serpentinized perido- tite.	CEN
		Dominican Republic		
Falconbridge Dominicana mines.	19° 01′N. 70° 23′W.	Laterite	Serpentinized perido- tite.	MIO
		Finland		
Keretti mine	62° 46′N. 28° 28′E.	Hydrothermal, vol- canic exhalative.	Quartzite	EPROT (2.1 Ga)
Vuonos mine	62° 43′N. 28° 56′E.	------do.----------------	Cherty quartzite	------do.--------------------
		Greece		
Euboea Island deposit	38° 41′N. 23° 37′E.	Laterite	Serpentinite	ECRET
Larymna mine	38° 28′N. 23° 17′E.	------do.----------------	------do.----------------	------do.--------------------
		Guatemala		
EXMIBAL mine	16° 30′N. 89° 20′W.	Laterite	Peridotite	CEN
		India		
Sukhinda deposit	21° 03′N. 85° 48′E.	Magmatic (massive layered sulfide) and laterite.	Peridotite	PROT (1.6 Ga)
		Indonesia		
Gag Island deposit	00° 30′S. 129° 45′E.	Laterite	Peridotite	LTERT; QUAT
		Morocco		
Bou Azzer mine	30° 32′N. 06° 55′E.	Hydrothermal (with residual enrich- ment).	Serpentinized perido- tite.	PREC; HERC
		New Caledonia		
DEPOSITS WORKED BY SOCIÉTÉ MÉTALLURGIQUE LE NICKEL (SLN):				
Kouaoua mine	21° 24′S. 165° 45′E.	Laterite	Serpentinized perido- tite.	CEN
Nepoui mine	21° 17′S. 164° 41′E.	------do.----------------	------do.----------------	------do.--------------------
Poro mine	21° 43′S. 165° 40′E.	------do.----------------	------do.----------------	------do.--------------------
Thio mine	21° 40′S. 166° 13′E.	------do.----------------	------do.----------------	------do.--------------------

ISMI records for cobalt deposits and districts—Continued

Tectonic setting	Local environment	Principal mineral assemblages	Reference
		Cuba—continued	
Obducted ophiolite	Tropical weathering	GTHT, LMON, MGNT, CRMT, GRNR.	Case (1980).
		Dominican Republic—continued	
Island arc, thrusted ophiolite.	Tropical weathering	SRPN, GTHT, OLVN, ENST.	Haldemann and others (1982).
		Finland—continued	
Fold belt	Structural emplacement into metasedimentary sequence.	PYTT, CLCP, SPLR, PYRT	Peltola (1978).
------do.------------------------	------do.------------------------	PYTT, CLCP, SPLR, CBLT, PNLD, PYRT.	Heiskanen and others (1981).
		Greece—continued	
Ophiolite belt	Tropical weathering	---	Albandakis (1980).
------do.------------------------	------do.------------------------	GRNR, ANGR, MMRL	Do.
		Guatemala—continued	
Orogenic belt	Tropical weathering	GRNR, LMON, SRPN	Case (1980).
		India—continued	
Orogenic fold belt	---	CRMT, LMON, Ni and Co silicates.	Law (1976).
		Indonesia—continued	
Ophiolite belt	Tropical weathering	GRNR, LMON, SRPN	Havryluk and Huff (1979).
		Morocco—continued	
Obducted ophiolite	Folded horsts and grabens	SKRC, SFLR, NCLT, CLCP, PYRT.	Leblanc and Billaud (1982).
		New Caledonia—continued	
Ophiolite belt	Tropical weathering	GTHT, LMON, SRPN, CRMT, GRNR.	Paris (1981).
------do.------------------------	------do.------------------------	GRNR, LMON, SRPN	Do.
------do.------------------------	------do.------------------------	GRNR, LMON, SRPN	Do.
------do.------------------------	------do.------------------------	GRNR, LMON, SRPN	Do.

Site name	Latitude/ longitude	Deposit type	Host rock	Age of mineralization
New Caledonia—continued				
DEPOSITS WORKED OR DEVELOPED BY CIE FRANCAISE D'ENTERPRISE MINIERES, MÉTALLURGIQUES ET D'INVESTISSEMENTS (COFREMMI):				
Poum prospect	20° 15'S. 164° 03'E.	Laterite	Serpentinized peridotite.	CEN
Tiébaghi mine	20° 27'S. 164° 13'E.	------do.----------------	------do.----------------	------do.--------------------
DEPOSIT EVALUATED BY SOCIÉTÉ NATIONAL DES PÉTROLES AQUITAINE (PART) AND INCO (PART):				
Goro prospect	22° 24'S. 167° 01'E.	Laterite	Serpentinized peridotite.	CEN
Note: Numerous other laterite deposits in New Caledonia are potential sources of cobalt. For further details see DeYoung and others (1986).				
Peru				
Marcona prospect	15° 10'S. 75° 10'W.	Hydrothermal	Limestone	PERM/TRI
Philippines				
Rio Tuba mine	08° 35'N. 117° 24'E.	Laterite	Pyroxenite	CRET
Surigao district	09° 51'N. 125° 37'E.	------do.----------------	Peridotite	PLIO/EPLEIS
South Africa				
Platreef sector (Potgietersrus).	23° 59'S. 28° 54'E.	Magmatic (stratiform).	Pyroxenite	EPROT (2.1 Ga)
Merensky Reef sector, Western Bushveld.	25° 40'S. 27° 15'E.	------do.----------------	------do.----------------	------do.--------------------
Merensky Reef sector, Eastern Bushveld.	24° 19'S. 29° 50'E.	------do.----------------	------do.----------------	------do.--------------------
Chromitite Layer sector, Western Bushveld.	25° 42'S. 27° 30'E.	------do.----------------	------do.----------------	------do.--------------------
Chromitite Layer sector, Eastern Bushveld.	24° 40'S. 30° 00'E.	------do.----------------	------do.----------------	------do.--------------------
Soviet Union				
Khuvo-Aksinsk deposit (Tura Autonomous Republic).	51° 05'N. 93° 40'E.	Hydrothermal, skarn	Carbonate rocks	EDEV
Noril'sk-Talnakh district (northern Siberia).	69° 20'N. 88° 08'E.	Magmatic (massive and disseminated).	Gabbro, dolerite	ETRI (230–220 Ma)

ISMI records for cobalt deposits and districts—Continued

Tectonic setting	Local environment	Principal mineral assemblages	Reference
		New Caledonia—continued	
Ophiolite belt	Tropical weathering	GRNR, LMON, SRPN	Paris (1981).
------do.------------------------	------do.------------------------	GRNR, LMON, SRPN	Do.
------do.------------------------	------do.------------------------	GRNR, LMON, SRPN	Do.
		Peru—continued	
Mobile belt	---	MRTT, PYRT, CLCP	Atchley (1956).
		Philippines—continued	
Mobile belt	Tropical weathering	GRNR, LMON	Wolff (1978).
Island arc thrust zone	------do.------------------------	ILLT, GTHT	Philippines Bureau of Mines and Geo-Sciences (1980).
		South Africa—continued	
Intracratonic	Plutonic	PYTT, PNLD, CLCP, COOP, BRAG.	Vermaak and von Gruenewaldt (1981).
------do.------------------------	------do.------------------------	PYTT, PNLD, CLCP, COOP, BRAG, SPRL, LART.	Coetzee (1976).
------do.------------------------	------do.------------------------	PNLD, CLCP, PYRT, PYTT, COOP, BRAG, LART, SPRL, ATOK.	Schwellnus and others (1976).
------do.------------------------	------do.------------------------	CRMT, ORPX, PLGC, LART, COOP, BRAG, PNLD, CLCP, PYTT, PYRT.	Vermaak and von Gruenewaldt (1981).
------do.------------------------	------do.------------------------	CRMT, ORPX, PLGC, LART, COOP, BRAG, PNLD, CLCP, PYTT, PYRT.	McLaren and De Villiers (1982).
		Soviet Union—continued	
Affected by regional block faulting.	Skarn-type metasomatism	SKRC, SFLR, SMLT, CLNT, NCLT.	Smirnov (1977).
Fold belt	Differentiated basic intrusion.	PYTT, CLCP, PNLD	Naldrett (1981).

TABLE 13.—*Selected geologic and location information from*

Site name	Latitude/ longitude	Deposit type	Host rock	Age of mineralization
		Soviet Union—continued		
Orsk combine (southern Urals).	51° 13'N. 58° 35'E.	Laterite	Serpentinized peridotite.	TRI/JUR
Pechenga district (Kola)	69° 20'N. 29° 44'E.	Magmatic (massive)	Gabbro, dolerite	PROT
Yuzhuralnickel complex (central Urals).	56° 46'N. 60° 18'E.	Laterite	Serpentinized peridotite.	TRI/JUR
		Uganda		
Kilembe mine	03° 00'N. 30° 01'E.	Sediment-hosted (strata-bound).	Chlorite biotite schist	PREC
		United States		
Blackbird mine (Idaho)	45° 05'N. 114° 30'W.	Sediment-hosted	Metasediments	PREC
Kawishiwi province (Duluth Complex) (Minnesota).	47° 45'N. 91° 40'W.	Magmatic, gabbroic	Gabbro	MPROT (1.1 Ga)
Fredericktown area (Missouri).	37° 33'N. 90° 25'W.	Hydrothermal	Dolomite	CAMB
Gasquet Mountain prospect (California).	41° 51'N. 123° 58'W.	Laterite	Peridotite	---
Riddle mine (Oregon)	42° 58'N. 123° 27'W.	------do.----------------	Serpentinite	MIO/PLIO
		Yugoslavia		
Kosovo mines	42° 28'N. 21° 03'E.	Laterite (residual enrichment).	Serpentinite	JUR; TERT
Řzanovo mine	41° 14'N. 22° 16'E.	------do.----------------	------do.----------------	---
		Zaire		
Dikuluwe-Mashamba mines.	10° 44'S. 25° 22'E.	Sediment-hosted (strata-bound).	Dolomite, shale, quartzite.	LPROT
Kakanda mine	10° 44'S. 26° 23'E.	------do.----------------	------do.----------------	------do.--------------------
Kambove West mine	10° 52'S. 26° 36'E.	------do.----------------	------do.----------------	------do.--------------------
Kamoto East mine	10° 43'S. 25° 25'E.	------do.----------------	------do.----------------	------do.--------------------
Kamoto North mine	10° 43'S. 25° 24'E.	------do.----------------	------do.----------------	------do.--------------------
Kamoto mine (underground).	10° 43'S. 25° 25'E.	------do.----------------	------do.----------------	------do.--------------------

Tectonic setting	Local environment	Principal mineral assemblages	Reference
		Soviet Union—continued	
Fold belt	Tropical weathering	SRPN, GRNR	Smirnov (1977).
------do.------------------------	Magmatic layered intrusion	PYTT, PNLD, CLCP	Naldrett (1981).
------do.------------------------	Tropical weathering	SRPN, GRNR	Smirnov (1977).
		Uganda—continued	
Fold belt	---	Co-bearing PYRT, PYRT, CLCP, PYTT.	Davis (1969).
		United States—continued	
Rift sedimentation	Strata-bound concentrations of volcanogenic type and hydrothermally remobilized.	CLCP, PYTT, CBLT, PYRT.	U.S. Bureau of Mines and U.S. Geological Survey (1952).
---	Concentrations in depressions at base of intrusive complex.	CLCP, PNLD, PYRT, BRNT.	Grosh and others (1955).
---	Reef facies carbonate deposit over basement.	GLEN, SPLR, PYRT	Cornwall (1967).
Fold belt	Tropical weathering	GRNR	---
Orogenic belt	------do.------------------------	GRNR	Chace and others (1969).
		Yugoslavia—continued	
---	Tropical weathering	GRNR, GTHT, PLML	Berthold (1980).
---	------do.------------------------	HMTT, LMON, MLRT, NCLT.	Do.
		Zaire—continued	
Intracratonic sedimentary basin.	Shallow marine	MLCT, CLCC, DGNT, CRLT, HETE.	Lombard and Nicolini (1961–63).
------do.------------------------	------do.------------------------	MLCT, HETE	Do.
------do.------------------------	------do.------------------------	CLCP, CLCC, CRLT, MLCT, HETE.	Do.
------do.------------------------	------do.------------------------	CLCC, CLCP, CRLT, DGNT, MLCT.	Do.
------do.------------------------	------do.------------------------	CLCC, BRNT, CRLT, DGNT.	Do.
------do.------------------------	------do.------------------------	CLCC, BRNT, CRLT, DGNT.	Do.

TABLE 13.—*Selected geologic and location information from*

Site name	Latitude/ longitude	Deposit type	Host rock	Age of mineralization
		Zaire—continued		
Mupine mine	10° 42′S. 25° 25′E.	Sediment-hosted (strata-bound).	Dolomite, shale, quartzite.	LPROT
Musonoi mine	10° 42′S. 25° 27′E.	------do.----------------	------do.----------------	------do.--------------------
Tenke-Fungurume mine	10° 37′S. 26° 17′E.	------do.----------------	------do.----------------	------do.--------------------
		Zambia		
Baluba mine (part Luanshya division).	13° 04′S. 28° 20′E.	Sediment-hosted (strata-bound).	Dolomite, schist	LPROT
Chibuluma mine (part Kalulushi division).	12° 23′S. 27° 57′E.	------do.----------------	Sericitic quartzite	------do.--------------------
Konkola division	12° 23′S. 27° 57′E.	------do.----------------	Siltstone	------do.--------------------
Nchanga division	12° 32′S. 27° 51′E.	------do.----------------	Feldspathic quartzite	------do.--------------------
Nkana division	12° 49′S. 28° 13′E.	------do.----------------	Argillites	------do.--------------------
		Zimbabwe		
Epoch mine	20° 25′S. 29° 15′E.	Magmatic	Komatiitic lava	ARCH
Madziwa mine	17° 05′S. 31° 50′E.	------do.----------------	Pyroxenite	------do.--------------------
Shangani mine	19° 40′S. 29° 15′E.	------do.----------------	Peridotite	------do.--------------------
Trojan mine	17° 18′S. 31° 20′E.	------do.----------------	Dunite	------do.--------------------

ISMI records for cobalt deposits and districts—Continued

Tectonic setting	Local environment	Principal mineral assemblages	Reference
Zaire—continued			
Intracratonic sedimentary basin.	Shallow marine	CLCC, CLCP, MLCT, HETE.	Lombard and Nicolini (1962–63).
------do.------------------------	------do.------------------------	CLCP, CLCC, MLCT, HETE.	Do.
------do.------------------------	------do.------------------------	MLCT, CLCC, CLCP, DGNT, CRLT.	Do.
Zambia—continued			
Intracratonic sedimentary basin.	Shallow marine	CLCP, CLCC, PYRT, CRLT.	Mendelsohn (1961).
------do.------------------------	------do.------------------------	CLCP, CLCC, PYRT, BRNT, CRLT.	Do.
------do.------------------------	------do.------------------------	CLCP, CLCC, MLCT, CRLT, BRNT.	Do.
------do.------------------------	------do.------------------------	CLCP, CLCC, MLCT, CRLT, BRNT.	Do.
------do.------------------------	------do.------------------------	CLCC, BRNT, CLCP, CRLT.	Do.
Zimbabwe—continued			
Fold belt	Layered intrusion	PNLD, CLCP, MLRT, PLDM.	Clutten and others (1981).
------do.------------------------	Intrusion into granites	PYTT, PNLD, CLCP, VOLR, MLRT, SPLR.	Moubray and others (1976).
------do.------------------------	Layered intrusion	PYTT, PNLD, CLCP, PYRT.	Viljoen and others (1976).
------do.------------------------	------do.------------------------	PNLD, MLRT, MGNT, CLCP, NCLT.	Clutten and others (1981).

Abbreviations for *mining method*:
S, surface; U, underground; N, not yet producing
Annual production and *cumulative production* figures pertaining to metals other than cobalt not entered unless this is necessary for clarification. Figures may be recorded as *ore* with or without metal content specified; as *Co* which implies cobalt-in-ore; as *Co metal*; or as *Co concentrate*. All tonnages are actual figures recorded in metric tons. Years for reported cumulative production are in parentheses.

Site name	Year of discovery	Mining method	First year of production
	Australia		
Agnew mine (Western Australia)	1971	U	1978
Kambalda-St. Ives district (Western Australia)	1965	U	1967
Windarra district (Western Australia)	1969	U, S	1974
Greenvale mine (Queensland)	1967	S	1974
	Botswana		
Selebi-Pikwe district	1963	U, S	1974
	Brazil		
Tocantins mine	1908	S	1979
	Burma		
Bawdwin mine	1412	U, S	1412
	Burundi		
Buhinda district	1972	N	None
	Canada		
SUDBURY BASIN, ONTARIO—FALCONBRIDGE LTD.:			
East mine, Falconbridge	1949	U	1953
Falconbridge mine	1916	U	1930
Fecunis North mine	1964	U	1965
Fraser mine	Pre-1970	U	1981
Lockerby mine	1919	U	1975
Onaping-Craig mine	1942	U	1961
Strathcona mine	1951	U	1962
SUDBURY BASIN, ONTARIO—INCO LTD.:			
Clarabelle pit	1883	S	1979

Resources include, for various resource categories, some or all of the following items (separated by semicolons): resource in thousand metric tons; U.N. resource classification (United Nations Economic and Social Council, 1979; Schanz, 1980); grade or other explanatory descriptor; and year of estimate.
Other abbreviations:
PGM, Platinum-group metals which are platinum, palladium, rhodium, ruthenium, iridium, and osmium.
---, Not reported on the ISMI record form.

Elements of economic interest	Annual production	Cumulative production	Resources (1,000 t)
		Australia—continued	
Ni, Cu, Co	167; Co	512; Co (1978-81)	2,700; R1E; ore; 1982.
Ni, Cu, Co, Au, Ag, S, Pb, Pd.	681; Co	---	25,000; R1E; ore; 1982.
Ni, Cu, Co	215; Co	890; Co (1978-82)	9,200; R1E; ore; 1982.
Ni, Co	2,162; Co	12,778; Co (1975-81)	21,800; R1E; 0.12 percent Co; 1981.
		Botswana—continued	
Ni, Cu, Co	247; Co	1,290; Co (1978-82)	52,392; R1E; ore; 1983.
		Brazil—continued	
Ni, Fe, Co	---	---	38,700; R1E; ore; 1983.
		Burma—continued	
Zn, Pb, Au, Ni	250,000; ore	---	30,000; R1E; ore; 1982.
		Burundi—continued	
Ni, Cu, Co, PGM	---	---	300,000; R1E; 0.1 percent Co; 1974.
		Canada—continued	
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	Aggregated with Falconbridge mine.	Aggregated with Falconbridge mine.	r1E (aggregated with Falconbridge mine).
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	579; Co	78,284,000; ore 0.04 percent Co (1953-83).	66,769; r1E; 0.04 percent Co; 1983.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	Aggregated with Falconbridge mine.	Aggregated with Falconbridge mine.	r1E (aggregated with Falconbridge mine).
Ni, Cu, PGM, Au, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	Aggregated with Creighton mine.	Aggregated with Creighton mine.	r1E (aggregated with Creighton mine).

TABLE 14.—*Selected production and mineral-resource information*

Site name	Year of discovery	Mining method	First year of production
Canada—continued			
Coleman mine	Pre-1964	U	1971
Copper Cliff North mine	Pre-1960	U	1967
Copper Cliff South mine	Pre-1967	U	1970
Crean Hill mine	Pre-1905	U	1905
Creighton mine	1900	U	1901
Frood mine	1884	U	1889
Garson mine	1891	U	1908
Levack mine	1888	U	1914
Levack East mine	Pre-1970	U	None
Little Stobie mine	1885	U	1902
McCreedy West mine	Pre-1939	U	1973
Murray mine	1883	U	1889
Stobie mine	1884	U	1887
Totten mine	1885	U	1966
THUNDER BAY DISTRICT, ONTARIO—INCO LTD.:			
Shebandowan mine	Pre-1936	U	1972
THOMPSON NICKEL BELT, THE PAS MINING DISTRICT, MANITOBA:			
Birchtree mine	1964	U	1969
Moak mine	1952	N (U)	None
Pipe No. 1 mine	1959	U	1970
Pipe No. 2 open pit	1959	S	1970
Soab North and South mines	1959	U	1967
Thompson mine	1956	S, U	1961

from ISMI records for cobalt deposits and districts—Continued

Elements of economic interest	Annual production	Cumulative production	Resources (1,000 t)
Canada—continued			
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	Aggregated with Creighton mine.	Aggregated with Creighton mine.	r1E (aggregated with Creighton mine).
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co	2,100; Co	438,250,000; ore *also* 25,000; Co (1950–83).	360,000; r1E; 0.05 percent Co; 1983.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	Aggregated with Creighton mine.	Aggregated with Creighton mine.	r1E (aggregated with Creighton mine).
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, PGM, Au, Ag, Co, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, Co, PGM, Au, Ag, Se, Te.	Aggregated with Thompson mine.	Aggregated with Thompson mine.	r1E (aggregated with Thompson mine).
Ni, Cu, Co	Development work suspended.	---	Do.
Ni, Cu, Co, PGM, Au, Ag, Se, Te.	On standby	Aggregated with Thompson mine.	Do.
Ni, Cu, Co, PGM, Au, Ag, Se, Te.	Aggregated with Thompson mine.	------do.------------------------	Do.
Ni, Cu, Co, PGM, Au, Ag, Se, Te.	------do.------------------------	------do.------------------------	Do.
Ni, Cu, Co, PGM, Au, Ag, Se, Te.	500; Co	4,700; Co (1961–83)	73,000; r1E; 0.05 percent Co; 1983.

TABLE 14.—*Selected production and mineral-resource information*

Site name	Year of discovery	Mining method	First year of production
Canada—continued			
NEW QUEBEC DISTRICT, QUEBEC:			
Donaldson deposit	1954	N	None
Katiniq deposit	1961	N	None
TIMISKAMING MINING DISTRICT, ONTARIO:			
Beaver-Temiskaming mine	1907	U	1907
Castle-Trethewey mine	1919	U	1920
Coniagas mine	1905	U	1906
Langis mine	1907	U	1907
CASSIAR MINING DISTRICT, BRITISH COLUMBIA:			
Windy Craggy deposit	1965	N	None
China			
Jinchuan mine (Gansu Province)	1958	U, S	1964
Cuba			
Moa Bay district	1905	S	1959
Nicaro district	1905	S	1944
Punta Gorda district	1905	S	1985 (planned)
Dominican Republic			
Falconbridge Dominicana mines	1918	S	1971
Finland			
Keretti mine	1910	U	---
Vuonos mine	1965	S, U	1970
Greece			
Euboea Island deposit	---	S	---
Larymna mine	1900	S, U	1966
Guatemala			
EXMIBAL mine	1955	S	1977

from ISMI records for cobalt deposits and districts—Continued

Elements of economic interest	Annual production	Cumulative production	Resources (1,000 t)
		Canada—continued	
Ni, Cu, Co, PGM	---	---	2,377; R1M; 0.03 percent Co; 1969.
Ni, Cu, Co	---	---	4,411; R1M; 0.03 percent Co; 1969.
Ag, Co, Ni, Cu	15; Co	---	No estimates of indicated ore resources are available owing to erratic nature of deposits.
Ag, Co	Aggregated with Beaver mine.	---	Do.
Ag, Co, Ni, Cu	------do.------------------------	---	Do.
Ag, Co, Ni, Cu	------do.------------------------	---	Do.
Ni, Cu, Co	200; Co (estimated capacity)	---	91,000; R1S; 0.09 percent Co; 1983.
		China—continued	
Ni, Cu, Co	200	---	4,760; R1E; ore; 1982.
		Cuba—continued	
Ni, Fe, Co	1,650; Co	---	400,000; R1E; ore; 1978.
Ni, Fe, Co, Cr	189; Co	---	153; R1E; Co-in-ore; 1964.
Ni, Fe, Co	---	---	60; R1E; ore; 1984. 100; R1M; ore; 1984.
		Dominican Republic—continued	
Ni, Fe, Co	23; Co	---	70,000; R1E; ore; 1977.
		Finland—continued	
Cu, Zn, Co	650; Co	3,270; Co (1979–83)	3,100; R1E; ore; 1983.
Cu, Co, Zn, Ni	310; Co	1,550; Co (1979–83)	1,800; R1E; 0.15 percent Co; 1980.
		Greece—continued	
Ni, Fe, Co	---	---	200,000; R1E; ore; 1980.
Ni, Fe, Co	---	---	30,000; R1E; ore; 1973.
		Guatemala—continued	
Ni, Co	---	---	50,000; R1E; ore; 1982.

TABLE 14.—*Selected production and mineral-resource information*

Site name	Year of discovery	Mining method	First year of production
India			
Sukhinda deposit	1949	N (S, U)	None
Indonesia			
Gag Island deposit	1952	N (S)	None
Morocco			
Bou Azzer mine	1931	U	1930's
New Caledonia			
DEPOSITS WORKED BY SOCIÉTÉ MÉTALLURGIQUE LE NICKEL (SLN):			
Kouaoua mine	1860's	S	1870's
Nepoui mine	1965	S	1973
Poro mine	1865	S	1875
Thio mine	1863	S	1880's
DEPOSITS WORKED OR DEVELOPED BY CIE FRANCAISE D'ENTERPRISE MINIERES, MÉTALLURGIQUES ET D'INVESTISSEMENTS (COFREMMI):			
Poum prospect	1864	N (S)	None
Tiébaghi mine	1965	S	1982
DEPOSIT EVALUATED BY SOCIÉTÉ NATIONAL DES PÉTROLIES AQUITAINE (PART) AND INCO (PART):			
Goro prospect	1960	N (S)	None
Peru			
Marcona prospect	1905	S	1920's
Philippines			
Rio Tuba mine	1967	S	1977
Surigao district	1912	S	1974
South Africa			
Platreef sector (Potgietersrus)	1924	S	1926
Merensky Reef sector, Western Bushveld	1926	U	1920's

Elements of economic interest	Annual production	Cumulative production	Resources (1,000 t)
	India—continued		
Cr, Ni, Co	200; Co (estimated capacity)	---	65,000; R1E; 0.06 percent Co; 1979.
	Indonesia—continued		
Ni, Co	---	---	160,000; R1E; 0.12 percent Co; 1981.
	Morocco—continued		
Co, Ni, Cu	7,207; Co concentrate	2,429; Co metal (1978–82); 50,000; Co metal (1930-82).	Limited.
	New Caledonia—continued		
Ni, Fe, Co	180,000; ore (partial figure only).	---	---
Ni, Fe, Co	---	---	11; R1E; ore; 1972.
Ni, Fe, Co	960,000; ore	---	30; R1E; ore; 1976.
Ni, Co, Fe	312,000; ore	---	8; R1E; ore; 1972.
Ni, Co	---	---	50,000; R1E; ore; 1976.
Ni, Cr, Co	---	---	13,250; R1E; garnierite ore; 1974. 17,100; R1E; laterite ore; 1974.
Ni, Co	---	---	150; R1E; ore; 1972. 500; R2E; ore; 1972.
	Peru—continued		
Fe, Co	750; Co	---	250,000; R1E; iron ore; 1970.
	Philippines—continued		
Ni, Fe, Co	299,000; ore	---	20,000; R1E; ore; 1983.
Ni, Fe, Co	1,195; Co	5,977; Co (1977-81)	60,000; R1E; 0.13 percent Co; 1983.
	South Africa—continued		
Ni, Cu, PGM, Co	---	---	1.5; R1E; Co-in-ore; 1984. 3.8; R2S; Co-in-ore; 1984.
PGM, Ni, Co, Cu	---	---	2.7; R1E; Co-in-ore; 1984. 2.7; R2S; Co-in-ore; 1984.

TABLE 14.—*Selected production and mineral-resource information*

Site name	Year of discovery	Mining method	First year of production
South Africa—continued			
Merensky Reef sector, Eastern Bushveld	1924	U	1969
Chromitite Layer sector, Western Bushveld	1924	U	1970's
Chromitite Layer sector, Eastern Bushveld	1924	N	None
Soviet Union			
Khuvo-Aksinsk deposit (Tura Autonomous Republic).	1947	U	---
Noril'sk Talnakh district (northern Siberia)	1961	U	---
Orsk combine (southern Urals)	---	S	1938
Pechenga district (Kola)	Pre-1914	U	Pre-1939
Yuzhuralnickel complex (central Urals)	1874	S	1934
Uganda			
Kilembe mine	1908	U	1955
United States			
Blackbird mine (Idaho)	1893	U	About 1916
Kawishiwi province (Duluth Complex) (Minnesota)	1948	S, U	---
Fredericktown area (Missouri)	1720	U	1844
Gasquet Mountain prospect (California)	1851	N (S)	None
Riddle mine (Oregon)	1864	S	1954
Yugoslavia			
Kosovo mines	1970	S	1982
Ržanovo mine	1958	S	---
Zaire			
Dikuluwe-Mashamba mines	1972	S	1980's
Kakanda mine	1900's	S	1946
Kambove West mine	1901	U, S	1963
Kamoto East mine	1900's	S	1945

from ISMI records for cobalt deposits and districts—Continued

Elements of economic interest	Annual production	Cumulative production	Resources (1,000 t)
	South Africa—continued		
PGM, Ni, Co, Cu	---	---	0.2; R1E; Co-in-ore; 1984. 4.1; R2S; Co-in-ore; 1984.
PGM, Ni, Co, Cu	---	---	0.8; R1E; Co-in-ore; 1984. 0.7; R2S; Co-in-ore; 1984.
PGM, Ni, Co, Cu	---	---	0.6; R1E; Co-in-ore; 1984. 2.6; R2S; Co-in-ore; 1984.
	Soviet Union—continued		
Co, Ni	---	---	100; R1E; Co-in-ore; 1977.
Ni, Cu, Co, PGM	2,200; Co	11,000; Co (1979–83)	380,000; R1E; ore; 1984.
Ni, Fe, Co	---	---	---
Ni, Cu, Co	700; Co metal	---	---
Ni, Fe, Co	---	---	---
	Uganda—continued		
Ni, Fe, Co	---	---	38,700; R1E; ore; 1983.
	United States—continued		
Co, Cu, Au, Ag	980; Co (1957, mine closed 1959).	1,900; Co (1951–58)	4,300; R1S; 0.73 percent Co; 1981.
Co, Ni, Cu	Not yet in production	---	115; R2S; metal-in-sulfide; 1979. 1,100,000; R2S; ore; 1977.
Co, Ni, Cu, Pb, Zn	Last production 1961	---	3,000; R1S; 0.28 percent Co; 1962.
Ni, Co	910; Co (estimated)	---	37,000; R1E; 0.09 percent Co; 1984.
Ni, Co	---	7,119,257; Ni ore with 0.05 percent Co (1954–64).	16,000; R1E; 0.05 percent Co; 1969.
	Yugoslavia—continued		
Ni, Co	983,000; ore	---	26,700; R1E; 0.07 percent Co; 1982.
Ni, Co	23,000,000; ore (planned capacity).	---	110,000; R1E; ore; 1980.
	Zaire—continued		
Cu, Co	2,000,000; ore (estimated)	---	125,000; R1E; ore (28,000 Dikuluwe).
Cu, Co	970,000; ore	---	Nearly exhausted.
Cu, Co	1,500,000; ore	---	Exhaustion expected 1986.
Cu, Co	2,000,000; ore (estimated)	---	Large.

TABLE 14.—*Selected production and mineral-resource information*

Site name	Year of discovery	Mining method	First year of production
Zaire—continued			
Kamoto North mine	1900's	S	1960's
Kamoto mine (underground)	---	U	1963
Mupine mine	1900's	S	1950's
Musonoi mine	1900's	S	1946
Tenke-Fungurume mine	1970's	N	---
Zambia			
Baluba mine (part Luanshya division)	1929	U	1973
Chibuluma mine (part Kalulushi division)	1939	U	1955
Konkola division	1940	U	1957
Nchanga division	1925	S, U	1939
Nkana division	1923	S, U	1932
Zimbabwe			
Epoch mine	1969	U	1976
Madziwa mine	1958	U	1967
Shangani mine	1969	U	1975
Trojan mine	1957	U	1968

from ISMI records for cobalt deposits and districts—Continued

Elements of economic interest	Annual production	Cumulative production	Resources (1,000 t)
		Zaire—continued	
Cu, Co	750,000; ore (estimated)	---	Limited.
Cu, Co	2,760,000; ore	---	55,000; R1E; ore (in north extension).
Cu, Co	500,000; ore (estimated)	---	---
Cu, Co	500,000; ore (estimated)	---	Nearly exhausted.
Cu, Co	---	---	51,000; R1E; ore.
		Zambia—continued	
Cu, Co	1,902,000; ore	---	53,754; R1E; ore; 1983.
Cu, Co	666,000; ore	12,900,000; ore (1956–83)	7,220; R1E; ore; 1983.
Cu, Co	1,769,000; ore	---	55,361; R1E; ore; 1983.
Cu, Co	150,700; ore	452,000; Co concentrate (1981–88 estimated).	9,897; R1E; ore; 1983.
Cu, Co	4,000,000; ore	57,476; Co metal (1934–83)	12,685; R1E; ore; 1983.
		Zimbabwe—continued	
Ni, Cu, Co	473,000; ore	2,367,000; ore (1979–83)	901; R1E; ore; 1983. 1,373; R1M; ore; 1983. 2,745; R1S; ore; 1983.
Ni, Cu, Co	389,700; ore	1,948,500; ore (1979–83)	571; R1E; ore; 1983. 1,661; R1M; ore; 1983. 487; R1S; ore; 1983.
Ni, Cu, Co	725,600; ore	2,902,300; ore (1980–84)	914; R1E; ore; 1983. 1,662; R1M; ore; 1983. 11,917; R1S; ore; 1983.
Ni, Cu, Co	---	2,703,000; ore (1979-83)	1,926; R1E; ore; 1983. 3,300; R1M; ore; 1983. 7,529; R1S; ore; 1983.

Annual capacity is in metric tons of cobalt unless other material is indicated.
Annual production may include one or both of the following items: production in metric tons and year of production in parentheses.
---, Not reported

Site	Operator	Raw material	Origin of raw material
		Australia	
Kwinana, near Perth	Western Mining Corp. Holdings Ltd.	Nickel matte and concentrates.	Material from company sources includes concentrates from Kambalda and matte from Kalgoorlie. Also custom material.
		Belgium	
Olen, Antwerp	Metallurgie-Hoboken Overpelt S.A. (partially owned by Union Minière).	Cathode and white metal	Shituru and Panda plants, Zaire
		Brazil	
Niquelandia, Goias	CODEMIN S.A.	Lateritic ore	Laterite from Tocantins mine
		Canada	
Fort Saskatchewan, Alberta.	Sherritt Gordon Mines Ltd.	Nickel matte and concentrate.	Feed now obtained from overseas, for example Australia and Philippines, and other Canadian companies.
Port Colbourne, Ontario	INCO Ltd.	Nickel sulfide concentrate and nickel matte.	Sudbury basin ores
Thompson, Manitoba	------do.---------------------	------do.---------------------	Ore from The Pas mining district and overseas.
Cobalt, Ontario	Agnico-Eagle Mines Ltd.	Sulfide ore	Ore from company mines in Timiskaming mining district.
		China	
Jinchuan, Gansu Province.	Jinchuan Non-Ferrous Metal Co.	Sulfide ore	Ore from nickel mine
		Finland	
Harjavalta	Outokumpu Oy	Sulfide ores	Company mines
Kokkola	------do.---------------------	Sulfide ores, copper smelting waste.	Ores from company mines and foreign sources. Waste from German Democratic Republic.
Luikonlahti, near Kaavi	Myllykoski Oy	Sulfide ores	Ore from company mine
		France	
Sandouville, near Le Havre.	Soc. Métallurgique le Nickel (SLN).	Nickel matte	New Caledonian laterite mines
Pombliere Saint Marcel, Savoie.	Metaux Spéciaux S.A.	Concentrates, oxides, residues, scrap	---

Type of plant	Product	Annual capacity	Annual production	Comments
		Australia—continued		
Sherritt Gordon process refinery.	Cobalt salts?	125	---	Current production status of cobalt products uncertain.
		Belgium—continued		
Electrolytic	Cobalt oxide, salts, and metal powders.	8,400	---	---
		Brazil—continued		
Electrolytic plant at Sao Miquel Paulista (Sao Paulo).	Cobalt metal	1,000	---	Capacity relates to expansion plans scheduled for 1983.
		Canada—continued		
Refinery	Cobalt metal	900	800	Sherritt Gordon now custom refining for Amax following closure of company refinery.
------do.-------------------	------do.--------------------	900	800 (1983)	Electrolytic plant scheduled to begin separation in 1983.
Smelter and refinery	Cobalt oxide	---	---	---
Mill and refinery at Penn mill.	Cobalt products as byproduct to silver output.	---	25 (1981-83)	---
		China—continued		
Smelter and electrolytic refinery.	Cobalt metal	450	200 (1980–81)	---
		Finland—continued		
Smelter and refinery	Cobalt hydroxide	---	---	---
Refinery	Cobalt metal and salts	---	1,450 (1984)	---
Concentrator	Cobalt-nickel concentrates.	---	---	Cobalt content of concentrates low.
		France—continued		
Refinery	Cobalt chloride	600	358 (1983)	---
------do.-------------------	Cobalt metal	1,500 (cobalt products).	---	Refinery originally designed to treat Moroccan ore, the stockpile of which is now believed to be exhausted.

Site	Operator	Raw material	Origin of raw material
		German Federal Republic	
Duisburg	Duisburger Kupferhutte (owned by RTZ Ltd.).	Cobaltiferous pyrite sinter.	Imported
Oker, near Goslar	Hermann C. Starck	Cobalt catalyst residues, unrefined metal.	Various
		Japan	
Hitachi, Ibaraki prefecture.	Nippon Mining Co. Ltd.	Nickel matte, mixed sulfide.	Indonesia, Australia and other foreign sources.
Niihama	Sumitomo Metal Mining Co.	Mixed nickel cobalt sulfide concentrate.	Philippines
		Norway	
Kristiansand	Falconbridge Nikkelwerk A/S.	Nickel-copper matte	Material from company mines at Sudbury, Canada and custom material.
		South Africa	
Rustenburg, Transvaal	Rustenburg Platinum Mines Ltd.	Converter matte	Company sources
Springs, Transvaal	Impala Platinum Ltd.	------do.--------------------	Company mines in western Bushveld
		Soviet Union	
Khalilovsk, southern Urals.	---	Nickel concentrates	Southern Ural (Orsk) mines
Monchegorsk, Kola peninsula.	Pechenganickel	Sulfide ores	Local ore and ore shipped from Noril'sk.
Nadezhada, northern Siberia.	Noril'sk Metallurgical Combine.	------do.--------------------	Local
Pechenga, Kola peninsula.	Pechenganickel	------do.--------------------	Local ore
Rezh, northeast of Sverdlovsk.	Rezhevsk Nickel Smelter	Nickel concentrates	------do.------------------------------------
Ufaley, south-southwest of Sverdlovsk.	Ufaleisk Nickel Smelter	------do.--------------------	------do.------------------------------------
Ufaley region	Yuzhuralnickel	------do.--------------------	------do.------------------------------------
		United Kingdom	
Clydach, Wales	Inco Europe Ltd.	Laterite and sulfide matte.	Canada, Indonesia, Guatemala
		United States	
Braithwaite, Louisiana	Amax Inc.	Copper-nickel matte	Botswana, Australia, New Caledonia

from primary resources—Continued

Type of plant	Product	Annual capacity	Annual production	Comments
		German Federal Republic—continued		
Refinery	Cobalt metal	1,000	100 (1981)	Nonferrous metal production ceased 1982.
------do.--------------------	Cobalt metal, salts, oxide, and powder.	---	---	---
		Japan—continued		
Refinery	Fabricated products of cobalt.	1,200	835 (1983 estimate).	---
Smelter and refinery	Cobalt salts	1,600	587 (1983)	---
		Norway—continued		
Refinery	Cobalt metal	1,800	879 (1983)	---
		South Africa—continued		
Refinery	Cobalt sulfate	---	---	Refinery owned until 1983 by Matthey Rustenburg Refiners (Pty.) Ltd.
------do.--------------------	Cobalt metal powder	---	---	---
		Soviet Union—continued		
Smelter and refinery	Uncertain cobalt products.	---	---	---
------do.--------------------	------do.--------------------	---	---	---
------do.--------------------	------do.--------------------	500,000 (matte).	---	Mining outstrips refining capacity. Ore and matte also sent to Monchegorsk.
------do.--------------------	------do.--------------------	---	---	---
------do.--------------------	------do.--------------------	---	---	---
Smelter only?	------do.--------------------	---	---	---
Refinery	------do.--------------------	---	---	---
		United Kingdom—continued		
Refinery	Cobalt salts and oxide	---	200 (1982)	Production of salts ceased 1984.
		United States—continued		
Refinery	Cobalt metal	450	408 (1983)	Now closed. Sherritt Gordon (Canada) now custom refining for Amax.

TABLE 15.—*Cobalt production*

Site	Operator	Raw material	Origin of raw material
Zaire			
Luilu, Kolwezi	Gecamines	Copper-cobalt concentrates.	Kolwezi concentrates
Panda, Likasi	------do.--------------------	------do.--------------------	Various local
Shituru, Likasi	------do.--------------------	------do.--------------------	------do.-----------------------------------
Zambia			
Chambisi	Zambia Consolidated Copper Mines Ltd.	Copper-cobalt concentrates.	Concentrates from Chibuluma and Baluba mines.
Nkana	------do.--------------------	------do.--------------------	Various
Zimbabwe			
Bindura	Bindura Nickel Corp. Ltd.	Nickel sulfide concentrates.	Company mines Trojan, Epoch, and Madziwa mines and does custom milling for Shangani mine and, formerly, Empress mine.

from primary resources—Continued

Type of plant	Product	Annual capacity	Annual production	Comments
		Zaire—continued		
Electrolytic refinery	Cobalt pellets and cathodes.	10,000	5,200 (1981–83).	---
Electric arc smelter	White-metal alloy (copper-cobalt).	1,000	---	Alloys refined at Olen, Belgium. Cobalt production now suspended.
Smelter and refinery	Cobalt cathodes, pellets, and granules.	8,400	4,600 (1981–83).	---
		Zambia—continued		
Roast-leach-electrowinning.	Cobalt-metal cathodes	2,800	1,560 (1981–82).	Started 1978 with induction melting/vacuum refinery added 1982.
------do.--------------------	------do.--------------------	2,600	990 (1981-82)	Started 1982. Could expand to 5,000 metric tons.
		Zimbabwe—continued		
Smelter and electrolytic refinery	Cobalt metal?	100	62 (1982)	---

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