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U.S. GEOLOGICAL SURVEY CIRCULAR 930–M

International Strategic Minerals Inventory Summary Report—Niobium (Columbium) and Tantalum

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

Geologic Time Scale

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	

International Strategic Minerals Inventory Summary Report—Niobium (Columbium) and Tantalum

By Richard N. Crockett and David M. Sutphin

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FOREWORD

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

The report was prepared by Richard N. Crockett of the British Geological Survey (BGS) of the Natural Environment Research Council and David M. Sutphin of the U.S. Geological Survey (USGS). David G. Bate, BGS, provided bibliographic assistance, and the report was transcribed by Dorothy J. Manley, USGS. The niobium and tantalum inventory information was compiled by Richard N. Crockett, BGS, with assistance from Richard J. Fantel, U.S. Bureau of Mines (USBM). Inventory records were additionally supplied by David A. Buckingham, USBM; Ian S. McNaught, Australian Bureau of Resource Sciences (BRS); and D. MacRobbie and J. Lepinis, Energy, Mines & Resources, Canada (EMR), Mineral Policy Sector (MPS). Additional contributions to the report were made by David A. Buckingham, USBM; Theodore J. Armbrustmacher, USGS; Ian R. McLeod, BRS; David C. Findlay, EMR, Geological Survey of Canada; and Antony B.T. Werner, EMR, MPS.

Dallas L. Peck

Director

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INTERNATIONAL STRATEGIC MINERALS INVENTORY SUMMARY REPORT

NIOBIUM (COLUMBIUM) AND TANTALUM

By Richard N. Crockett[1] and David M. Sutphin[2]

Abstract

Major world resources of niobium and tantalum 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. Part I of this report presents an overview of the resources and potential supply of niobium and tantalum based on inventory information; Part II contains tables of both geologic and mineral-resource information and includes production data collected by ISMI participants.

Niobium is used principally as an alloying element in special steels and superalloys, and tantalum is used mainly in electronics. Minerals in the columbite-tantalite series are principal ore minerals of niobium and tantalum. Pyrochlore is a principal source of niobium. These minerals are found in carbonatite, certain rocks in alkaline igneous complexes, pegmatite, and placer deposits. ISMI estimates show that there are over 7 million metric tons of niobium and almost 0.5 million metric tons of tantalum in known deposits, outside of China and the former Soviet Union, for which reliable estimates have been made.

Brazilian deposits, followed by Canadian deposits, contain by far the largest source of niobium. Tantalum production is spread widely among several countries, and Brazil and Canada are the most significant of these producers. Brazil's position is further strengthened by potential byproduct columbite from tin mining. Present economically exploitable resources of niobium appear to be sufficient for the near future, but Brazil will continue to be the predominant world supplier of ferrocolumbium. Tantalum, a byproduct of tin production, has been captive to the fluctuations of that market, but resources in pegmatite in Canada and Australia make it likely that future increases in the present modest demand will be met.

PART I—OVERVIEW

INTRODUCTION

The reliability of future supplies of so-called strategic minerals is of concern to many nations. This widespread concern 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. They were 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 niobium and tantalum in a format designed to benefit 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 also be

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[1] British Geological Survey (Natural Environment Research Council).
[2] U.S. Geological Survey.

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 developments are not specifically addressed in this report. This report addresses only the primary stages in the supply process for niobium and tantalum and some considerations of niobium and tantalum 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. In general, the term relates to a nation's perception of vulnerability to supply disruptions, and its concern to safeguard its industries from the disruptions of a possible loss of supplies.

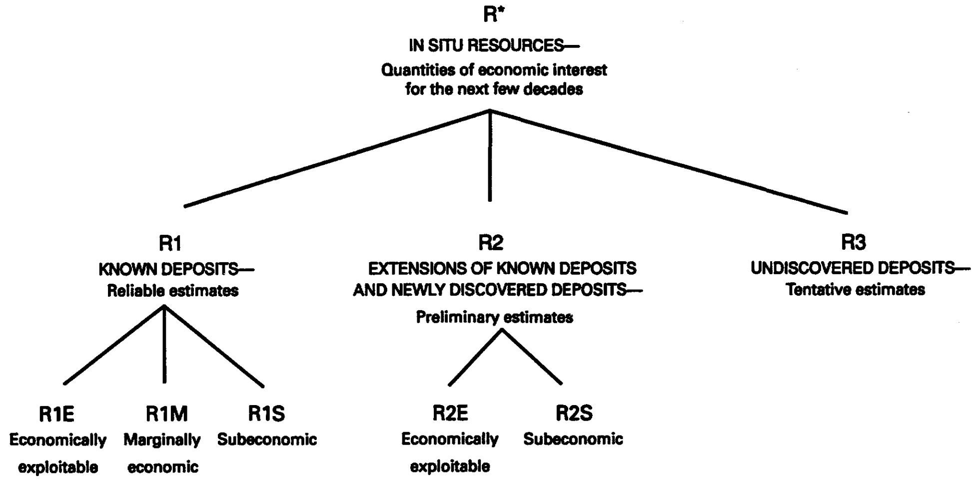
Because a mineral that is strategic to one country may not necessarily be strategic to another, no definitive list of strategic minerals can be prepared. The ISMI Working Group decided to commence with commodity studies on chromium, manganese, nickel, and phosphate. All of these studies, plus those of platinum-group metals, cobalt, titanium, graphite, lithium, tin, vanadium, and zirconium have now been published. Additional studies on niobium (columbium) and tantalum (this report), tungsten, and rare-earth oxides and yttrium have been subsequently undertaken. A regional survey of the strategic minerals of subequatorial Africa has been published, and a survey on eastern Europe is underway.

The data in the ISMI niobium and tantalum inventory were collected from January 1988 to January 1990. The report was submitted for review and publication in September 1991. The information used was the best available to the various agencies of the three countries that most directly participated in 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 of Canada and the Mineral Policy Sector of the Canadian Department of Energy, Mines & Resources; and the British Geological Survey, a component of the Natural Environment Research Council. Other ISMI participants from the Bureau of Resource Sciences of the Australian Department of Primary Industries and Energy; the Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany; and the Geological Survey and Minerals Bureau of the Department of Mineral and Energy Affairs of the Republic of South Africa have also assisted with later stages of production.

No geologic definition of a deposit or district is used for compiling records for this report. Deposits and districts are selected for the inventory on the basis of their present or expected future contribution to world supply. Records for all deposits compiled by ISMI participants meet this general "major deposit" criterion and are included in the inventory. No information is provided on deposits that were once significant but whose resources are now considered to have been depleted. In general, the term "ore" as used, for example, in the resources column of table 9 (Part II), refers to mineralized rock that contains an economic or subeconomic quantity of either or both niobium and tantalum in the form of minerals such as columbite, tantalite, or pyrochlore.

A special difficulty arises, however, in that most of the present world supply of tantalum, and formerly that of niobium as well, is a byproduct of tin production. Entries are not provided in tables 8 and 9 of Part II for deposits or districts primarily worked for tin, such as those in Nigeria, Malaysia, or Thailand, where niobium or tantalum are important byproducts of the beneficiation (processing to improve size distribution or grade) of tin ore. The extent of resources associated with such tin ores is either not known or not reported, and the amount of niobium or tantalum from such sources that reaches world markets follows the ups and downs of the tin industry and the fluctuating prices of tin. Further information on tin deposits from which niobium or tantalum are potential byproducts can be found in the ISMI summary report for tin (Sutphin and others, 1990). Production of, and trade in, niobium and tantalum arising as a byproduct of the beneficiation of tin ore or, in Southeast Asia, from the reprocessing of tin-smelting slags are, however, included as much as possible within other regional or national analyses contained within this report.

The ISMI record collection and this report on niobium and tantalum 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 United Nations (U.N.) resource classification used here. This report focuses on category R1, which includes reliable estimates of tonnages and grades of known deposits. The familiar term "reserves," which many would consider to



*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).

be equivalent to r1E or R1E has been interpreted inconsistently and thus has been deliberately avoided in the U.N. classification.

It should be noted that, generally, until a deposit has been extensively explored or mined, its size and grade are imperfectly defined. In many cases, deposit size will prove to be significantly larger, sometimes even several times larger, than was established when the decision to mine was made. Experts with a sound knowledge of a deposit and its geologic setting might infer that the deposit extends beyond the bounds reliably established up to that time. Tonnage estimates for such inferred extensions fall into category R2. For major deposits, ISMI records show R2 estimates in the few cases for which they are readily available. Category R3, postulated but undiscovered resources, is not dealt with in this report.

Not all companies or countries report resource data in the same way. In this report, all resource data are quoted as being in place. The proportion of ore extracted in the mining process, termed "mining recovery," depends on individual conditions and may vary considerably. However, most niobium and tantalum are produced from open pit mining where recovery from in-place ore may be about 75 to 90 percent. In the case of tin-bearing placer deposits from which some columbite or tantalite may be extracted, the recovery of unbeneficiated ore may be in excess of 90 percent. After mining, some part of the mineral content is likely to be lost in processing (concentration and separation stages). For placer deposits, this is generally not more than 5 percent, but the metallurgical recovery rates of hard-rock ore depend on grain size.

The World Bank economic classification of countries (World Bank, 1986, p. 180–181), which is based primarily on gross national product (GNP) per capita, has been used in other ISMI reports 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 and does not contain political bloc labels that might be perceived differently by different countries. Such a classification has not been attempted in this report since the concentration of resources and production in both commodities into a relatively small number of countries and, in the case of tantalum, the link with the fluctuating fortunes of the tin industry give such analyses little value.

BACKGROUND AND SUMMARY OF USES

Niobium and tantalum are relatively rare metallic elements and constitute, on average, only about 20 and 1.7 parts per million, respectively, of the material contained within the Earth's crust. Nevertheless, the crustal abundance of niobium is greater than that of some familiar metals such as lead and tin. Even tantalum is present at a geochemical concentration that is comparable to that of tin. Unlike these metals, however, ore deposits in which niobium- or tantalum-bearing minerals predominate are rare.

Niobium and tantalum occupy positions 41 and 73, respectively, in the periodic table of chemical elements.

Confusion has persisted for many years over the alternative names of niobium and columbium for element 41; niobium (Nb) is the preferred term in chemistry and most other sciences and was officially adopted by the International Union of Pure and Applied Chemistry in 1950. The term "columbium" is still used in metallurgy and mineral trades[3] (Parker and Adams, 1973, p. 443).

Uses of Niobium

The principal use of niobium is as an alloying element in high-strength, low-alloy (HSLA) steels and superalloys. HSLA's are so named because of their relatively high strengths that are obtained by the addition of less than 1 percent of alloying elements other than iron and manganese. There is widespread and increasing use of HSLA steels in oil and gas pipeline steels, in lighter and more fuel-efficient automobiles, and in major construction such as skyscrapers, bridges and nuclear reactors (Manker, 1981; Miller and others, 1986). Niobium is also used as a carbide stabilizer in stainless steels to improve their resistance to corrosion when used in exhaust manifolds, fire walls, and pressure vessels.

High-purity ferrocolumbium and nickel-niobium are gaining increasingly important applications as alloying elements in superalloys. Nickel-, cobalt-, and iron-based superalloys containing 1 to 5 percent niobium are used to make gas-turbine engine components, rocket-nozzle subassemblies, and heat-resistant combustion equipment (Cunningham, 1985a).

A possible new market for niobium is in the field of superconductors using specialized alloys with titanium (NbTi) or tin (Nb_3Sn). Superconducting magnets are used as accelerator magnets in high-energy physics research, in magnetic-confinement magnets for experimental work in controlled thermonuclear fusion, and for medical use in magnetic resonance imaging equipment (Gregory, 1984). Although current demand for superconducting materials is relatively low, continued research and development is expanding market applications and future demand may arise from magnetohydrodynamics, energy storage, superconduction transmission lines, and superconducting computers among others. At present, however, the prospects for expansion in demand for niobium in the field of superconductors has become somewhat uncertain following the discovery of rare-earth-element-bearing ceramic superconductors that promise more favorable performance characteristics.

Uses of Tantalum

In the United States, the electronics industry is responsible for about 60 percent of domestic tantalum consumption (Cunningham, 1985b). In Japan, a comparable figure of about 70 percent reflects the relatively greater importance of the manufacture of electronics to the economy of that country. The principal electronic use for tantalum is in capacitors; tantalum oxide has the highest known dielectric constant of any metallic oxide. Other electronic uses include rectifiers, amplifiers, oscillators, controls, signal devices, alarm systems, and timing devices in which the ability of tantalum to conduct alternating current in only one direction and the high electrical resistance of some tantalum alloys are utilized.

Tantalum carbide (TaC), alloyed with cemented carbides of metals such as tungsten, titanium, or niobium, and used in metalworking machinery, accounts for about 16 percent of U.S. consumption of tantalum.

A growth area in tantalum consumption in the United States is in aerospace and other transportation applications; 14 percent consumption was reported for this sector in 1983. Tantalum, with its high melting point of 2,996 °C, strength at elevated temperatures, and corrosion resistance, is combined with cobalt, iron, and nickel to produce refractory superalloys. Smaller amounts of tantalum are consumed in the manufacture of chemical process equipment, nuclear reactors, prosthetic devices, optical glass, laboratory equipment, and electroplating devices.

RECENT ASPECTS OF SUPPLY AND DEMAND

From the viewpoint of many market economy countries—notably the United States, most western European countries, and the industrialized countries of the Pacific rim—supplies of niobium and tantalum are strategic in the sense that a high proportion must be imported. Neither, however, are critical because substitutions are often possible, although with a cost or performance penalty.

Certain aspects of the recent history of niobium and tantalum supply and demand indicate the significant changes that are underway and deserve a more detailed assessment. For example:

- Figure 2 shows the significant change in the pattern of supply of niobium concentrates that has taken place in the last three decades. Nigeria was the main supplier

[3] This double name leads to ambiguities in the nomenclature of chemicals and minerals derived from this element. The niobium-rich ore mineral columbite is rarely given the name niobite even in those countries in which niobium is the element name in common usage. Columbite may be regarded conversely, in chemical terms, as a niobate (but rarely, or never, columbate) of iron or manganese.

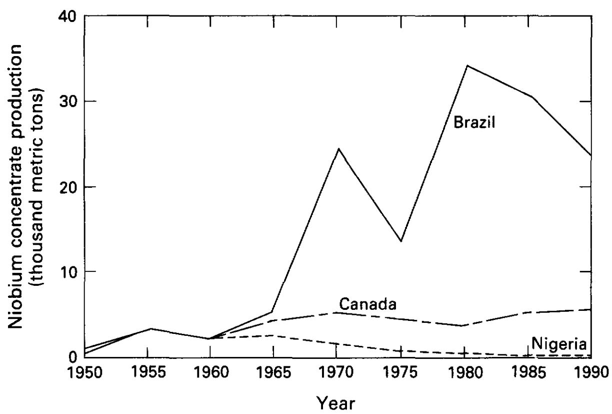


FIGURE 2. World mine production of niobium concentrate, for selected years 1950–90 (modified from U.S. Bureau of Mines, 1987, p. 75, with data from Cunningham, 1991, p. 17).

of the niobium requirement of market economy countries until the mid-1960's, but thereafter production in Nigeria declined significantly in comparison with that in Canada and, recently and more emphatically, in Brazil. At present, Western World niobium production is dominated by three producers that mine pyrochlore; the Araxá open pit in Minas Gerais, Brazil, the Catalão I open pit operation at Minerção Catalão de Goiás, Goiás state, also in Brazil, and the Niobec underground mine in Quebec Province, Canada. The Brazilian position is currently being further strengthened by the considerable potential for byproduct columbite output from tin mining in that country, particularly from the large Pitinga tin-dredging operation in Amazonas state. Although Pitinga as a tin producer is not included in the survey of niobium deposits in tables 8 and 9 in Part II, the U.S. Bureau of Mines reports the presence of at least 500,000 metric tons of Nb_2O_5 at that locality, and that estimate may be too small by a factor of three (Thorman and Drew, 1988).

- Work on other niobium prospects evaluated in recent years includes pilot-scale mining on the pyrochlore deposit at Lueshe, Zaire; design work for a laboratory-scale pilot plant to process complex ore from the Brockman rare-earth-element deposit in Western Australia; and the continuing examination of the Mount Weld carbonatite deposit, also in Western Australia. At a more advanced stage, a processing plant was commissioned in 1987 near São Paulo by the Brazilian group Paranapanema. By 1990, this plant was expected to produce 900 metric tons annually of mixed niobium and tantalum oxides (90 percent Nb_2O_5) derived as a byproduct output of ores from Pitinga.
- Other reports have appeared recently reporting the discovery of major new resources of niobium or tantalum at Motzfeldt in Greenland (Mining Journal, 1988; Jones, 1988a, p. 71) and Mabounie in Gabon (Laval and others, 1988). In neither case does there yet appear to have been any serious attempt at economic evaluation, so those deposits are not included in the ISMI niobium and tantalum inventory.
- The United States, while dominating world output of refined niobium products as opposed to steelmaking-grade ferrocolumbium, is facing increasing competition from Brazilian production of niobium oxide and superalloy-grade additives based on local ores. There is also increasingly aggressive competition from countries such as Japan, which, despite a lack of indigenous resources, are setting up their own processing facilities. Japan has previously imported most of its requirements for niobium metal and specialized alloys from the United States, but in 1986 Toho Titanium developed a process of chlorination and electron-beam melting to produce an anticipated annual output of 20 metric tons of niobium from ferrocolumbium.
- Prior to the acceptance of niobium as a major additive in special steels in the early 1960's, world demand for niobium was met by byproduct columbite concentrates from Nigerian tin production. Following the development of large deposits of pyrochlore, especially in Brazil, the contribution of tin-related byproduct columbite ores has become insignificant. While maintaining its position as a supplier of niobium ore mined in its own right, Brazil will contribute in the 1990's to a revival of niobium output associated with tin production following the startup of a niobium-tantalum processing operation based on concentrates from the Pitinga mine.
- In contrast to niobium, a significant proportion of world output of tantalum has always been associated with tin production. Tantalum can be recovered in any of three processes: concentrates can be produced along with those of tin from certain alluvial deposits; tantalum can be recovered from furnace slag at certain tin smelters; and tin-mining waste can be reprocessed to recover various minerals that can contain tantalum. The steep fall in tin prices following the financial collapse of the International Tin Council in October 1985 brought about an acceleration in the decline, already in evidence since 1980, of tantalum output associated with alluvial tin, particularly from Southeast Asian sources. Following the temporary peak in

tantalum prices experienced in 1979–80, commercial processors of tantalum concentrates and tantalum-rich slags had built up substantial inventories of raw materials, and thus the shortage of raw materials following the collapse of the tin price could be met by the run-down of such stocks. However, such stocks were considerably reduced by the end of 1987, and continuing weakness in the tin market will affect the tantalum supply position until well into the 1990's.

- Plans have been announced to rebuild the Thai niobium and tantalum processing plant that was destroyed by fire on June 23, 1986, just prior to commissioning.
- During the period 1986 to early 1989 when tin prices were exceptionally depressed, increasing demand for tantalum was met by enhanced output of tantalite from those few mines that either did not produce tin or that were able to sustain tantalite output even in the face of unfavorable market conditions for tin. The trend continues today. In particular, Greenbushes Ltd., in southwestern Western Australia, produces tantalite in concentrates as well as recovering tantalum oxide from high-grade slag derived from the company's tin smelter. Until recently, this output was won exclusively from a combination of surface alluvial mining and tailings retreatment, but now there is also a deep mine at Greenbushes, yet to be brought into production, that has a potential annual capacity of 160 metric tons (350,000 pounds) Ta_2O_5. Further resources at Greenbushes are accessible to hard-rock open-pit extraction, and production from this source is reported to have commenced in mid-1989. Further developments at Greenbushes are constrained, however, until a new grinding and crushing circuit is commissioned, at an estimated cost of A$6 million. In Canada, Tantalum Mining Corporation (Tanco), a non-tin producer, restarted tantalite production at Bernic Lake in Manitoba in August 1988; previous production ceased in 1982. In Minas Gerais, Brazil, Companhia de Estanho Brasil maintains a considerable output of tantalite despite the recent poor state of the tin market. An annual output of between 34 and 45 metric tons of tantalite is converted into oxide at a nearby chemical plant (Jones, 1988b, p. 96). It remains to be seen whether this diversification in tantalum supply will be maintained in the face of any recovery of the tin market after 1990.
- The People's Republic of China is reported to have an annual production base of approximately 100 to 200 metric tons Ta_2O_5 (Jones, 1989, p. C91), most of which is consumed internally. The two most significant sources are the Limu mine in Guangxi Province and the Yichun niobium-tantalum mine in Jiangxi Province (Werner, 1988). Yichun was reported to have been upgraded to treat 1,500 metric tons of ore per day during 1987, and foreign technical assistance was being sought to extend the output of tantalum powder at the Ningxia nonferrous metal smelter (Jones, 1988b, p. 97).
- Even less is known concerning the current levels of niobium and tantalum output in the former Soviet Union. Most production appears to be centered in the region of the major alkaline intrusive complexes of Lovozero in the Kola Peninsula and Vishnevogorsk in the middle Ural region.
- Both niobium and tantalum are held on the U.S. strategic stockpile. In 1988, the stockpile contained 1,368 metric tons of niobium in the form of concentrates (about 38 percent), ferrocolumbium (19 percent), metal (1.5 percent), and carbide (less than 1 percent); another 29 percent in concentrate and 11 percent in ferrocolumbium are designated as nonstockpile grade. Also in 1988, the tantalum stockpile contained 1,392 metric tons of tantalum in minerals (55 percent), metal (6.5 percent), carbide (1 percent), and nonstockpile-grade minerals (37.5 percent).
- In terms of world production, niobium and tantalum are low tonnage commodities, and the amount of tantalum that enters world trade is small, even relative to niobium. However, at 1989 price levels, the price of tantalum concentrates exceeds that of niobium approximately by a factor of ten. The change in the early 1960's from columbite to low-cost pyrochlore as the principal source of niobium, associated with the start of production from Araxá in Brazil, dampened the price growth for niobium despite a major growth in demand for it as a steel additive. In contrast, the tantalum price during the same period increased with the growth of the capacitor market and lately has expanded in response to the demand produced by the growth in the use of computers.

GEOLOGY AND MINERALOGY OF NIOBIUM AND TANTALUM

All of the minerals that include niobium and tantalum as economically important constituents can be regarded as multiple oxides or hydroxides in which the two elements are chemically combined with a variety of other metallic elements. The most important minerals from an economic point of view are those of the columbite-tantalite series, which is a source of both elements, and pyrochlore, which is the primary source of niobium.

Columbite ($(Fe,Mn)Nb_2O_6$) and tantalite ($(Fe,Mn)Ta_2O_6$) are similar in chemical composition and atomic structure as well as in minerals that have all degrees of intermediate composition from ferrocolumbite ($FeNb_2O_6$) and manganocolumbite ($(Mn,Fe)(Nb,Ta)_2O_6$) to ferrotantalite ($FeTa_2O_6$) and manganotantalite ($MnTa_2O_6$). Columbite-tantalite occurs mainly as an accessory mineral disseminated in granitic rocks or in pegmatites associated with granites. Economic mineral concentrations occur where, as in Nigeria or in Southeast Asia, weathering has led to residual or placer deposits or where, as in the Bernic Lake deposit in Canada, the pegmatites themselves contain a particularly high concentration of these minerals.

The other principal ore mineral is pyrochlore ($(Ca,Na)_2(Nb,Ta)_2O_6(O,OH,F)$). The ratio of niobium to tantalum in pyrochlore is about 200:1 or greater, and the mineral therefore has no importance as a source of tantalum. Pyrochlore is commonly found in rocks of alkaline igneous complexes, frequently in association with minerals of titanium, thorium, uranium, and rare earth elements. The pyrochlore deposits of Canada and Zaire occur in carbonatite and associated alkaline rocks. In Brazil, the occurrences are in eluvial deposits resulting from the weathering in place of carbonatites, which leaves an enriched concentration of magnetite, apatite, and bariopyrochlore (pandaite).

Other rarer minerals, of small or local economic importance, include pandaite $(Ba,Sr)_2(Nb,Ti)_2(O,OH)_7$, a barium-rich pyrochlore; loparite $(Ce,Na,Ca)_2(Ti,Nb)_2O_6$, the principal niobium mineral occurring in the Lovozero alkali rocks of the Kola Peninsula in the former Soviet Union; and ixiolite $(Ta,Nb,Sn,Fe,Mn)_4O_8$. Microlite is a tantalum-rich mineral analogous to pyrochlore, but, unlike the columbite-tantalite series, few mineral species having compositions intermediate between the pyrochlore and microlite end members have been recorded, and the characteristic occurrence of the latter is in the albitized zones of granite pegmatites and is often associated with tantalite or columbite. A titanium-bearing oxide, strüverite $(Ti,Ta,Fe)_3O_6$, is used as a low-grade source of tantalum that is recoverable from tin-mining wastes in Southeast Asia. Latrappite $(Ca,Na)(Nb,Ti,Fe)O_3$ is the main ore mineral at Oka, Quebec, Canada.

Prior to the 1970's, and because of the geochemical affinity between niobium and tantalum, concentrates from most sources contained mixtures of these elements. The upsurge in demand for niobium in the early 1970's was not matched by a corresponding trend in tantalum demand, and the extra requirement for the former was met by exploitation of pyrochlore, a mineral having negligible significance as a source of tantalum. This considerably reinforced the position of Brazil and Canada as world suppliers of niobium. In the 1980's, a modest resurgence in the production of mixed concentrates occurred, but Brazilian predominance is not challenged because that country's rapid emergence as the leading world supplier of tin has ensured that byproduct niobium-tantalum concentrates are in abundant supply.

MINING AND PROCESSING

Niobium Mining and Processing

Of the existing major pyrochlore mines, the Canadian Niobec is the only underground operation. Two other active Brazilian producers, as well as approximately 16 other properties that have been evaluated for possible production, employ or would employ open-pit mining. The only exception is the Lueshe deposit in Zaire where underground mining may commence after 5 or 6 years of surface mining.

Beneficiation of pyrochlore ore is carried out through crushing and grinding, magnetic separation, desliming (removal of extremely fine particles encountered in ore treatment), flotation, leaching, and calcining. Thereafter, the conversion of niobium-rich concentrates into alloys, metal, and compounds can be accomplished by various means. Generally, pyrochlore concentrates are now used to make ferrocolumbium, which is used principally in steelmaking but which can also be used as an intermediate step in the manufacture of high-purity ferrocolumbium, nickel niobium, and niobium metal.

In Brazil, Companhia Brasileira de Metalúrgia e Mineração makes steelmaking-grade ferrocolumbium in batches from pyrochlore concentrates using aluminum powder as a reductant in an exothermic reaction. The aluminothermic process involves the preparation of a charge consisting of a mixture of pyrochlore concentrate containing about 60 percent Nb_2O_5, iron oxide in the form of hematite (68 percent iron), and aluminum powder in the proportions 18:4:6, respectively. Smaller quantities of fluorspar and lime are added as a flux. A thoroughly mixed charge weighing about 30 metric tons is then ignited in a magnesite-lined steel cylinder. The reaction time is about 15 minutes during which temperatures of 2,400 °C are attained, and gangue material and impurities separate as slag from a ferrocolumbium "button." The normal grade of ferrocolumbium produced contains about 66 percent niobium. The process can, however, be adapted for the batch production of high-purity ferrocolumbium, nickel niobium, or metallic niobium. Process technology at Niobec is similar to that in Brazil except that ferrocolumbium containing 60 percent niobium is the assumed product (U.S. Bureau of Mines, 1987, p. 76).

Outside Brazil, other smaller producers of niobium, such as Shieldalloy at Newfield, N.J., principally use an electro-aluminothermic smelting process.

Tantalum Mining and Processing

In contrast to niobium, which currently is produced mainly from pyrochlore, mining developments associated with tantalum production usually depend upon the recovery of other products, generally tin but sometimes lithium, for economic viability. The nature of the concentrate from which tantalum is recovered may vary from a relatively pure tantalite to a concentrate that contains a considerable admixture of columbite that sometimes approaches a 50:50 niobium to tantalum ratio. The degree to which niobium is recovered from such mixed concentrates depends upon prevailing market prices.

Both alluvial and residual tin deposits, including tantalite, are mined either by primitive hand techniques or, in larger units, by hydraulic or dry open-pit methods. Pegmatites are mined by either underground or open-pit methods, operations that demand a higher degree of preliminary rock breaking and crushing than is the case for alluvial and residual deposits. Concentration is achieved by wet gravity methods followed by gravity, electrostatic, or electromagnetic separation from associated minerals.

A potentially important source of tantalum is slag produced at tin smelters (Jones, 1988b). The tantalum content of slags depends upon the nature of the original ore and upon smelting practice. Smelting of Bolivian tin ores, for example, produces no useful tantalum values. Material containing more than about 10 percent Ta_2O_5, produced principally from the Thaisarco smelter at Phuket, Thailand, can be processed directly for tantalum recovery, but slags produced at Penang, Malaysia, and Mamoré, Brazil, contain about 3 percent Ta_2O_5 and require further upgrading that may not be economic at times of low tantalum prices. As with tantalite concentrates, varying proportions of niobium may be recoverable.

Extraction of tantalum from mineral concentrates, slags, or other material is achieved by digestion with hydrofluoric acid followed by liquid-liquid extraction with methyl isobutyl ketone. The resultant fluotantalic acid solution is treated with potassium chloride or fluoride to precipitate potassium tantalum fluoride or, alternatively, with ammonia to produce pure tantalum pentoxide. Tantalum metal can be produced from the disassociation of potassium tantalum fluoride either by electrolysis when molten or by its reduction with molten sodium metal. Tantalum pentoxide is used for the manufacture of tantalum carbide by solid state reaction with carbon under vacuum or inert conditions at 1,600 °C (Cunningham, 1985b).

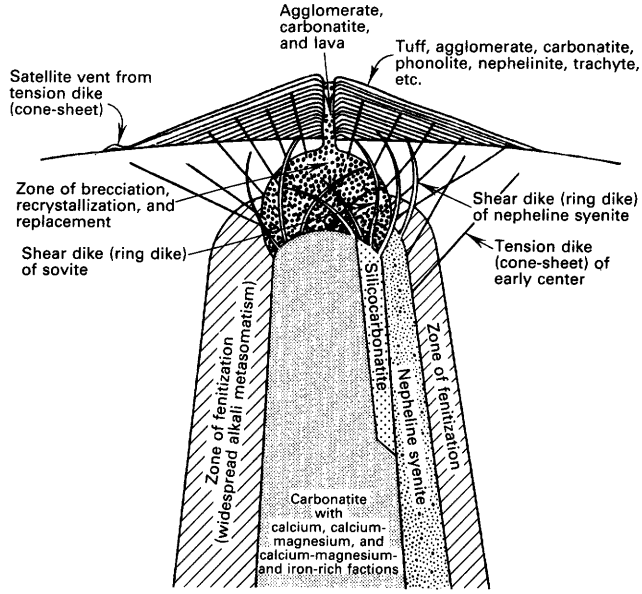


FIGURE 3. Schematic cross section through a carbonatite complex (from Krauss and others, 1982a, after Garson, 1966).

DISTRIBUTION OF NIOBIUM AND TANTALUM DEPOSITS

Carbonatites and Other Alkaline Igneous Deposits

Almost all of the 24 or so major niobium deposits identified in table 8 in Part II of this report are associated with the mineral pyrochlore, large concentrations of which are found in carbonatite or in other alkaline igneous or metamorphic rocks. Carbonatite—igneous rock composed primarily of calcium and (or) magnesium carbonate—is produced from plutonic activity, and many of the circular carbonatite complexes in which pyrochlore is found represent the deeply eroded roots of volcanoes from which the material was originally erupted (fig. 3). Carbonatite complexes can be common in the provinces in which they occur, but they are confined to a few geographic regions (fig. 4). Geographic groupings of carbonatites appear to be correlated broadly with rifting in parts of the otherwise stable shield areas of the Earth's crust.

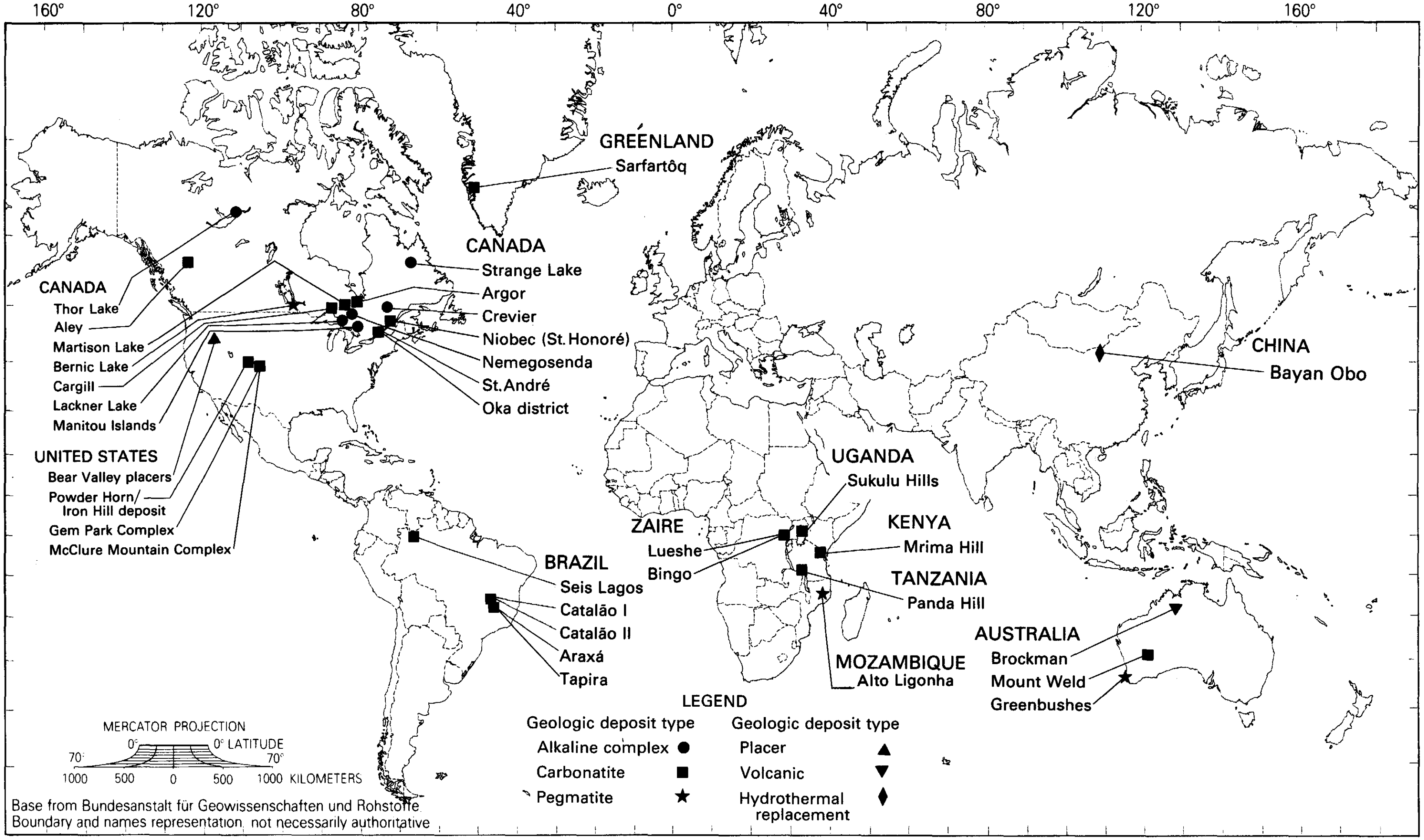


FIGURE 4. Location and geologic deposit type of the world's major niobium and tantalum deposits and districts. Locations and names are from tables 8 and 9 in Part II.

Alkaline igneous rocks and certain metamorphic equivalents are distinguished in that they tend to contain a higher proportion of the alkaline elements sodium and potassium compared with the average granitic composition of crustal rocks. Envelopes of alkaline rocks may surround carbonatite, but in other cases similar alkaline rocks may occur in zones that have carbonatite.

As few as four areally restricted provinces may be defined in which carbonatite and alkaline igneous rocks are not only present in some abundance but also contain significant pyrochlore mineralization (fig. 4). The Laurentian Highlands of the Canadian Shield between the St. Lawrence Valley and Hudson Bay and the southeastern Brazilian Shield within the states of Goiás and Minas Gerais at present produce virtually the entire Western World's output of niobium. A third carbonatite province in several conterminous countries of central Africa, and in close proximity to the Great Rift system, contains a number of pyrochlore deposits, but resource data are available only for the deposit at Lueshe in Zaire. At the northwestern extremity of the former Soviet Union, a continuation of the Baltic Shield is marked by the Kola Peninsula within which the Lovozero Complex (fig. 4), a major carbonatite and alkaline complex, probably supplies a large proportion of eastern Europe's requirement for niobium.

Outside these four provinces, scattered carbonatites, some of which have limited niobium resources, are known from certain localities and may be associated with somewhat more active tectonic zones around the margins of other large shields. Examples of this type occur in the southwestern United States and around the margins of the Siberian Shield in the former Soviet Union. As far as is known, the Vishnevogorsk deposit in the Ural Mountains is the only such deposit from which niobium is being produced.

Pegmatite Deposits and Tin Placers

Minerals within the columbite-tantalite series are common accessories in granitic rocks, but concentrations of economic interest are rare and are confined to certain pegmatites. Only a small proportion of world demand for niobium is met directly from such pegmatites, which are more important as a source of tantalum. Pegmatites at Bernic Lake in Manitoba, Canada, and at Greenbushes in Western Australia are mined principally for their tantalite content. The Alto Ligonha pegmatite in Mozambique may prove to be important in the future.

Indirectly, however, pegmatite is more significant as a source of columbite and tantalite. The larger proportion of Western World demand for tantalum, in particular, is not produced from pegmatite but as a valuable byproduct from the treatment of tin-bearing placer deposits located in Brazil and Southeast Asia that are in turn derived from the deep denudation of former pegmatite fields.

Although not strictly a geological occurrence, the link between tin and tantalum production is further reinforced by the recovery of tantalum from some tin-smelting slags—particularly in Southeast Asia. This intimate association with the tin industry and its fortunes means that most of the western supply of tantalum cannot be itemized in tables 8 and 9 in Part II. Apart from Asian tantalum of both placer and smelter origin, small quantities are also produced from tin-bearing placers in Nigeria and central Africa.

The status of tantalum production in the former Soviet Union and the People's Republic of China is less clear. It is uncertain whether pegmatites in these countries are worked specifically for tantalum or in association with other elements. Much of the Soviet Union's demand for tantalum may be met from pegmatite deposits within the Kola Peninsula—coincidentally, close to the main center of pyrochlore-based niobium production in that country. Although three pegmatite fields are identified in southern China, there is little information as to the contribution they make to that country's output; a substantial proportion may be recovered as a byproduct of tin-placer mining in the southwestern provinces.

NIOBIUM AND TANTALUM RESOURCES

Published data on which it might be possible to base world estimates of niobium and tantalum resources are, at best, fragmentary and incomplete. In general, accurate figures are available only from individual mines or prospects in Australia, Brazil, and Canada. Even in these three countries, there is no certainty that the collective total of such estimates approaches a realistic resource estimate for each nation as a whole. For most other countries where niobium and tantalum concentrates are produced, resource data are not published or have never been collected, particularly with respect to nations having centrally planned economies and certain others, such as Mozambique, that do not publish such data for niobium and tantalum.

Further complicating the assessment of resources is the fact that much of world demand for tantalum, and some for niobium, is met by the production of these elements as byproducts of tin mining and metallurgy. Because measuring and classifying niobium and tantalum resources that may exist within the tin sector in terms of either the U.N. classification or in parallel

TABLE 1.—*World niobium resources in 1989*

[Estimate of "reserves" is from unpublished data furnished by the U.S. Bureau of Mines unless otherwise noted. N.r., not reported. Figures are in metric tons of contained niobium]

Continent	Country	U.S. Bureau of Mines estimate of "reserves"	Total R1 estimates known to ISMI
North America	Canada	122,500	1,940,000
	Greenland	N.r.	500,000
	United States	[1]357,000	262,500
South America	Brazil	3,220,000	3,700,000
Africa	Gabon	N.r.	500,000
	Kenya	N.r.	240,000
	Nigeria[2]	63,500	N.r.
	Tanzania	N.r.	141,000
	Uganda	N.r.	182,000
	Zaire	31,700	32,000
Asia	Malaysia[2,3]	900	N.r.
	Soviet Union[3]	680,000	N.r.
	Thailand[2,3]	5,400	N.r.
Other economies			
Other market economies[4]		6,400	N.r.
Centrally planned economies		N.r.	N.r.
U.S. Bureau of Mines estimate of world total (excluding "uneconomic" U.S. total)			
(excluding Soviet Union)		3,747,000	
(including Soviet Union)		4,124,000	
World total of R1 resources reported in ISMI			7,497,500

[1] Considered an "uneconomic resource" by the U.S. Bureau of Mines.
[2] Byproduct of tin output; data not collected by ISMI.
[3] Unpublished update of figures previously published by the U.S. Bureau of Mines (Cunningham, 1985a).
[4] Cunningham (1990a, p. 51).

TABLE 2.—*World tantalum resources in 1989*

[Estimate of "reserves" is from unpublished data furnished by the U.S. Bureau of Mines unless otherwise noted. N.r., not reported. Figures are in metric tons of contained tantalum]

Continent	Country	U.S. Bureau of Mines estimates of "reserves"	Total R1 estimates known to ISMI
North America	Canada	1,800	5,000
	Greenland	N.r.	450,000
	United States	[1]1,500	N.r.
South America	Brazil	900	N.r.
Africa	Nigeria[2]	3,200	N.r.
	Zaire	1,800	
Asia	Malaysia[2,3]	900	N.r.
	Soviet Union[3]	4,500	N.r.
	Thailand[2,3]	7,300	N.r.
Australia		4,500	1,500
Other economies			
Other market economies[4]		1,400	N.r.
Centrally planned economies		N.r.	N.r.
U.S. Bureau of Mines estimate of world total (excluding "uneconomic" U.S. total)			
(excluding Soviet Union)		21,800	N.r.
(including Soviet Union)		26,300	N.r.
World total of R1 resources reported in ISMI			456,500

[1] Considered an "uneconomic resource" by the U.S. Bureau of Mines.
[2] Byproduct of tin output; data not collected by ISMI.
[3] Unpublished update of figures previously published by the U.S. Bureau of Mines (Cunningham, 1985b).
[4] Cunningham, (1990b, p. 171).

systems such as that adopted by the U.S. Bureau of Mines are difficult, little attempt has been made to do so.

In view of the incompleteness of published data concerning niobium and tantalum resources that are available to ISMI, tables 1 and 2 not only summarize such data but also include "reserves" (as well as "reserve base") information collected by the U.S. Bureau of Mines and published in the annual *Mineral Commodity Summaries*. This information represents a distillation of expert opinion within the Bureau.

Considerable caution should, however, be adopted in any line-by-line comparison of ISMI and U.S. Bureau of Mines estimates—not least because the incomplete R1 totals reported to ISMI have in some cases proved to be greater than the corresponding U.S. Bureau of Mines "reserves," which ostensibly embrace the total for the country concerned. Resources are shown for the major new discoveries in Motzfeldt, Greenland (tables 1 and 2), and in Mabounie, Gabon (table 1).

Niobium Resources

The total of R1 resources determined by ISMI for the two largest western niobium producers (table 1), Brazil and Canada, is somewhat greater than the corresponding reserves figure published by the U.S. Bureau of Mines. In Zaire, the Lueshe prospect appears to be the most promising pyrochlore deposit within the central African carbonatite belt. The U.S. Bureau of Mines statement of reserves for 1989 includes a figure for Nigeria that is not included within the definition of R1 resources recognized by ISMI since this figure represents a byproduct of that country's tin mining industry. However, for the sake of additional interest, separate figures for Malaysia and Thailand—also associated with tin production—previously published by the U.S. Bureau of Mines in 1985 are included. The world total of R1 resources determined by ISMI of over 7 million metric tons of contained niobium metal is considerably higher than the U.S. Bureau of Mines "reserves"[4] total of 3.75 million metric tons and is higher than the 4 million metric tons for "reserve base."[5] Closer agreement between the U.S. Bureau of Mines and ISMI totals is achieved if figures quoted by ISMI for Greenland, Gabon, Kenya, Tanzania, and Uganda are not accorded status even within "reserve base" by the U.S. Bureau of Mines; in view of the high degree of geological certainty of the existence of these deposits of niobium, however, it is hard to see how they can be properly accorded any status less than R1S (subeconomic known deposits) within the U.N. classification.

Tantalum Resources

Assessing the world resource position for tantalum (table 2) is more difficult than for niobium, and a comparison between U.S. Bureau of Mines and ISMI figures is harder to establish. ISMI data relate only to tantalum derived from pegmatite or similar deposits, whereas the U.S. Bureau of Mines assessment embraces estimates of the tantalum content of tin placers in several countries. Even so, the ISMI total for R1 resources far exceeds the U.S. Bureau of Mines "reserves" total for countries outside the former Soviet Union and China. As with niobium, however, the uncertain status of large resources in Greenland—possibly to be equated with R1S—has a distorting effect. If the Greenland figure is excluded from the ISMI total, the ISMI figure of 6,500 metric tons tantalum content in pegmatite deposits alone is compatible with the U.S. Bureau of Mines (1990) estimate of 21,800 metric tons covering both pegmatite and tin-placer deposits.

Figures 5 through 7 show the distribution of niobium and tantalum resources of the U.N. R1 category on a worldwide basis. The former Soviet Union and the People's Republic of China are, however, excluded owing to the complete lack of resource data. Despite a level of geologic knowledge of the Motzfeldt deposit that justifies inclusion within the R1 category, ISMI experts are not convinced that the measurement of resource tonnage has been undertaken with concomitant precision; therefore, Greenland totals included in tables 1 and 2 are not included in figures 5 to 7.

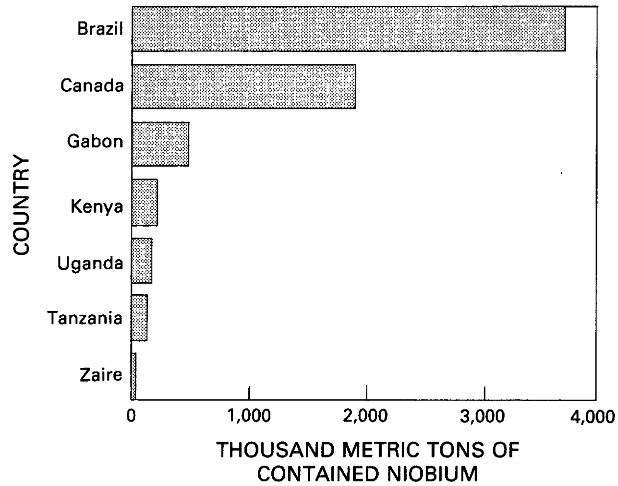


FIGURE 5. Distribution of world niobium resources in pyrochlore.

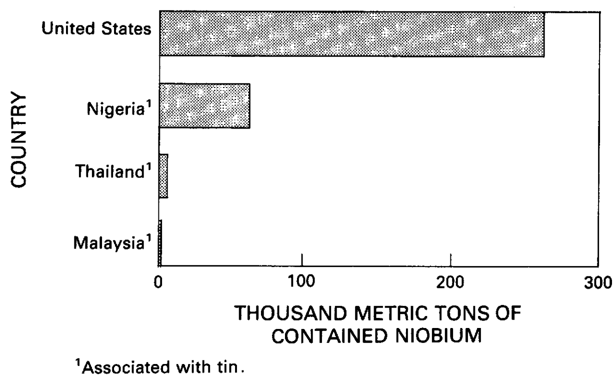


FIGURE 6. Distribution of world niobium resources in ores other than pyrochlore.

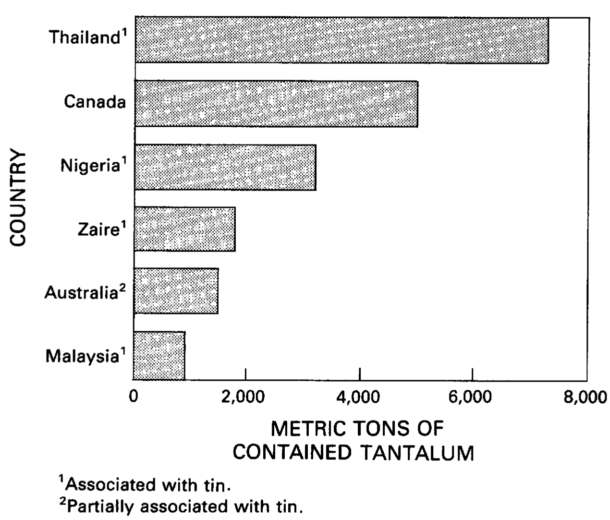


FIGURE 7. Distribution of world tantalum resources including an assessment of resources associated with tin placers.

[4] Reserves—That part of the reserve base that could be economically extracted or produced at the time of determination (from U.S. Bureau of Mines and U.S. Geological Survey, 1990, p. 195).

[5] Reserve base—That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth (from U.S. Bureau of Mines and U.S. Geological Survey, 1990, p. 195).

NIOBIUM AND TANTALUM PRODUCTION

Estimated cumulative production of niobium and tantalum contained in concentrates by country for the years 1971–87 is listed in table 3. For that period, Brazil was by far the largest producer of both niobium and tantalum followed by Canada for both elements. The reported world total in table 3 for both commodities indicates that niobium is produced in much greater amounts than tantalum and that tantalum production is less concentrated among a few countries than is niobium production.

Tables 4 and 5 show world production of, respectively, minerals other than pyrochlore used as a source of niobium or tantalum or both and pyrochlore used as a source of niobium only. For 1988, the total niobium content for all concentrates produced outside the former Soviet Union and China was almost 18,000 metric tons of which only about 1.2 percent originated from ores other than pyrochlore. About 15,200 metric tons (or 85 percent) of the 1988 production of niobium in concentrate was derived from Brazilian pyrochlore. In 1987, there was a temporary depression in world pyrochlore production; Brazil's output was half of its 1988 figure, but Brazil's contribution to world output of niobium in concentrate outside the Soviet Union and China was about 79.5 percent.

The volume of tantalum production in 1988 was far smaller than that of niobium (tables 4 and 5), and, although the data given in table 4 do not distinguish between tantalum-bearing concentrates produced as a primary product and those produced as a byproduct of tin-mining operations, total world output of tantalum in concentrate in 1988 was about 350 metric tons. No single country occupies a predominant position as a supplier of tantalum comparable to that of Brazil in the case of niobium (tables 3–5). The supply of non-pyrochlore concentrates from Spain, Namibia, Canada (from mine production or off stockpiles), Brazil, Thailand, and Australia is directed to tantalum rather than to niobium production. The output of concentrates from Spain and Namibia is negligible, but the other four countries, along with Malaysia, account for about 90 percent of the annual world production of tantalum in concentrate. Of these, Brazil and Thailand are the clear leaders with production in 1988 of about 187 and 78 metric tons, respectively.

A source of niobium and tantalum not included in tables 4 and 5 is metal recovered from the refining of tin slags. Output from this source is likely to be negligible in the case of niobium but is significant with respect to the limited amount of world output of tantalum. About 80 percent of tantalum from this source originates from three tin smelters in Southeast Asia—one in Thailand and two in Malaysia; the remainder are principally from smelters in South Africa and Zimbabwe. Figures provided by the Tantalum-Niobium International Study Center located in Brussels, Belgium (Jones, 1988b, p. 96), suggest that, for about 5 years prior to the collapse of the tin price in late 1985, annual production of tantalum from slags was between 300 and 450 metric tons thus considerably exceeding production from concentrates that were never more than 260 metric tons in the same period. Production of tantalum in concentrate estimated at 353 metric tons for 1988 (table 4) appears therefore to have remained more or less constant for several years. However, because of the downturn in the tin market, production from slags may be reduced to below that for concentrates.

World niobium and tantalum post-mill facilities (fig. 8) are located in countries, such as Australia, Brazil, and the United States, that have primary mine production of concentrates and in countries, such as the Federal Republic of Germany, Japan, and the United Kingdom, that rely on imports of concentrates. Statistics on ferrocolumbium production are not published on a systematic basis, and the British Geological Survey

TABLE 3.—*Estimated cumulative production of niobium and tantalum contained in concentrates, listed by country*

[Figures are in metric tons. Figures do not add to totals shown due to rounding. Figures in parentheses are percent of total. Source: U.S. Bureau of Mines, 1973–89]

Country	Cumulative production,[1] 1971–87			
	Niobium		Tantalum	
Brazil	151,816	(81.7)	1,499	(23.0)
Canada	27,392	(14.7)	1,290	(19.8)
Nigeria	4,344	(2.3)	621	(9.5)
Thailand	588	(0.3)	749	(11.5)
Australia	503	(0.3)	951	(14.6)
Zaire	328	(0.2)	335	(5.1)
Malaysia	295	(0.2)	97	(1.5)
Rwanda	223	(0.1)	150	(2.3)
Mozambique	134	(0.1)	460	(7.1)
Zimbabwe	81	(0.0)	212	(3.3)
Portugal	28	(0.0)	25	(0.4)
Namibia	12	(0.0)	13	(0.2)
Uganda	8	(0.0)	5	(0.1)
Argentina	4	(0.0)	5	(0.1)
South Africa	4	(0.0)	4	(0.1)
Burundi	2	(0.0)	2	(0.0)
Spain	0	(0.0)	88	(1.4)
Reported total	185,761	(100)	6,505	(100)

[1] China, the former Soviet Union, and Zambia are believed to have niobium and tantalum mineral-concentrate production.

TABLE 4.—*World production of ores and concentrates, other than pyrochlore, containing niobium and tantalum in 1988*

[Modified from British Geological Survey, 1990. N.r., not reported]

Country	Type of ore or concentrate	Estimated average content (in percent)		Mine production (in metric tons)	Estimated metal content (in metric tons)	
		Niobium	Tantalum		Niobium	Tantalum
Australia	Columbite-tantalite	20	33	[1]120	24.0	39.6
Brazil	Columbite-tantalite	20	30	622	124.4	186.6
Canada	Tantalite	3	30	37	1.1	11.1
Malaysia	Columbite	40	14	N.r. [2]	N.r.	N.r.
	Strüverite	N.r.	10	42	N.r.	4.2
Namibia	Tantalite	N.r.	14	7	N.r.	1.0
Nigeria	Columbite	43	6	50	21.5	3.0
Rwanda	Columbite-tantalite	30	23	7	2.1	1.6
Thailand	Columbite-tantalite	17	25	124	21.1	31.0
	Strüverite	N.r.	6	788	N.r.	47.3
Zaire	Columbite-tantalite	27	27	34	9.2	9.2
Zimbabwe	Columbite-tantalite	11	28	66	7.3	18.5
Total[3]				1,897	210.7	353.1

[1]British Geological Survey estimate based on 1987 production.

[2]Zero production recorded in 1988 is presumably the result of a cutback in tin output; 228 metric tons of niobium concentrate were produced in 1987.

[3]These totals exclude an unknown quantity of niobium and titanium concentrates produced in the former Soviet Union and the People's Republic of China. Minor amounts are believed to be produced intermittently in Argentina, Burundi, French Guiana, Portugal, Spain, and Zambia. No detailed information is available on the production of tantalum-bearing tin slags, but in recent years the major producers have been Malaysia and Thailand, and small amounts have come from Australia, Brazil, Nigeria, Portugal, South Africa, and Zaire.

TABLE 5.—*World production of pyrochlore concentrates in 1988*

[Modified from British Geological Survey, 1990]

Country	Mine production (in metric tons)	Niobium content (weight percent)	Estimated tonnage of niobium in concentrate (in metric tons)
Brazil	36,200	42	15,204
Canada	5,600	45	2,520
Total	41,800		17,724

(1990) is able to report regularly from primary sources those statistics with respect to only Brazil (19,106 metric tons), Japan (704 metric tons), and the reported world total (19,755 metric tons).[6] Brazil, by far the largest world producer of niobium in concentrate, dominates the production of steelmaking-grade ferrocolumbium. However, Canadian pyrochlore may be used as the basis for the production of this grade, principally in Japan and Luxembourg and somewhat in the United States. Most, but not all, of the remaining Western World production consists of specialist production of high-purity ferrocolumbium produced from niobium oxide. In the United States, Shieldalloy produces both standard and high-grade ferrocolumbium, and Cabot Corporation, Reading Alloys, and Teledyne Wah Chang Albany primarily produce high-purity grades. In Europe, Murex Ltd., in the United Kingdom, Gesellschaft für Elektrometallurgie (GfE) in the Federal Republic of Germany, and Continental Alloys of Luxembourg are the principal suppliers of ferrocolumbium, although not necessarily on a regular basis. Table 7 in Part II contains selected information on niobium and tantalum post-mill processing facilities.

[6] Production data for other countries are proprietary. European smelters, in particular, may produce ferrocolumbium only to special order. Apart from Japan, whose annual production of ferrocolumbium approached 2,000 metric tons for a time in the mid-1970's, no other country is believed to produce ferrocolumbium in excess of 1,000 metric tons per year, and the dominance of Brazil, especially in the production of steelmaking grades, is unchallenged.

NIOBIUM AND TANTALUM EXPORTS

Reports of the export of partially processed niobium and tantalum ores, concentrates, and tin slags from the United States, the United Kingdom, the Federal Republic of Germany, and Singapore are not significant in the context of world supply since these can be assumed to be re-exports (table 6). Canada is the biggest exporter of partially processed material other than ferrocolumbium (about 4,000 metric tons), and the bulk of this tonnage is niobium-rich concentrates derived from Niobec pyrochlore ore. The largest markets for Canadian pyrochlore in 1988 appear to have been the United States

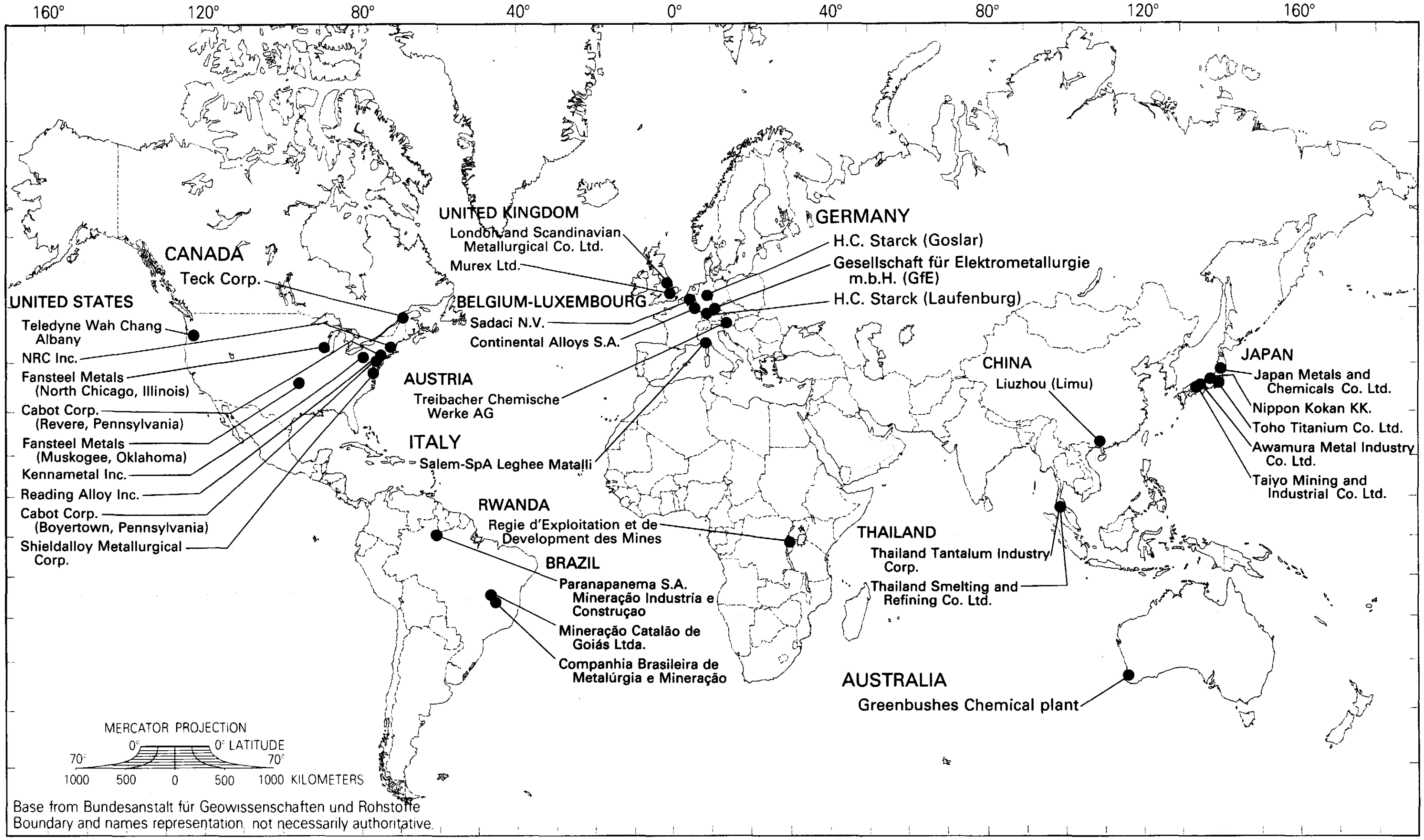


FIGURE 8. Location of major niobium and tantalum post-mill processing facilities. Locations and names are from table 7 in Part II.

TABLE 6.—*World exports of partially processed niobium and tantalum materials in 1988*

[Modified from British Geological Survey, 1990]

Country	Description of material in national trade return[1]	Exports (in metric tons)
Australia	Columbite-tantalite	208
Brazil	Columbite-tantalite	346
	Ferrocolumbium	14,352
Canada	Niobium and tantalum ores	4,000
Federal Republic of Germany.	Niobium and tantalum ores	95
	Ferrocolumbium	927
Malaysia	Columbite and tantalite	23
Nigeria	Columbite	[2]126
Singapore	Tantalum ores and concentrates (re-exports)	125
	Tin slags[3]	1,463
	Tin slags (re-exports)	690
Sweden	Ferrocolumbium	14
Thailand	Columbite and tantalite	243
	Tin slags[3]	[2]935
United Kingdom	Ferrocolumbium and ferrocolumbium-tantalum	486
United States	Tantalum ores and concentrates	97
Zaire	Columbite-tantalite	[2]119

[1] Official trade nomenclature varies from country to country, and the distinction between "ore" and "concentrate" may be applied inconsistently.

[2] Figure for 1987 (British Geological Survey, 1990).

[3] Estimates for concentrate from tin slags, primarily used for the recovery of tantalum values, are difficult to compare on a country by country basis. Slags originating in Thailand contain about 10 percent Ta_2O_5, for example, but slags of Malaysian origin contain considerably less Ta_2O_5.

(about 2,000 metric tons), Belgium and Luxembourg, and the Federal Republic of Germany, which probably share most of the remaining 2,000 metric tons. For the Federal Republic of Germany, Canada has replaced Brazil as principal supplier following the Brazilian decision in 1981 to ban exports of pyrochlore so as to increase exports of higher value ferrocolumbium (U.S. Bureau of Mines, 1987, p. 75). Until the early 1980's, the United States imported about 200 metric tons of niobium in concentrate from Nigeria—representing about 75 percent of Nigeria's output (Krauss and others, 1982a). The U.S. Bureau of Mines reports that such imports are now negligible, and the United States currently is dependent upon material derived from Canadian pyrochlore. Japan, the other major importer of niobium concentrates (1,300 metric tons in 1987), presumably uses nonpyrochlore material, principally of Southeast Asian origin.

Many countries export nonpyrochlore tantalum and niobium concentrates. Canada and Australia mine specifically for these concentrates; however, concentrates originating from African or Southeast Asian sources, in contrast, are derived as a byproduct of the tin industry. World trade in all such concentrates involves shipment of material whose value depends upon varying contents of niobium or tantalum or, usually, both. In most cases, however, niobium can be regarded as the byproduct within the concentrate because such material is valued mainly in terms of its tantalum content. Trade flow for partially processed tantalum is particularly difficult to determine in view of the inconsistency of individual countries' trade nomenclature. In volumetric terms, world trade in tantalum—not dependent on pyrochlore concentrates—is much less than that of niobium. A German study (Krauss and others, 1982b) suggests that Canadian tantalum concentrate is largely shipped to the United States. The remaining United States' requirement and also that of Western Europe is met from a mixture of Brazilian, African, Far Eastern, and Australian sources. The Japanese requirement appears to be met entirely from Far Eastern sources.

In the case of ferrocolumbium, Brazil is the only exporter of this commodity produced from locally mined ore; other, minor exports of ferrocolumbium originate from smelters in countries having no indigenous ore (table 6). Analysis of trade data made available to the British Geological Survey suggests that about 19,000 metric tons of ferrocolumbium and other materials produced by Brazil in 1988 was probably destined for the Federal Republic of Germany (4,000 metric tons), Italy (4,000 metric tons), the United States (4,500 metric tons), Japan (2,700 metric tons), and the United Kingdom (550 metric tons); the balance of 3,250 metric tons is harder to account for. A comparison of 1988 with 1980 export statistics (Krauss and others, 1982a, pl. 5), shows that about 1,000 metric tons is shipped to centrally planned economy countries, such as countries of the former Soviet Union. The remainder is sent to countries that make special steel grades.

CONCLUSIONS

Present economically viable resources of niobium appear to be more than sufficient to meet future demand. The concentration of ferrocolumbium production in Brazil, along with the location there of some of the largest deposits of pyrochlore, suggests that Brazil will continue to be a primary world supplier. Nevertheless, the ability of manufacturers of specialty steels to switch to ferrocolumbium production when necessary and the existence of large North American and African pyrochlore deposits having mining costs comparable to those of the Brazilian operations suggest that niobium is unlikely to become a critical material for industrially advanced nations.

The supply situation for tantalum is more complex. Much of world output of tantalum is as byproduct captive to tin production; during the 1980's, tantalum supply paralleled the ups and downs of the troubled tin market. Increased detachment from the tin market may come, however, from rising production from pegmatite sources in Canada and Australia and the potential for the development of similar deposits elsewhere. Therefore, supply difficulties will not constrain future increases in demand for tantalum.

PART II—SELECTED INVENTORY INFORMATION FOR NIOBIUM AND TANTALUM DEPOSITS AND DISTRICTS

Table 7 contains information on the world's niobium- and tantalum-producing facilities made available by the participating agencies. The information is primarily from publications of government agencies, such as the U.S. Bureau of Mines and the British Geological Survey, that report on mineral production and sources of mineral supply.

Tables 8 and 9 contain information from the International Strategic Minerals Inventory record forms for niobium and tantalum deposits and districts. Only selected items of information about the geology and location (table 8) and mineral production and resources (table 9) of the deposits are listed here; some of this information has been abbreviated.

Summary descriptions and data are presented in the tables 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.

Table 7.—*Selected information for niobium-*

Abbreviations used throughout this table include

Annual capacity includes some or all of the following items (separated by semicolons): annual capacity of material produced in metric tons; material produced; and year of capacity estimate.

Production includes some or all of the following items (separated by semicolons): amount in metric tons of material produced; material produced; and year of production.

—, not reported; t, metric tons

Producer	Latitude	Longitude	Plant type	Feed	Process
			AUSTRALIA		
Greenbushes Chemical plant (Western Australia).	33°50′S.	116°00′E.	—	Nb concentrates	Solvent extraction
			AUSTRIA		
Treibacher Chemische Werke AG (Seebach).	47°30′N.	14°30′E.	—	—	—
			BELGIUM-LUXEMBOURG		
Continental Alloys S.A. (CASA) (Dommeldange).	49°38′N.	06°09′E.	—	—	Thermit
Sadaci N.V. (Ghent, Belgium)	51°03′N.	03°43′E.	Electric furnace	—	—
			BRAZIL		
Companhia Brasileira de Metalúrgia e Mineração (Araxá).	19°35′S.	46°56′W.	Electron-beam furnace.	—	Aluminothermic reaction; proprietary chemical process.
Mineração Catalão de Goiás Ltda. (Catalão, Goiás).	18°11′S.	47°56′W.	—	—	Aluminothermic reaction
Paranapanema S.A. Mineração Industria e Construçao (Amazonas).	00°45′S.	60°W.	—	Nb concentrates	Solvent extraction
			CANADA		
Teck Corp. (St. Honoré, Quebec)	47°44′N.	69°08′W.	—	—	—
			CHINA		
Liuzhou (Limu) (Guangxi Province).	24°19′N.	109°24′E.	Smelter	—	—
			GERMANY		
Gesellschaft für Elektrometallurgie m.b.H. (GfE) (Nürnberg).	49°27′N.	11°05′E.	Smelter	Nb and Ta concentrates and tin slag.	Air furnaces, multiple heating roaster.
H.C. Starck (Goslar)	51°55′N.	10°25′E.	Chemistry and further processing.	Ta and Nb concentrates, Ta and Nb containing tin slag, Ta containing chemical residues, Ta scrap.	—
H.C. Starck (Laufenberg)	47°36′N.	08°04′E.	Smelter and tin slag chlorination.	....do........	—
			ITALY		
Salem-SpA Leghee Metalli (Genoa).	44°25′N.	08°57′E.	—	—	—

Annual capacity (metric tons)	Production (metric tons)	Comments	Reference
	AUSTRALIA—Continued		
150,000,000; tailings 100; tin 58.97; Ta_2O_5	21.9; Ta_2O_5; 1988 8.82; Nb_2O_5; 1988 21.95; Ta_2O_5 in Ta glass; 1988	Ta_2O_5 production is scheduled to be 290 metric tons per year by 1992.	Cunningham (1990c).
	AUSTRIA—Continued		
50; carbide products	—	A joint venture with Greenbushes of Australia to market niobium and tantalum carbide products.	Cunningham (1990c).
	BELGIUM-LUXEMBOURG—Continued		
Not definitely known. Capacity information on ferroalloy production believed to be at least 10,000 metric tons per year.	—	Ferrocolumbium is only one of several products, but plant has long-term contracts.	Cunningham (1985a).
Not stated for ferrocolumbium	—	Minor carbon production of ferro-columbium evident in 1985 but is believed not to be producing now. Principal products are molybdenum and ferromolybdenum.	Do.
	BRAZIL—Continued		
2,300; Nb_2O_5 23,000; ferrocolumbium	17,000; Nb_2O_5 16,200; ferrocolumbium 128; high-purity ferrocolumbium	Produced 85 percent of Brazil's ferrocolumbium in 1987.	Cunningham (1990c).
2,800; ferrocolumbium with 60–70 percent Nb.	2,700; ferrocolumbium	Produced 15 percent of Brazil's ferrocolumbium in 1987.	Ensminger (1989).
900; Nb_2O_5; 1987 90; Ta_2O_5; 1987	—	—	Cunningham (1989).
	CANADA—Continued		
—	2,900; Nb_2O_5; 1987 3,400; Nb_2O_5; 1986	—	Cunningham (1989).
	CHINA—Continued		
—	—	Niobium and tantalum are byproducts of tin smelting.	Werner (1988).
	GERMANY—Continued		
—	—	Produces niobium and tantalum metal and powder and capacitor-grade tantalum powder.	Cunningham (1985a).
—	—	Produces Ta and Nb compounds, oxide, metal powder, capacitor grade Ta powder, mill products (e.g., wire, sheets, etc.).	—
—	—	....do........	—
	ITALY—Continued		
500; ferrocolumbium	—	In 1986, sold to Liguria Gas; since then, no ferroalloy production has occurred.	Sexton and Calas (1988).

TABLE 7.—*Selected information for niobium-*

Producer	Latitude	Longitude	Plant type	Feed	Process
			JAPAN		
Awamura Metal Industry Co. Ltd. (Uji, Kyoto).	34°53′N.	135°48′E.	Submerged furnaces	—	Aluminothermic reaction
Japan Metals and Chemicals Co. Ltd. (Oguni, Yamagata).	38°04′N.	139°45′E.	—	—	—
Nippon Kokan KK. (Toyama and Niigata).	36°40′N.	137°11′E.	—	—	—
Taiyo Mining and Industrial Co. Ltd. (Ako City, Hyogo).	34°44′N.	134°22′E.	Thermit	—	—
Toho Titanium Co. Ltd. (Chigasaki, Kanagawa).	35°19′N.	139°22′E.	—	—	—
			RWANDA		
Regie d'Exploitation et de Development des Mines.	02°S.	30°E.	—	—	—
			THAILAND		
Thailand Smelting and Refining Co. Ltd. (Thaisarco) (Phuket).	07°53′N.	98°24′E.	Smelter	Tin concentrates	—
Thailand Tantalum Industry Corp. (TTIC) (Phuket).	07°55′N.	98°22′E.	"Chemical plant"	—	—
			UNITED KINGDOM		
London and Scandinavian Metallurgical Co. Ltd. (Rotherham, Yorkshire).	53°25′N.	01°20′W.	Approximately 20 furnaces of several types.	Nb_2O_5, Ta_2O_5	—
Murex Ltd. (Rainham, Essex)	51°21′N.	00°36′E.	Various types	Nb and Ta concentrates.	Aluminothermic reaction
			UNITED STATES		
Cabot Corp.(Boyertown, Pa.)	40°20′N.	75°38′W.	—	Ta and Nb ores	Concentrate-digesting solvent extraction.
Cabot Corp. (Revere, Pa.)	40°31′N.	75°10′W.	—	—	—
Fansteel Metals (Muskogee, Okla.)	35°45′N.	95°22′W.	Smelter	Ore	—
Fansteel Metals (North Chicago, Ill.).	40°50′N.	87°40′W.	Fabrication only	—	—
Kennametal Inc. (Latrobe, Pa.)	40°19′N.	79°24′W.	Vacuum furnace	—	Carbon reaction in a vacuum furnace.
NRC Inc. (Newton, Mass.)	42°21′N.	71°12′W.	Refinery	Columbite, tantalite	—
Reading Alloy Inc. (Robesonia, Pa.).	40°21′N.	76°08′W.	Aluminothermic smelter.	—	Metallothermic reduction of Nb_2O_5.
Shieldalloy Metallurgical Corp. (Newfield, N.J.).	39°32′N.	75°01′W.	—	—	Aluminothermic reaction
Teledyne Wah Chang Albany (Albany, Oreg.).	44°34′N.	123°00′W.	Refinery	—	....do........

Annual capacity (metric tons)	Production (metric tons)	Comments	Reference
		JAPAN—Continued	
300; 60–70 percent ferrocolumbium.	86; ferrocolumbium	—	Cunningham (1985a).
—	—	Principal product is ferrochromium. Ferrocolumbium production is minor.	Krauss and others (1982a); Cunningham (1985a).
—	—	Company mentioned in first edition of ferroalloy directory but not second (1988). Minor production of ferrocolumbium and several other ferroalloys.	Sexton and Calas (1988).
130; ferrocolumbium with 60–70 percent Nb.	130; ferrocolumbium	Small plant produces a variety of ferroalloys.	Sexton and Calas (1988).
50; Nb metal; 1986	—	Principal product is titanium sponge. Niobium metal from this plant is a minor product for superconducting magnet applications.	Cunningham (1987).
		RWANDA—Continued	
—	—	State mining corporation created to manage 20 mines.	Cunningham (1990c).
		THAILAND—Continued	
320; Ta in tin slags	—	Operated significantly under capacity in 1988.	Cunningham (1990c).
300; Ta_2O_5 300; Nb_2O_5	—	Construction delayed because of a delay in supplying the technology by Hermann C. Starck of Germany.	Wu (1989).
		UNITED KINGDOM—Continued	
Total capacity is approximately 25,000–30,000 metric tons per year of FeA, FeB, FeTi, FeV, Cr metal, Bats alloy, and melting base.	—	Output of ferrocolumbium may always be limited.	Krauss and others (1982a); Cunningham (1985a).
2,000; 60–70 percent Ni	—	Produces a variety of ferroalloys, other metals, and alloys.	Do.
		UNITED STATES—Continued	
—	—	Produces niobium and tantalum products	Cunningham (1990c).
—	—	Produces ferro- or nickel-columbium	Do.
—	—	Produces both niobium and tantalum products.	Do.
—	—	Produces tantalum and niobium rolled products and wire tube.	Do.
—	—	Produces niobium and tantalum carbide products.	Do.
—	—	Produces niobium and tantalum metal products.	Do.
—	—	Produces ferro- or nickel-columbium products.	—
—	—	Associated with London and Scandinavian Metallurgical Co. Ltd. of the United Kingdom.	—
—	—	Produces tantalum and several other metals.	Metal Bulletin Books Ltd. (1988).

TABLE 8.—*Selected geologic and location information from*

[Byproduct niobium and tantalum associated with tin products are not covered by this table; deposits, principally in centrally planned economy countries, for which ISMI data are inadequate also are omitted]

Host rock includes all or some of the following items (separated by semicolons): main host rock type; formation name; geologic age; geologic age-dating method; and host rock age.

Pleistocene	PLEIS	Cambrian	CAMB	Early	E
Cretaceous	CRET	Precambrian	PREC	Middle	M
Permian	PERM	Proterozoic	PROT	Late	L
Mississippian	MISS	Archean	ARCH		

Abbreviations used throughout this table include
- —, not reported on the ISMI record form
- Ma, Million years
- Ga, Thousand million years

Part A—Principal niobium mines and deposits

Site name	Latitude	Longitude	Deposit type	Host rock	Age of mineralization
			AUSTRALIA		
Brockman (Western Australia)	18°19′S.	127°46′E.	Volcanic	Volcanic; ARCH, EPROT.	EPROT
Mount Weld (Western Australia)	28°52′S.	22°32′E.	Carbonatite	Carbonatite; PROT (2.0 Ga).	PROT (2.0 Ga)
			BRAZIL		
Araxá (Minas Gerais)	19°35′S.	47°00′W.	Carbonatite	Quartzite; PREC	LCRET
Catalão I (Goiás)	18°08′S.	47°48′W.	....do........	Araxá Group	Unknown
Catalão II (Goiás)	18°08′S.	47°47′W.	....do........	....do........	....do........
Seis Lagos (Amazonas)	~00°S.	66°W.	....do........	Gneiss and migmatite; Guianese Complex.	—
Tapira (Minas Gerais)	19°53′S.	46°50′W.	....do........	Quartzite; Canastra Group; PREC.	—
			CANADA		
Aley (British Columbia)	56°27′N.	123°43′W.	Carbonatite	Carbonatite; MISS	MISS
Argor (Ontario)	50°50′N.	80°38′W.	....do........	Dolomite carbonatite; EPROT; K-Ar; 1,655 Ma.	EPROT; K-Ar; 1,655 Ma
Cargill (Ontario)	49°18′N.	82°49′W.	....do........	Carbonatites; Cargill Alkaline Complex; PREC; K-Ar; 1,745 Ma.	PREC; K-Ar; 1,745 Ma CRET
Crevier (Quebec)	49°29′N.	72°45′W.	Alkaline complex	Nepheline syenite; LPROT; K-Ar; 879 Ma.	LPROT; K-Ar; 879 Ma
Lackner Lake (Multi-Minerals) (Ontario).	47°47′N.	83°08′W.	....do........	Ijolite; MPROT; K-Ar; 1,090 Ma.	MPROT; K-Ar; 1,090 Ma
Manitou Islands (Ontario)	46°15′N.	79°35′W.	....do........	Fenite; LPROT-CAMB; K-Ar; 570 Ma.	LPROT-CAMB; K-Ar; 570 Ma
Martison Lake (Ontario)	50°19′N.	83°24′W.	Carbonatite	Residuum; CRET Carbonatite; PROT	PROT; CRET

ISMI records for niobium and tantalum deposits and districts

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

Aegirine	AGRN	Crandallite	CRND	Monazite	MNZT	Sphalerite	SPLR
Albite	ALBT	Dolomite	DLMT	Muscovite	MSCV	Spodumene	SPDM
Allanite	ALNT	Elpidite	ELDP	Narsarsukite	NRSR	Sulfides	SLPD
Amphibole	AMPB	Euxenite	EXNT	Nepheline	NPLN	Tantalite	TNLT
Ankerite	ANKR	Feldspar	FLDP	Niocalite	NOC	Thorite	THRT
Apatite	APTT	Fersmite	FRSM	Pandaite	PNDT	Titanite	TTNT
Arfvedsonite	AFVD	Fluorite	FLRT	Perovskite	PRVK	Tourmaline	TRML
Armstrongite	ARMS	Gadolinite	GDLN	Phlogopite	PLGP	Uraninite	URNN
Astrophyllite	ASPH	Garnet	GRNT	Plagioclase	PLGC	Vlasovite	VLSV
Barite	BRIT	Gittinsite	GTTN	Pyrite	PYRT	Wodginite	WDGN
Bastnaesite	BSNS	Goethite	GTHT	Pyrochlore	PCLR	Wollastonite	WLST
Beryl	BRYL	Hematite	HMTT	Pyroxene	PRXN	Zircon	ZRCN
Biotite	BOTT	Ilmenite	ILMN	Pyrrhotite	PYTT		
Calcite	CLCT	Kaolin	KOLN	Quartz	QRTZ		
Cassiterite	CSTR	Lepidolite	LPDL	Richterite	RCHT		
Catapleiite	CTPL	Magnetite	MGNT	Riebeckite	RBCK		
Chlorite	CLRT	Microcline	MCCL	Rutile	RUTL		
Clay	CLAY	Microlite	MCRL	Siderite	SDRT		
Columbite	CLMB	Monticellite	MNCL	Simpsonite	SMPS		

Part A—Principal niobium mines and deposits—Continued

Tectonic setting	Local environment	Principal mineral assemblages	References
	AUSTRALIA—Continued		
Geosynclinal sediments and volcanics marginal to mobile zone.	Stratabound mineralization in steeply dipping tuff-lava-sediment sequence.	CLMB, TNTL, PCLR, ZRCN, BSNS, CSTR, SPLR, FLRT, and others.	Roberts (1988).
Associated with Laverton tectonic zone imposed on greenstone-granite terrane.	Enrichment in residual zone over carbonatite body.	APTT, MGNT, ILMN, PCLR, MNZT	Willett and others (1988).
	BRAZIL—Continued		
—	—	—	—
—	—	—	Harben (1984).
—	—	—	—
—	—	SDRT, ANKR, DLMT, BRIT, GTHT, PYRT, Nb-RUTL.	Woolley (1987).
—	—	PCRL, PNDT	Do.
	CANADA—Continued		
Continental margin	Carbonatite-syenite complex intruding Cambrian to Devonian sedimentary rocks.	FRSM, PCLR, CLMB, DLMT, CLCT, APTT, CLRT, RUTL, AMPB, PYRT, rare earth carbonates.	Mader (1986).
Intracratonic	Carbonatite dike cutting Precambrian granulitic rocks of the Kapuskasing structural zone.	PCLR, CLMB, MGNT, HMTT, DLMT, APTT, RBCK, PLGC.	Fielder (1970).
Canadian Shield	Kapuskasing "High"	APTT; minor: GTHT, SDRT, MGNT, CRND; PYRT.	Sage (1988).
Intracratonic	Anorogenic alkaline intrusion emplaced in migmatitic metasedimentary rocks.	PCLR, ALBT, MCCL, NPLN, BOTT; Urano-PCLR, CLCT, BOTT.	Gagnon and Gendron (1981).
—	Alkaline complex emplaced in Archean granitic gneiss of the Kapuskasing structural zone.	PCLR, MGNT, APTT, PRXN, NPLN	Ferguson (1971).
Intracratonic	Alkaline stock emplaced in Proterozoic gneissic rocks.	PCLR, K-FLDP, PRXN, BOTT, CLCT, APTT, MGNT, PYRT, PYTT, URNN.	Do.
....do........	Proterozoic carbonatite complex emplaced in Archean metamorphic rocks.	PCLR, APTT, MGNT, GTHT, HMTT, CLAY, CLCT, DLMT, BSNS.	Do.

Table 8.—*Selected geologic and location information from*

Site name	Latitude	Longitude	Deposit type	Host rock	Age of mineralization
			CANADA—Continued		
Nemegosenda (Ontario)	48°01′N.	83°05′W.	Alkaline complex	Fenitized gneiss; ARCH. Syenite; MPROT; Rb-Sr; 1,015 ± 63 Ma.	MPROT
Niobec (St. Honoré) (Quebec)	48°32′N.	71°10′W.	Carbonatite	Carbonatite; LPROT; K-Ar; 650 Ma.	—
Oka district (Quebec)	45°30′N.	74°02′W.	....do........	Sovite; CRET; K-Ar; 116 ±4 Ma.	CRET; K-Ar; 116 ± 4 Ma
St. André (Quebec)	45°34′N.	74°17′W.	....do........	Carbonatite; CRET	—
Strange Lake (Newfoundland)	56°19′N.	64°07′W.	Alkaline complex	Altered peralkaline granite; MPROT; K-Ar; 1,270 ± 30 Ma.	MPROT
Thor Lake (Northwest Territories)	62°06′N.	112°36′W.	....do........	Syenite; EPROT; U-Pb; 2,094 ± 10 Ma.	EPROT; U-Pb; 2,094 ± 10 Ma
			CHINA		
Bayan Obo (Inner Mongolia)	41°45′N.	110°E.	Hydrothermal replacement.	Dolomite; Y8 (MPROT). Dolomite; MPROT	Pre-PERM
			GREENLAND		
Sarfartôq (West Greenland)	66°30′N.	51°15′W.	Carbonatite	Granulites; ARCH Gneiss; PROT	LPROT; 600 Ma
			KENYA		
Mrima Hill	04°30′S.	39°16′E.	Carbonatite	—	—
			TANZANIA		
Panda Hill (Mbeya)	08°59′S.	33°14′E.	Carbonatite	—	—
			UGANDA		
Sukulu Hills (Buganda)	00°29′N.	33°12′E.	Carbonatite	—	—
			UNITED STATES		
Bear Valley placers (Idaho)	44°21′N.	115°24′W.	Placer	Black sands derived from Idaho batholith; PREC.	PLEIS
Gem Park Complex (Colorado)	38°15′N.	105°32′W.	Carbonatite dikes	Igneous rocks and carbonatites. Precambrian metamorphic rocks.	CAMB
McClure Mountain Complex (Colorado).	38°21′N.	105°28′W.	Carbonatite	Syenite and ijolite; CAMB; 535 ± 5 Ma. Gneiss and amphibolite; PROT; 1.6–2.5 Ga.	CAMB (about 520 Ma)
Powder Horn/Iron Hill deposit (Colorado).	38°16′N.	107°03′W.	....do........	Carbonatite plug into pyroxenites.	PREC

Tectonic setting	Local environment	Principal mineral assemblages	References
		CANADA—Continued	
Intracratonic	Anorogenic alkalic complex emplaced in gneissic rocks of the Kapuskasing structural zone.	PCLR, PRXN, APTT, MGNT, WLST, GRNT.	Ferguson (1971).
Intracratonic; Saguenay rift zone.	Carbonatite and related alkaline rocks that have intruded Proterozoic metamorphic rocks.	PCLR, CLMB, APTT, BOTT, MGNT, DLMT, CLCT, PRXN, ZRCN, HMTT, PYRT, PYTT.	Gagnon and Gendron (1981); Vallée and Dubuc (1970).
Intracratonic; St. Lawrence Valley rift system.	Carbonatite and related alkaline rocks emplaced in Proterozoic gneiss.	PCLR, APTT, PRXN, BOTT, MGNT, MNCL, PRVK, RCHT, NOC.	Gold and others (1967).
....do........	Carbonatite emplaced in granitic rocks.	PCLR, FLRT	—
Intracratonic	Anorogenic peralkaline granite emplaced in Proterozoic gneissic granitoid rock.	GTTN, ELDP, VLSV, CTPL, ARMS, NRSR, ASPH, ZRCN, PCLR, FLRT, BSNS, HMTT, MNZT, AGRN, RBCK, ALBT, SDRT, TTNT, GDLN, ALNT, THRT, SLPD.	Unpublished data.
Intracratonic	Anorogenic Proterozoic alkaline complex emplaced in Archean granitic and metasedimentary rocks.	CLMB, BSNS, ALNT, ZRCN, MNZT, AMPB, BOTT, K-FLDP, ALBT, MGNT, FLRT.	Trueman and others (1988).
		CHINA—Continued	
Intracontinental rifting (800 Ma).	Hydrothermal replacement near the top of a system associated with an unexposed alkaline-carbonatite pluton.	MGNT, HMTT, FLRT, MNZT, BSNS, PLGP, DLMT.	Drew and others (1990).
		GREENLAND—Continued	
Zone of weakness in Precambrian shield.	Hydrothermal activity gave rise to several phases of mineralization in veins and shear zones.	PCLR, ZRCN, Nb-RUTL, DLMT-ANKR, APTT, PLGP, RCHT-AFVD, MGNT.	Woolley (1987).
		KENYA—Continued	
—	—	PCLR, PNDT, MNZT	—
		TANZANIA—Continued	
—	—	—	—
		UGANDA—Continued	
—	—	—	—
		UNITED STATES—Continued	
—	—	ILMN, MGNT, GRNT, TTNT, MNZT, ZRCN, CLMB, EXNT.	Savage (1961).
—	—	—	Woolley (1987).
—	Intruded into Proterozoic metamorphic rocks.	Ti-MGNT, BSNS, MNZT	Do.
—	—	DLMT, ANKR, SDRT, CLCT, PCLR, APTT, MGNT, ILMN, HMTT, GTHT, PYRT, RUTL, ZRCN, MNZT, FLRT, BOTT, BRIT.	Staatz and others (1979).

TABLE 8.—*Selected geologic and location information from*

Site name	Latitude	Longitude	Deposit type	Host rock	Age of mineralization
			ZAIRE		
Bingo (Upper Zaire)	00°32′N.	29°19′E.	Carbonatite	Pyrochlore carbonatite.	—
Lueshe (Kivu)	01°00′S.	29°00′E.	....do........	....do........	—

Part B—Principal tantalum mines and deposits

Site name	Latitude	Longitude	Deposit type	Host rock	Age of mineralization
			AUSTRALIA		
Greenbushes (Western Australia)	33°50′S.	115°59′E.	Pegmatite	Pegmatite; ARCH	ARCH; 2.53 Ga
			CANADA		
Bernic Lake (Manitoba)	50°26′N.	95°27′W.	Pegmatite	Albitic aplite; ARCH	ARCH
			MOZAMBIQUE		
Alto Ligonha (Zambézia)	15°45′S.	38°15′E.	Pegmatite	CRET	—

ISMI records for niobium and tantalum deposits and districts—Continued

Tectonic setting	Local environment	Principal mineral assemblages	References
ZAIRE—Continued			
—	—	—	—
—	—	—	—

Part B—Principal tantalum mines and deposits—Continued

Tectonic setting	Local environment	Principal mineral assemblages	References
AUSTRALIA—Continued			
Metamorphosed sediments and mafic volcanics.	Emplacement of rare-earth-bearing pegmatites during shearing and metamorphism.	CSTR, TNTL, SPDM, BRYL, KOLN, stibio-TNTL.	Blockley (1980).
CANADA—Continued			
Bird River greenstone belt	Internal zones within a complex pegmatite body.	WDGN, SMPS, MCRL, TNTL, ALBT, QRTZ, MSCV, APTT, TRML, MCCL, CSTR, ILMN, ZRCN, SPDM, LPDL, SLPD.	—
MOZAMBIQUE—Continued			
—	—	—	—

TABLE 9.—*Selected production and mineral-resource information*

[Byproduct niobium and tantalum associated with tin production are not covered by this table; deposits, principally in centrally planned economy countries, for which ISMI data are inadequate also are omitted]

Abbreviations used throughout this table include
- —, not reported on the ISMI record form
- t, metric tons
- REE, rare earth elements; REO, rare earth oxides
- conc, concentrate
- kg/t, kilograms per metric ton

Part A—Principal niobium mines and deposits

Site name	Year of discovery	Year of first production	Mining method	Elements and minerals of economic interest	Annual production (in 1,000 t)
				AUSTRALIA	
Brockman (Western Australia).	1973	None	N	Nb, Ta, Y, Zr, Hf, Ga, REE.	—
Mount Weld (Western Australia).	1973	None	N	Nb, REE, Ta, P, Y	—
				BRAZIL	
Araxá mine (Minas Gerais)	1954	1961	S	Nb	Ore: 3,350; 2.5 percent Nb_2O_5; 1984; Acc Leach conc: 0.14; 60.0 percent Nb_2O_5; 1984; Acc Fe-Nb conc: amount not published; 66.0 percent Nb_2O_5; 1984.
Catalão I (Goiás)	1894	1976	S	Nb	Ore: 1.6; Nb grade not available; 1985; Acc
Catalão II (Goiás)	1894	1985	S	Nb	Ore: 1.1; Nb-Ta grade not available; 1985; Est
Seis Lagos (Amazonas)	—	—	—	—	—
Tapira (Minas Gerais)	—	—	—	—	—
				CANADA	
Aley (British Columbia)	1980	None	N	Nb, REE	—
Argor (Ontario)	1960	None	N	Nb	—
Cargill (Ontario)	1975	None	N	Nb, P	—
Crevier (Quebec)	1981	None	N	Nb, Ta	—
Lackner Lake (Multi-Minerals) (Ontario).	1954	None	N	Nb, Fe, P, U, REE	—
Manitou Islands (Ontario)	1952	1954	U	Nb, U, P	—

from ISMI records for niobium and tantalum deposits and districts

Abbreviations for *mining method* are S, surface; U, underground; N, not yet producing.

Annual production and *cumulative production* figures are reported as ore or concentrate. The descriptors that follow are separated by semicolons and, in order, are annual and cumulative production in thousand metric tons; grade of reported material; year of reported production; and (where reported) accurate (Acc) or estimated (Est). Years for reported cumulative production are in parentheses.

Resources includes, for various resource categories, some or all of the following items (separated by semicolons): ore or other reported category; resource in thousand metric tons; U.N. resource classification (see fig. 1; United Nations Economic and Social Council, 1979; Schanz, 1980); grades of one or more commodities; and year of estimate.

Part A—Principal niobium mines and deposits—Continued

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
	AUSTRALIA—Continued	
—	Ore: 4,290; R1E; 0.44 percent Nb_2O_5; 0.027 percent Ta_2O_5, 0.124 percent Y_2O_3, 1.04 percent ZrO_2, 0.011 percent Ga; 1985. Ore: 5,000; R1E; 0.44 percent Nb_2O_5; 0.027 percent Ta_2O_5, 0.124 percent Y_2O_3, 1.04 percent ZrO_2, 0.011 percent Ga, 0.035 percent Hf, 0.09 percent REO; 1986.	—
—	Ore: 7,400; 9.4 percent REO (5 percent cutoff); 1988 Ore: 6,100; 0.33 percent Y_2O_3 (0.33 percent cutoff); 1988 Ore: 22,800; 1.86 percent Nb_2O_5 (1 percent cutoff); 1988 Ore: 2,200; 0.0999 percent Ta_2O_5 (0.05 percent cutoff); 1988 Ore: 250,000; 18 percent P_2O_5 (10 percent cutoff); 1988 Ore: 39,000; 2.5 percent CeO, 1.36 percent LaO, 0.12 percent Y_2O_5; 1988 Ore: 273,000; 0.9 percent Nb_2O_5; 1988 Ore: 145,000; 0.34 percent Ta_2O_5; 1988	Future startup dependent on viability of several commodities. The resources reported are a mixture of various resource categories within the U.N. classification.
	BRAZIL—Continued	
—	Ore: 131,612; R1E; 2.5 percent Nb_2O_5; 1979 Ore: 288,335; R2E; 2.5 percent Nb_2O_5; 1979	—
—	Ore: 10,000; 1.3 percent Nb_2O_5; 1984	—
—	No data published	—
—	—	Deposit has 230 m of unconsolidated cover.
—	Ore: 60,000; 1.5 percent Nb_2O_5; 1976	Substantial apatite and anatase resources occur at this deposit.
	CANADA—Continued	
—	No data published	—
—	Ore: 50,000; 0.52 percent Nb_2O_5; 1970	—
—	Ore: 56,700; R1M; 20 percent P_2O_5; 1976 Ore: 7,600; R1M; 31.4 percent P_2O_5; 1987 Ore: >900; R1S; 0.015 percent U_3O_8; 0.07 percent Nb_2O_5; 1 percent REE; 1977.	Ore is residual capping on carbonatite. The carbonatite is not ore.
—	Ore: 15,200; R1S; 0.189 percent Nb_2O_5, 0.02 percent Ta_2O_5; 1981	—
—	Ore: 33,566; R1S; 0.198 percent Nb_2O_5, 21.3 percent apatite, 13.7 percent magnetite; 1968. Ore: 4,558; R1S; 0.173 percent Nb_2O_5, 21.9 percent apatite, 69.6 percent magnetite; 1968. Ore: 45,360; R1S; 0.26 percent Nb_2O_5; 1968 Ore: 798; R1S; 0.9 percent Nb_2O_5; 1968 Ore: 689; R1S; 0.23 percent Nb_2O_5; 1968	—
—	Ore: 3,262; R1S; 0.67 percent Nb_2O_5, 0.032 percent U_3O_8; 1973	Uranian pyrochlore is concentrated in steeply dipping shoots 6 to 18 m wide.

Table 9.—*Selected production and mineral-resource information*

Site name	Year of discovery	Year of first production	Mining method	Elements and minerals of economic interest	Annual production (in 1,000 t)
			CANADA—Continued		
Martison Lake (Ontario)	1980	None	N	Nb, P	—
Nemegosenda (Ontario)	1956	None	N	Nb, U, Th, REE, Zr, P, Fe.	—
Niobec (St. Honoré) (Quebec).	1969	1976	U	Nb, REE, P	Ore: 762; 0.66 percent Nb_2O_5; 1987
Oka district (Quebec)	1956	1961	S, U	Nb	—
St. André (Quebec)	1969	None	N	Nb	—
Strange Lake (Newfoundland).	1980	None	N	Nb, Zr, Y, Be, REE	—
Thor Lake (Northwest Territories).	1979	None	N	Nb, Ta, Zr, Y, Be	—
			CHINA		
Bayan Obo (Inner Mongolia).	—	1957 (Fe, REE).	S	Fe, REE, Nb	Ore: 7,000; Fe ore; 1987; Est REE conc: 15; REE; 1987; Est
			GREENLAND		
Sarfartôq (West Greenland)	—	None	N	Nb, REE, U, P	—
			KENYA		
Mrima Hill	1934	None	N	Nb, Th, Ba, Ta, Ti, P.	—
			TANZANIA		
Panda Hill (Mbeya)	1950	None	N	Nb, REE, U, Th, Ti, Ta.	—
			UGANDA		
Sukulu Hills (Buganda)	1939	1964	S	Nb, P	—
			UNITED STATES		
Bear Valley placers (Idaho).	1950	1954	N	Nb, U, Ta, Ti, Zr, REE.	Ore: 23; estimated capacity only. Some production (possibly from stockpile) until 1959.
Gem Park Complex (Colorado).	1880	—	N	Nb, REE, Th, U, Sr, P, Ba, Mo.	Ore: 3; estimated capacity only
McClure Mountain Complex (Colorado).	1963	—	N	Th, Nb, U, REE	—
Powder Horn/Iron Hill deposit (Colorado).	1880	—	N	Nb, U, Th, REE, P, Ba, Ta, Ti, mica.	—

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
	CANADA—Continued	
—	Ore: 140,000; R1S; 0.35 percent Nb_2O_5, 20 percent P_2O_5; 1983 Ore: 57,000; R1S; 0.4 percent Nb_2O_5, 23 percent P_2O_5, 0.4 percent REO; 1984.	—
—	Ore: 18,144; R1S; 0.47 percent Nb_2O_5; 1956	—
Conc; 52; (1961–68)	Ore: 12,260; R1E; 0.656 percent Nb_2O_5; 1988	—
Conc; 10; 0.306 percent Nb_2O_5; (1961–70).	Ore: 23,193; R1M; 0.44 percent Nb_2O_5; 1974 Ore: 15,785; R1S; 0.3–0.4 percent Nb_2O_5 Ore: 96,620; R1S; 0.26 percent Nb_2O_5 Ore: 20,412; R1S; 0.4–0.5 percent Nb_2O_5, 0.2–0.5 percent REO, 0.06 percent ThO_2. Ore: 27,216; R1S; 0.6 percent Nb_2O_5 Ore: 22,680; R1S; 0.35 percent Nb_2O_5 Ore: 3,447; R1S; 0.31 percent Nb_2O_5, 0.5 percent REO	Ceased production 1976.
—	No data published	—
—	Ore: 52,000; R1S; 0.56 percent Nb, 3.25 percent ZrO_2, 0.66 percent Y_2O_3, 1.3 percent REE, 0.12 percent BeO; 1981.	—
—	Ore: 62,500; R1S; 0.57 percent Nb_2O_5, 0.04 percent Ta_2O_5, 1.99 percent REO, 4.73 percent ZrO_2; 1987.	—
	CHINA—Continued	
—	Ore: 770,000; R1M; 0.13 percent Nb; 1990 Ore: $\geq$ 800,000; R1E; 6 percent REE; 1990 Ore: $\geq$ 4,300,000; R1E; 35 percent Fe; 1990	Nb is not produced but is present in the slag from iron smelting.
	GREENLAND—Continued	
—	—	Concentrations of REE, U, Nb, and P occur in amounts that may attract economic interest.
	KENYA—Continued	
—	Ore; 51,000; 0.67 percent Nb_2O_5	—
	TANZANIA—Continued	
—	Ore; 67,500; 0.3 percent Nb_2O_5	—
	UGANDA—Continued	
—	Ore; 130,000; 0.2–0.25 percent Nb_2O_5	—
	UNITED STATES—Continued	
—	No data published	Production ceased in 1959.
—	No data published	—
—	No data published	REE and niobium grades are low, but thorium is abundant in vein-type deposits.
—	Ore: 655,622; R1E; 0.0041 ThO_2, 0.00127 percent U_3O_8, 0.3965 percent REO, 0.057 percent Nb_2O_5; 1979. Ore: 2,423,998; R2E; 0.0041 ThO_2, 0.00127 percent U_3O_8, 0.3965 percent REO, 0.057 percent Nb_2O_5; 1979.	—

TABLE 9.—*Selected production and mineral-resource information*

Site name	Year of discovery	Year of first production	Mining method	Elements and minerals of economic interest	Annual production (in 1,000 t)
				ZAIRE	
Bingo (Upper Zaire)	1958	—	N	Nb	—
Lueshe (Kivu)	1938	—	N	Nb	—

Part B.—Principal tantalum mines and deposits

Site name	Year of discovery	Year of first production	Mining method	Elements and minerals of economic interest	Annual production (in 1,000 t)
				AUSTRALIA	
Greenbushes (Western Australia).	1888	1944 (for Ta).	S	Sn, Ta, Nb, Li	Ore: 1,500; 0.027 percent Ta_2O_5; 1985–86; Acc Ore: 1,270; 0.027 percent Ta_2O_5; 1986–87; Acc Ore: 1,630; 0.057 percent Ta_2O_5; 1987–88; Acc
				CANADA	
Bernic Lake (Manitoba)	1928 (for Sn).	1969	U	Ta, Li, Cs, Be, Ga, Nb, Rb, quartz, Sn, feldspar, Ti, Mn.	Ta_2O_5 in conc: 0.125; grade not available; 1981; Est
				MOZAMBIQUE	
Alto Ligonha (Zambézia)	—	—	S	Ta, Nb	—

from ISMI records for niobium and tantalum deposits and districts—Continued

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
	ZAIRE—Continued	
—	Ore; 4,800; 2.3 percent Nb_2O_5	—
—	Ore; 34,500; 1.02 percent Nb_2O_5	—

Part B.—Principal tantalum mines and deposits—Continued

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
	AUSTRALIA—Continued	
Tantalite conc: 1.241; (until 1975); Acc. Ta_2O_5: 0.712; (1976–87); Acc.	Soft rock: 7,280; R1E; 0.26 kg/t Sn, 0.07 kg/t Ta_2O_5, 0.03 kg/t Nb_2O_5; 1988 Tailings: 8,950; R1E; 0.06 kg/t Sn, 0.045 kg/t Ta_2O_5, 0.03 kg/t Nb_2O_5; 1988 Hard rock: 13,460; R1E; 1.50 kg/t Sn, 0.060 kg/t Ta_2O_5, 0.40 kg/t Nb_2O_5; 1988.	—
	CANADA—Continued	
Ta conc: 1.7;(1969–87); Acc.	Ore: 1,879; R1E; 0.216 percent Ta_2O_5; 1979 Ore: 981; R1E; 0.138 percent Ta_2O_5; 1983 Tailings: 637; R1E; 0.065 percent Ta_2O_5; 1983	Production was suspended in 1982 and re-started in 1988.
	MOZAMBIQUE—Continued	
—	—	Believed to have begun production in about 1988.

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