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NIOBIUM (COLUMBIUM) AND TANTALUM RESOURCES OF BRAZIL

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NIOBIUM (COLUMBIUM) AND TANTALUM

RESOURCES OF BRAZIL

By

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U.S. Geological Survey

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NIOBIUM (COLUMBIUM) AND TANTALUM RESOURCES OF BRAZIL

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ABSTRACT

Most of the niobium resources of Brazil occur as pyrochlore in carbonatites within syenitic intrusives of Late Cretaceous to early Tertiary age in western Minas Gerais and southeastern Goiás. Minor amounts of it are produced together with tantalum from columbite-tantalite concentrates from pegmatites and placers adjacent to them, in the São João del Rei district in south-central Minas Gerais. All the niobium and tantalum produced in Brazil is exported.

The only pyrochlore mined is from the Barreiro carbonatite deposit near Araxá in Minas Gerais where concentrates and ferroniobium are produced. Exploration work for pyrochlore and other mineral resources are being undertaken on other carbonatites, particularly at Catalão I in southeast Goiás and at Tapira and Serra Negra in western Minas Gerais.

Annual production and export from the Barreiro deposit are about 8,000 metric tons of pyrochlore concentrate containing about 60 percent Nb_2O_5 and about 2,700 metric tons of ferroniobium with 63 percent Nb_2O_5.

The annual production capacity of the Barreiro plant is 18,000 tons of concentrate and 4,000 tons of ferroniobium. Ore reserves of the Barreiro deposit in all categories are 380 million tons with 3 percent Nb_2O_5. Annual production of tantalite-columbite from the São João del Rei district, most of which is exported to the United States, is about 290 tons, of which about 79 percent is tantalite and about 22 percent is columbite. Reserves of tantalite-columbite in the São João del Rei district are about 43,000 tons of proved and 73,000 tons of probable ore.

INTRODUCTION

Although pyrochlore is known to occur in at least trace amounts in most carbonatites in Brazil, some of which have been the object of intensive exploration work, it is mined only from the Barreiro deposit near Araxá in western Minas Gerais. The pyrochlore at Barreiro was discovered in 1954 during investigation of radioactive minerals in the region by the Government of Brazil. By the late 1950s sufficient study had been conducted to determine the magnitude of pyrochlore reserves and to work out the beneficiation of the pyrochlore; mining was undertaken by the Wah Chang Corporation producing pyrochlore concentrate.

In the early 1960s the mining rights to the deposit were acquired by the Companhia Brasileira de Metalurgia e Mineração (CBMM) and a plant was installed for production of ferroniobium in addition to concentrates. The CBMM reports a production of more than 50,000 tons of pyrochlore concentrates and 9,000 tons of ferroniobium by mid-1972.

The name niobium is used in this report in preference to columbium. In 1950 the International Union of Pure and Applied Chemistry adopted the name niobium as having precedence over columbium. Although niobium is preferred in many sciences, columbium is in general use in the mining and metallurgical industries of the United States.

PYROCHLORE RESOURCES

Production, reserves, and resources potential

Production and exports

All Brazil's current production of niobium from pyrochlore $(Na, Ca)_2 (Nb, Ta)_2, O_6(OH,F)$ is from the Barreiro deposit near Araxá in western Minas Gerais, from concessions held by the Companhia Brasileira de Metalurgia e Mineracão (CBMM). The company operates three open pits on the deposit; a processing plant for production of pyrochlore concentrates by milling, selective flotation, leaching and calcining; and a facility where ferroniobium is produced from the concentrates by an aluminothermic process. The tenor of the ore mined is 3 to 4 percent Nb_2O_5, the concentrates contain 60 percent Nb_2O_5, and the ferroniobium contains 65 percent Nb_2O_5. The CBMM plant has an annual production capacity of 18,000 metric tons of pyrochlore concentrates and 4,000 tons of ferroniobium. The capacity for producing concentrates could be doubled in three months, that for producing ferroniobium doubled in one month and tripled in two months (CBMM written communication, 1972).

Brazil is the world's largest producer of niobium and provides upwards of 60 percent of the non-communist world comsumption. The CBMM exports of pyrochlore concentrates and of ferroniobium for the period 1965 through 1972 are as follows:

	Concentrates (metric tons of 60% Nb_2O_5)	Ferroniobium (metric tons of 63% Nb_2O_5)
1965	1,304	211
1966	3,795	408
1967	2,850	554
1968	3,021	988
1969	6,206	2,095
1970	8,085	1,754
1971	2,180	1,050
1972	9,635	2,781
Total	37,076	9,841

Export figures for 1971 (written commun., Minerals Attache, Consulate General, Rio) show the destinations of pyrochlore concentrates and ferroniobium from the CBMM mining operations near Araxá:

Metric tons

Country	Pyrochlore concentrates	Ferroniobium
U.S.A.	724	563
Japan	485	130
Europe	475	245
U.K.	400	50
Canada	50	62
Africa	46	--
Totals	2,180	1,050

Reserves and resources potential

The CBMM (written comm., 1972) reports ore reserves of the Barreiro pyrochlore deposit as follows:

	Millions of metric tons	Percent Nb_2O_5
Proved	27	4
Probable	84	3
Possible	270	3
Total	381	3

These tonnage figures are based on drilling of the deposit, by the company, to an unspecified depth. It is reported, however, that bottom has not been reached in the mineralized carbonatite ore body and the figures are considered as minimum ones. The total resources may be close to the 1 billion ton magnitude, but have a lower grade, 2 percent or less Nb_2O_5.

Ore reserves for the Tapira carbonatite deposit, based on trenching done by the DNPM, is reported (Alves, 1960) to be 11 million tons, average grade of 0.45 percent Nb_2O_5 to a depth of 4 meters in an area 1,000 by 1,800 meters in the carbonatite.

The Catalão deposit has reserves of 20 million tons of material containing 1.5 to 1.8 percent Nb_2O_5, based on drilling of a portion of the carbonatite.

The Companhia de Pesquisa de Recursos Minerais has completed an exploratory drilling program of the Serra Negra carbonatite, but no results are as yet available.

In summary, the reserves and resources potential of pyrochlore in carbonatite is as follows:

Millions of tons

	Recoverable reserves	Conditional reserves	Hypothetical resources	Grade Percent
Barreiro	381	---	---	Nb_2O_5
(Araxá)				3.0
			620	< 2.0
Catalão I	---	40	---	> 1.0
		160		< 1.0
Tapíra	---	11	45	< 0.5
Serra Negra	NA	NA	NA	
TOTAL	381	211	665	

The published figures for ore reserves of the Barreiro deposit make it by far the largest known pyrochlore deposit in the world. For comparitive purposes with other areas in the world, the following are metric ton conversion of figures published by the U.S. Bureau of Mines (1970) for reserves of niobium in selected countries that have substantial pyrochlore resources, nearly all in carbonatites:

	Metric tons of contained metal
Brazil	11,430,000
U.S.S.R.	3,200,000
Canada	910,000
Nigeria	295,000
Uganda	250,000
Tanzania	160,000
Kenya	114,000
Zaire	45,000
Norway	23,000
Total	16,427,000

The figure for Brazil is a minimum value for pyrochlore reserves of the Barreiro deposit (Araxá), which is only one of several carbonatite-alkalic intrusives in the region that contain pyrochlore; some have appreciable reserves, such as the Catalão and the Tapira deposits. To the potential worth of this very large niobium resource can be added the value of the apatite and titanium mineral resources, each of which is thought to be present in multibillion ton magnitude in some of the intrusives. The economic worth of the minerals in the carbonatite-alkalic rock intrusives of the region point up the importance of detailed evaluation of the known localities, as well as of regional geological exploration to attempt to discover further intrusives.

Certain features of these intrusives distinguish them from the Precambrian metasedimentary rocks in which they are found. They are circular or oval in plan; they weather to a brown or reddish lateritic soil that contrasts with the surrounding metamorphic rocks; they may have arched or domed exposures, particularly where there is a capping of Cretaceous sedimentary rocks; they contain uranium and/or thorium associated with pyrochlore, monazite, apatite or barite, and exposures, therefore, show anomalously high radioactivity; have an abundance of magnetite and other iron minerals which cause strong magnetic anomalies. Some of these intrusives are associated with thermal springs or mineral springs such as those at Araxá, Serra Negra, and Poços de Caldas, where resort hotel centers are built around the springs.

PYROCHLORE DEPOSITS

Geologic setting

The pyrochlore along with associated resources of apatite, barite, titanium, rare earth, and strontium minerals is found in carbonatite within some of the alkalic intrusive complexes that rim the Paraná Basin of south Brazil. To date carbonatites have been reported from the following intrusives (numbers refer to location on figure 1):

2 Lages
3 Anitapolis
4 Itapirapuan
8 Jacupiranga
9 Serrote
10 Ipanema
24 Tapíra
25 Barreiro (Araxá)
26 Serra Negra
27 Salitre
31 Catalão I
32 Catalão II
40 Môrro do Engenho
53 Pedro Juan Caballero

The alkalic intrusives of the Paraná Basin generally are circular or oval in plan and may range in diameter from less than 1 km to as much as 30 km or more. They frequently are difficult to identify in the field except by detailed mapping and searching for rock exposures in generally deeply weathered rock; airborne geophysical surveys locate them by magnetic anomalies.

Within the intrusives the carbonatites are surrounded by various types of alkalic rock, but their position within the intrusive is not predictable. Search for carbonatite is made difficult because they are generally obscured by deep weathering and soil and rubble cover. A field clue to the presence of a carbonatite mass is the presence of a canga capping which may be as much as 1 meter thick; and which contains a high percentage of magnetite, limonite, and hematite in a consolidated clay matrix. Most of the carbonatites contain uranium or thorium associated with various minerals which, residually concentrated in the surface soil mantle or the canga, make the carbonatite distinctly radioactive. Detection of the radioactivity not only serves to locate a carbonatite but to delimit mineral zoning within it.

To 1970 the sole production of pyrochlore was from the Barreiro carbonatite near Araxá in western Minas Gerais, which has the largest known reserves of the mineral. Additional pyrochlore resources are known in the carbonatites of Group VII in this region (Table 1, Fig. 1), particularly Catalão I, Tapíra, and Serra Negra which are described in some detail in this report. Pyrochlore has been found at least in trace amounts in most of the carbonatites. It should be noted that many of the carbonatites have been discovered only in the past 15 to 20 years, and their importance as sources of niobium, titanium, phosphate, rare earths, and strontium has been recognized only in the past few years. Research on mineral concentration and metallurgical extraction to date has resulted in the industrialization of the mineral resources of only the Barreiro carbonatite with production of marketable pyrochlore concentrate and ferroniobium, and apatite concentrates. Research continues on other minerals at Barreiro and other carbonatite of the region, particularly of Catalão I, Serra Negra, and Tapíra.

The only other producing carbonatite is the intrusive at Jacupiranga where apatite concentrates are produced; this may have as much as 38 percent P_2O_5 as a by-product resulting from the manufacture of cement from the carbonatite limestone in which the apatite is disseminated.

Because of their important resource potential, the search for additional carbonatites is underway in the intrusives of southern Brazil, particularly in the Group VII region of western Minas Gerais and southeast Goiás. This search should be extended to the region from Santa Catarina to Rio de Janeiro State where alkalic intrusives of predominantly syenitic composition are found. There are three intrusives in Group VI, for example, where there would seem to be a possibility of finding carbonatite:

1. In the large alkalic intrusive at Poços de Caldas which contains potentially important resources of zirconium-hafnium, molybdenum, and uranium. Of particular interest is the possible relationship to a carbonatite of the Morro do Ferro deposit (Wedow, 1967), a magnetite stockwork in red laterite with which are associated thorium and rare earth minerals. The stockwork forms a lenticular zone 500 meters long and 300 meters wide. The country rock in the area is believed to be syenite, but the degree of weathering is such as not to allow positive confirmation of the type of host rock in which the stockwork is emplaced. Magnetite is frequently the most common mineral found on the Brazilian carbonatites.

2. In one or more of the alkalic intrusives in the State of Rio de Janeiro where barite occurrences have been reported (Menezes and Klein, 1973). Barite is ubiquitous in the Brazilian carbonatites.

3. In the large syenite massif of Itatiaia where narrow veins of highly weathered material contain thorium and rare earth minerals.

Description of deposits

Although pyrochlore is reported to be present even as traces in almost all the carbonatite-alkaline intrusives in Brazil, (Leonardos, 1956; Guimaraes; Alves, 1960; Melcher, 1966) appreciable amounts of it are reported only at Catalão, Serra Negra, Tapíra, and Barreiro (Araxá).

The Barreiro (Araxá) deposit

Araxá is a resort town located (Lat. 19° 35'; Long. 46° 55') in western Minas Gerais about 300 km air line west of Belo Horizonte. Although the deposit of pyrochlore and associated minerals is generally referred to in geological literature as the Araxá deposit, and it lies 6 km south of the town of Araxá, it is known locally as the Barreiro deposit.

The ore deposits are in carbonatite associated with jacupirangite and malignite. The intrusion is of Cretaceous age; it cuts metasedimentary rocks of the Araxá Group of Precambrian B (900 to 1,300 m.y.) age. It is roughly circular and has a diameter of about 6.5 km. As the rocks of the area have been deeply laterized to depths of more than 200 meters, fresh rock exposures are scarce, making difficult the geological interpretation of mineral zoning on the surface of the carbonatite and of the enclosing intrusive alkalic rocks. The red soil on the carbonatite contrasts sharply with soil on the surrounding metasedimentary rock.

The area of mineralized carbonatite of the Barreiro deposit is 2,500,000 m^2 in which are distributed the principal ore minerals, reported to be (Guimaraes, 1957) pyrochlore, apatite, barite, ilmenite, magnetite, and limonite along with which are associated varying amounts of rare earths, uranium, thorium and strontium minerals. These minerals are concentrated residually in separate areas on the deposit as the result of weathering of the carbonatite host rock in which they were originally disseminated (deSouza and Castro, 1968).

There is good evidence of zoning, segregation, or some form of control of the ore minerals in the deposit as indicated by the mineral and trace-element distribution. For example, pyrochlore is being mined by CBMM on three working fronts near the center of the Barreiro deposit, and the Companhia Agricola de Minas Gerais is mining a substantial concentration of apatite near its northwest edge. Uranium investigations of the carbonatite (Castro, 1968) revealed reserves of 3,385 metric tons of uranium oxide found largely in pyrochlore; of which concentrates contain as much as about 1.0 percent U_3O_8, and subordinately in monazite (Ce, La, Nd, Th) PO_4 that contains an unusually low 0.35 percent ThO_2. However, according to Castro, the uraniferous pyrochlore is found only in certain restricted zones of the carbonatite, and the bulk of the pyrochlore reserve is essentially non-uraniferous, containing no more than about 0.005 percent U_3O_8. As further evidence of mineral zoning, near the northern edge of the carbonatite there is an elliptical area 900 m long (east-west) and 300 m wide surrounded by a cap of limonite. This area has been found to have only trace amounts of magnetite and barite as compared to most of the Barreiro deposit, in which these minerals are common (deSouza and Castro, 1968). There appears to be distinct mineral zoning within this elliptical area with a 3-to-17-m wide belt rich in uraniferous monazite and non-uraniferous pandatite, a barian pyrochlore. This belt is enclosed within a wider belt in which the predominant mineral is goyazite ($SrAl_3 (PO_4)_2 (OH)_5.H_2O$), but is also unusually rich in niobium, rare earths, and barium. The mineralogy (Mendes, Murta and Castro, 1968) of a composite of splits from samples taken across these belts is:

	Percent
Goyazite	49.0
Monazite	18.0
Quartz	15.0
Goethite	9.0
Rutile	5.0
Pyrochlore	2.5
Magnetite	0.5
Barite	0.5
Zircon	0.5

In the Barreiro deposit apatite-rich carbonatite exposures in the northwest part of the intrusive may be another instance of possible mineral zoning, where appreciable amounts of autunite ($Ca(UO_2)_2(PO_4)_2.10\text{-}12H_2O$) are found in joints, fractures, and as encrustations. Whether this is indeed a unique primary zone depends on whether the autunite was derived _in situ_ from a primary uranium mineral or from uranium contained in the apatite; or whether the autunite was formed from uranium transported from some outside source, such as a zone of uraniferous pyrochlore. The importance of locating zoning or other control of mineral distribution is that if particular minerals are concentrated in certain zones and are not disseminated throughout the deposit, this will affect the manner in which the carbonatites are prospected, not only at the surface but at depth.

Tapíra deposit

The Tapíra alkaline intrusive is located (Lat. 19° 55'; Long. 46° 53') at the town of that name about 50 km south of Araxá in western Minas Gerais. It is elliptical in plan, and occupies an area of 18 km^2. Carbonatite in the center of the intrusion is surrounded by a suite of rocks that includes volcanic breccia, phonolite porphyry, pyroxenite, tinguaite, and bostonite (Alves, 1960). The age of the intrusive is reported (Hasui and Cordani, 1968) as Late Cretaceous to early Tertiary. It cuts metasedimentary rocks of the Araxá Group of Precambrian B (900 to 1,300 m.y.) age.

The rocks of the area have been lateritized to a depth of upwards of 100 meters which has resulted in a residual concentration of the ore minerals. These are found in place as disseminations in the carbonatite, as filling in the volcanic breccia, and in veins cutting the alkalic rocks. The principal minerals found in the Tapíra deposit are pyrochlore, magnetite, martite, geothite, apatite, barite, niobian perovskite, anatase, and leucoxene. Minerals occurring in minor or in trace amounts are rutile, quartz, vermiculite, calzirtite ($CaZr_3TiO_9$), gorceixite ($BaAl_3(PO_4)_2(OH)_5 \cdot H_2O$), pyrrhotite, chalcopyrite, pyrite, marcasite, fluorite, and fersmite $(Ca,Ce,Na)(Nb,Ti)_2(O,OH,F)_6$. In addition, a minor amount of uranium is reported (Alves, 1960) in pyrochlore; and rare earths and thorium, probably in monazite.

The niobium resources of Tapíra are of medium size compared to those of the Barreiro deposit; and Tapíra is noteworthy principally for very large reserves of titanium. Based on work performed by the Departmento Nacional de Produção Mineral, the published measured reserve figure

(Alves, 1960) for niobium at Tapíra is 11 million tons with an average grade of 0.45 percent Nb_2O_5 to a depth of 4 m in an area 1,000 by 1,800 m in carbonatite.

The Catalão intrusives

There are two oval-shaped alkalic-carbonatite intrusives in the vicinity of the city of Catalão, southeast Goiás. Catalão I, located 7 kilometers northeast of the city is the larger, 5.5 kilometers in diameter, having known economic mineral potential; Catalão II, a small intrusive, is located a few kilometers south of Catalão I. Considerable exploratory work has been undertaken on the Catalão I intrusive, but only minimal work has been done on Catalão II. Pyrochlore has been found in the central core of both carbonatites. Fresh rock exposures at both these intrusives are limited. Mostly they are covered by lateritic soil, typical of the surface expression of these masses in this region, making field detection difficult. They both show strong magnetic anomalies which coincide with their area of exposure and they appear as oval features on aerial photographs.

The Catalão I intrusive has a central core of carbonatite surrounded by serpentinized ultramafic pyroxenite and peridotite (C.C. Berbert, written commun., 1973). Substantial reserves of pyrochlore, apatite, vermiculite, and titanium, and rare earth minerals are concentrated in different zones in the weathered carbonatite.

Three mining companies are exploring the Catalão deposits primarily for pyrochlore. These companies are Metais de Goias, S.A. (METAGO), Mineração Pato do Brasil, Ltda., and the Mineração Catalão de Goiás. Ore dressing research for the concentration of pyrochlore has been contracted to Batelle Memorial Institute, to the Fundação Joao Pinheiro, to the Krupp Rohstoffe Co., and to Serrana, S.A. No feasible process has as yet been reported for concentration of the niobium or the rare earth minerals, largely because of the fineness of grain of the minerals and their diverse chemical composition. Apparently, concentration of the titanium minerals and the apatite has been achieved.

Magnetite and secondary iron oxides are the most abundant minerals at Catalão I; the niobium is present largely as barian pyrochlore (pandaite) and to a lesser extent in a species of the aechynite-priorite series and of marignacite, a species of the pyrochlore-microlite series. The titanium is contained in anatase, leucoxene, ilmenite, rutile, and perovskite, Monazite and parisite are the principal rare-earth minerals. Barite, is a common accessory mineral.

The niobium reserves at Catalao I are reported (W.T. Carvalho, written commun., 1973) to be 40 million tons of ore containing more than 1.0 percent Nb_2O_5. This figure is based on drilling in only a portion of the intrusive and includes proven, probable, and possible reserves. Rock with a Nb_2O_5 content less than 1.0 percent is estimated at about 160 million tons. These estimates are for concessions held by METAGO and Mineração Catalão, but do not cover concessions held by Mineração Pato.

The Serra Negra deposit

This deposit is located (Lat. 18° 50'; Long. 46° 48') about 20 km northeast of the city of Patrocinio in western Minas Gerais. It is a carbonatite-alkalic intrusive, in plan, having an area of about 35 km^2.

The intrusive cuts quartzite and phyllite of the Bambuí Group of Eocambrian (570 to 620 m.y.) age and is overlain by sandstone of the

Upper Cretaceous Uberaba Formation (Hasui and Codani, 1968). Isotopic age determination (K-Ar) of 82 m.y. made on pyroxenite from Serra Negra is reported by Amaral and Codani (1967).

Jacupirangite is the principal alkalic rock with which the carbonatite is associated, but pyroxenite, periodotite, and dunite are also present. These rocks have been weathered to an average depth of about 150 m, and as much as 250 m in places. It is in this mantle of altered rock that are found the residual concentrations of minerals including magnetite, apatite, pyrochlore, perovskite, anatase, leucoxene, rutile, barite, and vermiculite.

The CPRM has undertaken drilling and sampling of this deposit but no report has been made available.

Distribution of alkalic intrusives in southern Brazil

Fifty six known alkalic intrusions that rim the Paraná Basin in south Brazil may be grouped on the basis of lithologic composition and regional distribution into ten groups (fig. 1) as follows:

I. Intrusives in the area near Piratini, Rio Grande do Sul, with an assemblage of alkaline rocks from tinguaite to phonolite.

II. The single alkalic stock near Lages in Santa Catarina, consisting largely of syenite and phonolite with carbonatite.

III. The intrusives at Anitápolis in Santa Catarina and Itapirapuan in São Paulo composed of ultramafic rocks, syenite, and carbonatite.

IV. A group of phonolitic intrusives found in the vicinity of Mato Prêto, Ponta Grossa, and Sete Quedas in Paraná.

V. The intrusives at Jacupiranga, Serrote, Piedade, Impanema, and Tatuí in São Paulo, which include ultramafic rocks, syenite, and carbonatite, with which are associated basaltic dikes and flows.

VI. This group of 11 syenitic intrusions extend from Poços de Caldas in São Paulo eastward to Cabo Frio in the State of Rio de Janeiro. These are not known to contain carbonatites.

VII. This group of 10 alkalic ultramafic and carbonatite intrusives contain important resources of economic minerals; it is located in western Minas Gerais and southeastern Goías.

VIII. This group of 15 intrusions in southwest Goías comprises alkalic gabbros and pyroxenites, and periodotite and dunite on which potentially important deposits of nickeliferous laterite occur.

IX. The syenitic intrusives with some carbonatite located in southwest Mato Grosso, Brazil, and in northeast Paraguay.

X. A group of syenitic intrusives with possibly some carbonatite located in southern Paraguay.

As reported here the characteristics of these groupings reflect recent information from Brazilian geologists engaged in investigation of the alkalic rocks of Brazil. Little of this work is as yet in published form and as reported here represents oral or written communication of researchers in São Paulo and Goiás (F.F.M. Almeida, U. Cordani, G. Amaral, C.O. Berbert, J.C.R. De Melo).

Very likely additional alkalic complexes will be found surrounding and possibly within the Paraná Basin as geological investigations, particularly of the more inaccessible parts of the region, are carried out. Of special interest in this connection will be the results of regional airborne geophysical surveys planned to be made in the Basin. The search for and detailed study of these masses assume considerable economic importance in Brazilian geological research because some of the complexes contain enormous resources of valuable minerals. In addition they are of scientific significance in relation to the tectonic reactivation of the Precambrian Brazilian platform that took place in Cretaceous and early Tertiary times (Almeida, 1967; Amaral 1968) and involved the emplacement, not only of the alkalic complexes (some of which such as Amorinopolis and Agua Emendada in Goías and the Acahay crater in Paraguay still preserve their distinct geomorphic expression as extinct volcanoes with alkaline lava flows), but of the impressive basalt flows that fill the Basin over an area greater than 900,000 km^2 and have a thickness of as much as 1.5 km in places.

Alkalic intrusions on the eastern side of the Parana Basin

The belt of alkalic intrusions extends into Goiás (C.C. Berbert, written commun. 1973) northwest of the Catalão intrusions, to include one near Rio Verde and one that probably is present in the domed structure at Caldas Novas. These masses are typically circular, domed structures, poorly exposed, and mantled by detrital-lateritic colluvium.

In southwest Goías in the region between Jussara (Lat. 15°58'; Long. 50°51') and Aragarças (Lat. 15°55'; Long. 52°15') a cluster of 15 intrusives (Group VIII, fig. 1) is characterized by oval forms and predominance of ultramafic rocks over felsic alkalic rocks. Dunite, peridotite, pyroxenite, and gabbro probably constitute the bulk of the intrusions; they may form the central cores of the bodies, or rings around cores of syentitic or gabbroic rock. These Mesozoic intrusives are located at their intersection with a north-trending belt of upwards of 100 Precambrian dunitic plutons and at least three large peridotite-gabbro complexes and at the border of the Paraná Basin. Deposits of nickelferous laterite occur in several Precambrian plutons, most notably on the Niquelandia (Lat. 14°58'; Long. 48°27') and Barro Alto (Lat. 15°04'; Long. 48°27') complexes where substantial reserves of nickel have been blocked out. It is noteworthy that at least three of the Mesozoic alkalic-ultramafic intrusives, Morro do Engenho, Agua Branca, and Tira-Pressa (fig. 1) have appreciable resources of nickeliferous laterite. It is interesting to speculate whether, and in what way, the ultramafic rocks associated with the alkalic Mesozoic intrusions may be related to the Precambrian peridotites.

In the region of extreme southwestern Mato Grosso, along the Paraguay River, circular alkalic intrusions have been found--two of these are known together as Fecho dos Morros (also called Pão de Açucar), just north of Porto Murtinho (Lat. 21°42'; Long 57°54') in Brazil, and two others are located near Puerto Guarani in Paraguay (fig. 1). A circular intrusive, 7.5 km in diameter has been found in Paraguay 30 km west of the Brazilian border between Pedro Juan Caballero and Cerro Cora. This intrusive has an exposed central core of unweathered carbonatite. The intrusives of southwestern Mato Grosso are of syenitic-foyaitic composition with some diabase but no ultramafic rocks.

With the exception of the Catalão and Fecho dos Morros intrusives, which have been known since the late 19th century, almost all the alkalic intrusions of the Goías-Mato Grosso region have been discovered since 1968. The details of their geologic and tectonic relationships to the setting of the Paraná Basin, as well as their content of economic minerals are as yet incompletely known, or in any case very little has been published about them. Except for veins and stringers of calcite in a drill core in the Morro do Engenho intrusive, which may indicate the presence of carbonatite, it has been found in this region only in the Pedro Juan Caballero intrusive (C. C. Berbert, oral commun.) in Paraguay. This carbonatite is reported to have best exposures of unweathered rock of this type yet found in the Paraná Basin, and the fresh limestone is quarried for local application as soil conditioner. Vermiculite and barite are the only minerals of possible economic importance reported to date, although geochemical exploration of this occurence for Nb, P, and Ti has been reported (Berbert and Trigui, 1973).

The only deposits of economic importance developed so far in the intrusives of the Goiás-Mato Grosso region are the large reserves of nickeliferous laterite referred above.

In addition to the Pedro Juan Caballero locality, the alkalic intrusives extend into Paraguay as reported by Eckel (1959) and include the extension to the west of the Fecho dos Morros intrusive across the Paraguay River, several small intrusives between the Apa River and the Aquidaban River, eastern tributaries of the Paraguay River, and upwards of 15 intrusive and extrusive occurrences in southern Paraguay, southeast of Asuncion in the areas near Sapucai, Villarica, and the Acahay caldera. A reconaissance survey of the alkalic bodies of southern Paraguay undertaken in 1970 (Russel et al, 1971) in the search for apatite and limestone for agricultural use apparently did not find any carbonatite, although the importance of carbonatites as potential sources was recognized. The intrusives consist mainly of syenite and phonolite with some shonkinite and essexite. Very fine grained apatite was reported from some of the exposures of alkaline rocks, and some limestone and dolomite beds, probably not related to the intrusives were reported to be phosphatic. More detailed study of the alkalic plugs might reveal the presence of carbonatites and attendant economic mineral deposits. Of particular interest is the large Acahay caldera, located 85 km air line distance southeast of Asuncion, which Eckel (1959) reports to be in part of alkalic composition. The caldera, dormant at present, is considered to be quite recent, is relatively uneroded, and has extensive exposures of fresh rock.

Age of the alkalic intrusives

The ages of the alkalic intrusives surrounding the Paraná Basin are based on K/Ar isotope dating of about 150 rock samples, done at the Geochronology Center at the University of São Paulo. The intrusives fall within three age groups, spanning Cretaceous to early Tertiary time. The youngest age group, 45 to 90 m.y., (table 1) includes all the intrusives in Goiás, Mato Grosso, and Paraguay (Groups VIII, IX, and X) and those extending through São Paulo and Rio de Janeiro (Group VI). An age of 90 to 115 m.y. is assigned to the intrusives of Itapirapuan, Anitápolis, and Lages (Group II and III) and those in the Araxá region of western Minas Gerais and in southeastern Goiás (Group VII). The oldest intrusives, with ages 115 to 140 m.y., are those in São Paulo on the east side of the Ponta Grossa Arch (Group V), the intrusives in central and western Paraná (Group IV), and the Pirantini intrusive complex in Rio Grande do Sul (Group I). These older intrusives are considered to be of about the same age as the extensive plateau basalts that fill the Paraná Basin.

Table 1. Location of alkalic intrusives of the Paraná Basin (see also figure 1)

Age	Group	Location	South Latitude	West Longitude
115-140 m.y.	I	1. Piratini, Rio Grande do Sul	31°28'	53°08'
90-115 m.y.	II	2. Lages, Santa Catarina	27°50'	50°20'
90-115 m.y.	III	3. Anitápolis, Santa Catarina	27°54'	49°08'
		4. Itapirapuan, São Paulo	24°20'	49°12'
115-140 m.y.	IV	5. Mato Preto, Paraná	24°46'	49°12'
		6. Pontal Grossa, Paraná	25°03'	50°10'
		7. Sete Quedas, Paraná	24°44'	49°13'
115-140 m.y.	V	8. Jacupiranga, São Paulo	24°41'	48°02'
		9. Serrote(Juquiá),São Paulo	24°19'	47°36'
		10. Ipanema, São Paulo	23°24'	47°40'
		11. Piedade, São Paulo	23°43'	47°24'
		12. Tatuí, São Paulo	23°21'	47°51'
45-90 m.y.	VI	13. Poços de Caldas,São Paulo	21°48'	46°33'
		14. S.Sebastião Is., São Paulo	23°50'	45°20'
		15. Itatiaia, São Paulo-Rio	22°30'	45°08'
		16. Gericinó, Rio de Janeiro	22°18'	43°15'
		17. Tinguá, Rio de Janeiro	22°30'	43°33'
		18. Taquarí, Rio de Janeiro	22°49'	43°40'
		19. Itauna, Rio de Janeiro	23°15'	43°00'
		20. Rio Bonito, Rio de Janeiro	22°42'	42°36'
		21. Sao Gonçalo, Rio de Janeiro	22°45'	43°05'
		22. Casemiro de Abreu, Rio de Janeiro	22°19'	42°12'
		23. Cabo Frio, Rio de Janeiro	23°00'	42°00'
95-115 m.y.	VII	24. Tapíra, Minas Gerais	19°55'	46°53'
		25. Araxá, Minas Gerais	19°38'	46°55'
		26. Serra Negra, Minas Gerais	18°50'	46°48'
		27. Salitre, Minas Gerais	19°08'	46°40'
		28. Pantano, Minas Gerais	18°32'	46°44'
		29. São Gotardo, Minas Gerais	19°19'	46°03'
		30. Morro das Brôas, Minas Gerais	18°35'	46°15'
		31. Catalão I, Goías	18°10'	47°57'
		32. Catalão II, Goías	18°00'	48°02'
		33. Caldas Novas, Goiás	17°44'	48°38'
45-90 m.y.	VIII	34. Rio Verde, Goiás	17°48'	50°56'
		35. Agua Emendada, Goiás	17°15'	51°30'
		36. Amorinopolis, Goiás	17°05'	51°56'
		37. Areianopolis, Goiás	16°28'	51°30'
		38. Morro Preto I, Goiás	16°12'	51°33'
		39. Morro Preto II, Goiás	16°07'	51°42'
		40. Morro do Engenho, Goiás	15°25'	51°40'
		41. Agua Branca, Goiás	15°30'	51°08'
		42. Tira-Pressa, Goiás	15°50'	51°02'
		43. Salobinha, Goiás	15°55'	51°15'
		44. Lambarí, Goiás	16°10'	51°18'
		45. Diorama, Goiás	16°20'	51°14'

Table 1. Location of alkalic intrusives of the Parana Basin Continued. (see also figure 1)

Age	Group	Location	South Latitude	West Longitude
		46. Rio dos Bois, Goiás	16°25'	51°05'
		47. Burití, Goiás	16°26'	51°13'
		48. Morro dos Macacos, Goiás	16°30'	51°04'
45-90 m.y.	IX	49. Feixo dos Morros (Pão de Açucar), Mato Grosso	21°43'	51°13'
		50. Puerto Guaraní, Paraguay	21°16'	57°56'
		51. Centurion, Paraguay	22°12'	57°33'
		52. Santa Maria, Paraguay	22°37'	57°30'
		53. Pedro Juan Caballero, Paraguay	22°32'	55°34'
45-90 m.y.	X	54. Sapucai, Paraguay	25°37'	56°57'
		55. Villa Rica, Paraguay	25°42'	56°27'
		56. Acahay Caldera, Paraguay	25°50'	57°10'

TANTALITE AND COLUMBITE RESOURCES

Location and geologic setting of deposits

The tantalum resources of Brazil are in tantalite-columbite, (Fe,Mn)(Ta,Nb)$_2$O$_6$, found in pegmatites in southern and eastern Minas Gerais; in southern Bahía; in the Borborema Plateau region of Paraiba, Rio Grande do Norte and Ceará, northeastern Brazil; and in alluvial placers in the Territory of Amapá.

The principal tantalite-producing districts have been those of southern Minas Gerais (Guimaraes, 1956) and Paraiba-Rio Grande do Norte (Johnston, 1945). In both areas tantalite-columbite concentrates have been extracted from beryllium-lithium-tin-bearing pegmatites or from placer deposits adjacent to them.

Minas Gerais

The present principal sources of Brazilian tantalite-columbite concentrates are from pegmatites in the southern Minas Gerais district of São João del Rei (Lat. 21° 08'; Long. 44° 13') about 12 km air line south of Belo Horizonte. The pegmatite district covers an area of about 1,200 km^2 west of the city of São João del Rei. This district is also a producer of cassiterite and spodumene in addition to microlite (Na,Ca)$_2$(Ta,Nb)$_2$O$_6$(O,OH,F), referred to locally as djalmaite, which may make up an appreciable percentage of the tantalite concentrates shipped from the district. The deposits are in alluvial gravels and in several weathered pegmatites.

The pegmatites cut gneiss and other metasedimentary rocks shown on the geologic map of Brazil (DNPM, 1972a) as undivided Precambrian in age. Age determinations reported by Belezkij (1956) are 1,670 m.y. for gneiss, about 1,065 m.y. for the staniferous pegmatites, which are cut by another generation of non-tin-bearing pegmatites with an age of 375 m.y.

Some tantalite-columbite concentrates have been produced from pegmatites in eastern Minas Gerais located in the Municipio de Ubá, (Lat. 21°07'; Long. 42°56'), the Municipio de Pomba, and the Municipio de Muriaé, as byproduct of the extraction of beryl, lithium minerals, mica, and kaolin (Aberu, 1962).

Bahia

Some small production of tantalite-columbite concentrates has come from pegmatites in the Municipios de Itambé and Vitoria da Conquista (Lat. 13°50'; Long. 40°50') in southern Bahia, in connection with production of beryl and mica.

Northeastern Brazil

The beryl-lithium-tantalum pegmatite dikes of this region are of two types: (1) tabular and narrow, 1 to 2 meters in width and as much as several hundred meters in outcrop length. These dikes do not exhibit internal differentiation and have uniform texture and accessory mineral distribution wall to wall. They have been designated by Johnston (1945) as homogeneous dikes. They number in the tens of thousands but are not known to have produced economic minerals, save for minor amounts of rare-earth minerals. (2) The other type of dike, from which minerals have been produced, has been designated heterogeneous by Johnston (1945). They are lens-shaped bodies as much as 500 m in outcrop length and 100 m in outcrop width. These pegmatities have pronounced internal zoning. Characteristically the essential minerals--microcline, muscovite, and quartz--as well as many of the accessory minerals--tantalite, columbite, beryl, spodumene, and amblygonite--form unusally large crystals. Four mineral zones in these pegmatites are characterized by specific mineral assemblages. Zone I is narrow, on the walls of the dike, and is distinguished by abundant large crystals of biotite. This is the zone where tourmaline and cassiterite are likely to be found. Zone II is the bulk of the pegmatite and consists of feldspar, muscovite, and quartz in very large crystals. Zone III is made up predominantly of large feldspar crystals and is the zone in which are found most of the beryl, tentalite, columbite, microlite, and the lithium minerals. Zone IV is the central core of the dikes and consists of large masses of milky or rose quartz. This zone may yield very large crystals of beryl. The heterogeneous pegmatites number in the thousands, of which several dozen are large enough to have been mined for economic minerals.

The pegmatites of the region cut schists and quartzite of the Ceara Group of Precambrian A (620-900 m.y.) age.

Territory of Amapá

During World War II a few tons of tantalite-columbite and cassiterite concentrates were produced from diamond-gold alluvial gravels in Amapá (Klepper and Dequech, 1967). No production has been reported in later years. The district is in the upper part of the Amapari and Vila Nova River valleys in south-central Amapá within an area in which the Companhia de Pesquisa de Recursos Minerais in 1972 undertook a reconnaissance mineral survey. The sources of the minerals are considered to be pegmatites found in metasedimentary rocks of Precambrian age. Reserves of tantalite-columbite are believed to be small, not more than a few tons.

Production, reserves, and resources potential

Production and exports

The DNPM reports (1972-b) the following figures for production and export of tantalite-columbite for the six years ending in 1971, almost all of it from the São del Rei district of Minas Gerais. A breakdown of the content (tons) of tantalite and columbite in the tonnages reported are as follows:

	Tantalite	Columbite	Total
1966	160	59	219
1967	205	101	306
1968	271	63	334
1969	203	69	373
1970	209	41	350
1971	290	63	353
TOTAL	1,338	396	1,734

The United States is the principal destination of most of the exports of tantalite and columbite from Brazil.

It should be pointed out that by "tantalite" as is frequently found in reports on production or exports of this mineral, is meant tantalite-columbite concentrates. If a chemical analysis shows more Ta_2O_5 than Nb_2O_5 in a concentrate, it is classified as tantalite; if the opposite is the case it is classsified as columbite (Abreu, 1962, vol. II, p. 412). Moreover, it is reported (A. L. Ransome, written commun.) that the tantalite concentrates from the São João del Rei district contain a high percentage of microlite $(NA,Ca)_2TaO_6(O,OH,F)$. The presence of microlite in the concentrates increases the tantalum values in relation to that of niobium--hence their designation as tantalite concentrates. The stream concentrates from the district may contain as much as 10 percent tantalite-columbite and 10 percent microlite (Guimarães, 1956).

The principal production from the São João del Rei district is from the Nazarêno pegmatite at Volta Grande near the Rio das Mortes, mined by the Companhia de Estanho de São João del Rei. This dike is 1,700 m in outcrop length and as much as 30 m in outcrop width. For many years it was principal source of cassiterite in addition to tantalite-columbite. About 1 kg of concentrate per cubic meter is recovered from weathered rock that may contain as much as 68 percent cassiterite, 15 percent tantalite-columbite and 10 percent microlite (djalmaite). Stream concentrates may contain as much as 35 percent cassiterite, 10 percent tantalite-columbite, 10 percent microlite, and 40 percent ilmenite (Guimarães, 1956).

Currently, a small production of tantalite-columbite beryl, cassiterite, spodumene, and amblygonite from the beryl-lithium-tantalum pegmatites of northeastern Brazil is obtained by hand-cobbing of pegmatites by individual miners. According to Johnston (1945), 600 tons of tantalite-columbite along with 8,000 tons of beryl were mined from the pegmatites during the World War II period. Most of this production came from the Picuí-Paralhas area of the States of Rio Grande do Norte and Paraiba, but a small amount of minerals came from the Quixeramobim area in central Ceará. Analyses of tantalite-columbite lots shipped from northeastern Brazil in the period 1942 through 1944 show maximum values of 67.5 percent Ta_2O_5, 32.9 percent Nb_2O_5 and minimum values of 31.9 percent Ta_2O_5 and 15.8 percent Nb_2O_5 (Abreu, 1962, vol. II, p. 411-412).

During World War II production was obtained by semi-mechanized mining; since then the pegmatites have been worked sporadically by prospectors using primitive methods. Over the years this has left a jumble of rock debris that effectively masks the zoning and makes it difficult now to evaluate the remaining mineral potential.

Reserves

Official figures for Brazilian reserves of tantalite-columbite as published by the DNPM (1972-b) are 43,388 tons proved and 72,620 tons probable, all contained in pegmatites in Minas Gerais. Although most of these reserves are probably in the São João del Rei district, the extent to which they may be found in other pegmatite districts of Minas Gerais is not known.

No information is available on the reserves of tantalite-columbite in northeastern Brazil. Considering, however, that past production has come from several dozen pegmatites in the region, and that unexplored pegmatites number in the thousands, the reserves could be considerable magnitude.

Resources potential

Minas Gerais.--The pegmatites of the São João del Rei district in Minas Gerais have been mined since 1942 and are believed by now to have been largely depleted. Over the years the district has been mainly a producer of cassiterite with tantalite-columbite and microlite as by-products. Cassiterite production has declined to the extent that in 1971 tin concentrates were trucked in from Rondônia to feed the Companhia Industrial Fluminense smelter located near São João del Rei. Since then the company has moved the plant to Manaus for closer proximity to the Rondônia cassiterite deposits. Tantalite-columbite production apparently has remained constant at between 250-300 tons per year, but there is a question of whether the production can be maintained independently of production of cassiterite.

The potential of tantalite-columbite for the eastern Minas Gerais pegmatite district is not known. Mining interest has been centered on production of beryl, kaolin, mica, and gem stones, with apparently little concerted effort at production of tantalite-columbite. The dikes may have a potential for Ta-Nb, but this remains to be determined.

Northeastern Brazil.--No detailed study has been made of the accessory minerals of the heterogeneous pegmatites of the region. This could be accomplished on heavy-mineral concentrates derived by mining, crushing, and tabling several large samples from surface exposures of select dikes. This would provide an opportunity for evaluation of the resource potential of tantalite-columbite as well as of other minerals such as those of the rare-earth group. Such an activity would also serve the useful purpose of cleaning, at least in part, the exposures of some dikes, making them accessible for study. The heterogeneous dikes occur by the thousands in the region, only a few dozen of which have been worked. Similarly, mineralogical study should be made of the potential of the homogeneous dikes, which have not been the object of exploration and development. They are present in tens of thousands in this region.

Research suggestions

The tantalum resources of Brazil are found only in pegmatites, which are the present principal economic world-wide sources. Geochemical research needs to be undertaken in the search for other types of deposits in which tantalum may be concentrated. This requires research to develop new, sufficiently sensitive analytical techniques for routine detection of tantalum in various kinds of minerals and rocks.

The crustal abundance of tantalum is estimated to be 2 ppm as compared to about 20 ppm for niobium (Parker and Fleischer, 1968), which makes the concentration of tantalum in minable amounts a rare event.

There is a close chemical affinity of tantalum and niobium and the two are found together in close association. Such association suggests that, in Brazil, it might be fruitful to investigate the potential for tantalum resources in the various pyrochlore-bearing carbonatites of southeastern Brazil. Generally, niobium deposits in carbonatites are regarded as having a very low tantalum content and this is borne out, apparently, in the large niobium-carbonatite deposit near Araxá where Abreu (1962) reports that export concentrates contain about 60 percent Nb_2O_5 and only 0.1 percent Ta_2O_5. It should be noted, however, that there is distinct zoning of rare elements in the carbonatite, and that zones may be present where tantalum may occur in a higher ratio to niobium. On the other hand, Melcher (1966) reports that the Jacupiranga pyrochlore-bearing carbonatite has an unusually high tantalum:niobium ratio of 1:4 and the characteristics of the pyrochlore place it as an intermediate member of the pyrochlore (Na,Ca,Nb_2O_6F)-microlite (Na,Ca,Ta_2O_6F) series. This may be a clue to the possible presence of undetected microlite in some zones, and might make the southeastern Brazil carbonatites the targets of geochemical investigations for tantalum concentration.

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