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Geology and geochronology of carbonatites and associated alkaline rocks peripheral to the Paraná Basin, Brazil-Paraguay

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Abstract—Apatite and titanite fission-track ages have been determined for carbonatite complexes and associated alkaline rocks of the Paranaíba province, Brazil, and the Amambay and Concepción provinces, Paraguay. Close agreement between previously determined K-Ar ages and the apatite fission-track ages indicates that the complexes were emplaced at shallow levels and quickly cooled to the low temperatures (<70°C) required for the retention of fission tracks in apatite. The complexes in Paranaíba province, with the exception of the somewhat older Catalão I (114 Ma), were emplaced between 79 Ma and 88 Ma, in two apparently separate pulses of activity *ca.* 80 Ma and *ca.* 88 Ma. The alkaline complexes of the Amambay and Concepción provinces exhibit a greater range of emplacement ages, from 86 Ma to 147 Ma, with most of the complexes emplaced between 111 Ma and 126 Ma. At both Chiriguelo and Cerro Sarambi, much younger ages obtained for transgressive carbonatite units indicate a renewal of the igneous activity that led to mineralization.

Resumo—Foram determinadas por geocronologia de traços de fissão, utilizando-se apatita e titanita, as idades dos complexos carbonatíticos e rochas alcalinas associades das províncias de Paranaíba, Brasil, e Amambay e Concepción, Paraguay. A concordância próxima entre idades K-Ar anteriormente determinadas e as idades por traços de fissão em apatita, indica que os complexos foram intrudidos em níveis rasos e resfriaram rapidamente as temperaturfas baixas (<70°C) requeridas para a retencão dos traços de fissão em apatitas. Os complexos da província Paranaíba, com excecão do complexo pouco mais antigo de Catalão I (114 Ma), foram intrudidos entre 79 Ma e 88 Ma, em dois pulsos aparentemente separados de atividade, *ca.* 80 Ma e *ca.* 88 Ma. Os complexos alcalinos das províncias Amambay e Concepción mostram uma variacão maior de idades, de 86 Ma a 147 Ma, com a maior parte dos complexos intrudidos entre 111 Ma e 126 Ma. Tanto em Chiriguelo como em Cerro Sarambi, foram obtidas idades muito mais jovens para as unidades de carbonatito transgressivo, indicando uma renovacão da atividade ígnea, que levou à mineralizacão.

Resumen—Mediante el método geocronológico de huellas fisión (fission track), en apatito, y titanita se han determinado edades para complejos carbonatíticos y rocas alcalinas asociadas, en las provincias de Paranaíba, Brasil, y de Amambay y Concepción en Paraguay. La estrecha correlación entre etades obtenidas previamente por el método de K-Ar y las edades por huellas de fisión en apatito, indican que los complejos fueron emplazados a niveles someros, con un enfriamiento rápido a bajas temperatures (<70°C), condición requerida para retener las huellas de fisión en el apatito. Los complejos en la provincia de Paranaíba, con excepción del de Catalão I, que parece un poco más viejo (114 Ma), fueron emplazados entre 79 Ma y 88 Ma, en pulsos &parentemente separados *ca.* 80 Ma y *ca.* 88 Ma. Los complejos alcalinos de la provincias de Amambay y Concepción muestran un rango más amplio en sus edades de emplazamiento, variando desde 86 Ma, hasta 147 Ma, con la mayoría de los complejos emplazados entre 111 Ma y 126 Ma. Tanto en Chiriguelo como en Cerro Sarambi, edades mucho más jóvenes obtenidas sobre carbonatitas trensgresivas indican una renovación de la actividad ígnea, la cual produjo la mineralización.

INTRODUCTION

THE PARANÁ BASIN is floored by a sequence of flood basalts (continental tholeiites) which overlie Triassic and Jurassic eolian and fluvial sediments. The basalts were emplaced between 147 and 119 Ma, with the main eruptive phase occurring between 130 and 120 Ma (Cordani and Vandoros, 1967). Coincident with this period of basaltic magmatism was the first of several periods of alkaline igneous activity. Herz (1977) defined these periods as follows: Jacupiranga, São Paulo, and Anitapolis, 122 to 138 Ma; São Paulo and Paraná and Santa Catarina, 65 to 110 Ma; the Minas Gerais-Goiás Belt, 64 to 91 Ma; and the São Paulo-Rio de Janeiro littoral belt, 51 to 80 Ma. Herz (1977) interpreted these periods of alkaline magmatism to be due to either hot spots or rifts developed during the separation of South America from Africa.

The present study deals with the geochronology of carbonatites and their associated alkaline rocks, which are peripheral to the Paraná Basin. The purpose is two-fold: first, to extend the existing geochronology to previously undated complexes, and second, to investigate the ages of emplacement of the various units within each carbonatite complex. From the Brazilian portion of the basin we have dated Araxá, Catalão I, Catalão II, Salitre I, Salitre II, Serra Negra, and Tapira (all members of the Alto Paran-

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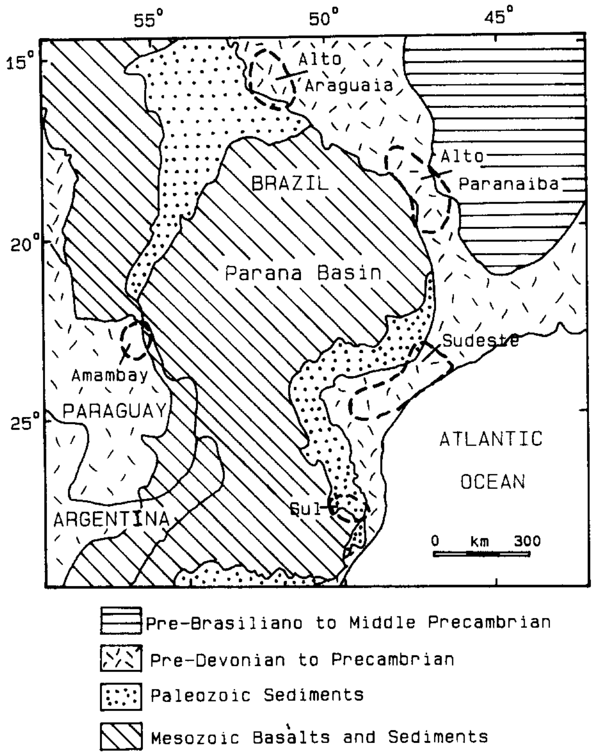

Fig. 1. Location of the alkaline-carbonatite complexes surrounding the Paraná Basin.

aíba province; Grossi Sad and Torres, 1968), and from the Paraguay portion of the basin we have dated Chiriguelo and Sarambi and associated alkaline rocks at Cerro Apuá, Arroyo Gasory, and Cerro Guzaú, which comprise the Amambay District (Amambay and Concepción provinces) of eastern Paraguay (Fig. 1).

FISSION-TRACK GEOCHRONOLOGY

Analytical Methods

Samples were selected from outcrops and drill cores, and brief descriptions of the samples and their locations are given in the appendix. Apatite and titanite were separated using standard electromagnetic and heavy liquid techniques. Apatite ages were determined by the population method, and titanite ages by the external detector method. This laboratory uses the zeta calibration technique recommended by the IUGS Subcommission on Geochronology (Hurford, 1990). For apatite, our age standards are Fish Canyon and Durango, and for titanite, our age standards are Fish Canyon, Mount Dromedary, and two additional intralaboratory standards for which either Ar/Ar biotite or U/Pb zircon ages have been determined. Our zeta calibrations are 311.4 ± 8.8 for apatite and 316.7 ± 6.0 for titanite. NBS glass SRM962 is used as our dosimeter. The results of the fission-track determinations are given in Table 1 (Paranaíba province) and Table 2 (Amambay and Concepción provinces). Where two separate counts are listed for apatite, they represent two different populations of grains counted in separate counting sessions, and the error for the mean age represents the standard deviation of these replicate counts plus the uncertainty in the apatite zeta calibration.

Thermal Constraints on Fission-Track Ages

Apatite fission tracks are susceptible to annealing at relatively low temperatures, which limits their usefulness for dating igneous events. A simplified model for the annealing behavior of apatite distinguishes three stages: (1) complete annealing of fission tracks at temperatures above 130°C; (2) partial track annealing at temperatures between 130°C and 60°C (the so-called partial annealing zone); and (3) complete track retention at temperatures below 60°C (Wagner, 1990). If a magma is intruded to within 2 km or less of the surface, in a region of otherwise average geothermal gradient, it will have cooled to temperatures required for complete track retention in about 1 million years. Thus, while the apatite fission-track age is somewhat younger than the true intrusion age, for intrusions more than about 50 million years old the difference is well within the limits of the error associated with most radiometric measurements.

In this study we have not done track-length measurements to investigate the possibility of apatite fission-track annealing. However, the generally close agreement between fission-track ages and other radiometric ages, where available, for some of the intrusions that we have dated suggests that the intrusions cooled quite quickly to the temperatures required for complete track retention. Because track annealing cannot be definitively ruled out, the apatite fission-track ages reported in this paper should be considered as minima. Where intrusions occurring in close geographic proximity yield different ages, it is likely that real differences do exist, but the measured differences may be biased by partial annealing of the older ages relative to the younger.

In this paper we report only one titanite age. In general, titanite fission-track ages and K-Ar biotite ages are concordant (*e.g.*, Stump *et al.*, 1990). Thus, we infer that the track-retention temperature for titanite is similar to the closure temperature for the K-Ar biotite radiometric system.

In the discussion that follows, previously determined K-Ar ages have been corrected, where appropriate, for the new K-Ar constants (Steiger and Jaeger, 1977) using the table in Dalrymple (1979).

RESULTS

Carbonatite Complexes of the Alto Paranaíba Province

The carbonatite complexes of Brazil have been grouped into five alkaline-carbonatite provinces: Amazónica, Alto Araguaia, Alto Paranaíba, Sudeste, and Sul (Rodrigues and dos Santos Lima, 1984) (Fig. 1). They occur on the

Table 1. Fission-track data for Paranaíba province.

Location and Sample		Mineral	No. Xryls.	Spontaneous		Induced		Dosimeter		Age (Ma)	Mean Age (Ma)
				ρ_s	(N_s)	ρ_i	(N_i)	ρ_d	(N_d)		
Araxá	C1B27	Apatite	50/50	1.00	(120)	1.21	(145)	3.314	(2630)	85.6 ± 10.4	84.4 ± 1.9
			50/50	0.83	(99)	1.01	(121)	3.314	(2630)	84.2 ± 11.2	
	T510F	Apatite	100/100	0.75	(180)	0.92	(220)	3.314	(2630)	83.5 ± 10.7	81.9 ± 3.4
			50/50	0.69	(83)	0.88	(105)	3.314	(2630)	80.3 ± 16.3	
	T629D	Apatite	100/100	0.61	(147)	0.73	(174)	3.276	(2630)	84.8 ± 12.9	
Catalão I	9A	Apatite	100/100	0.43	(103)	0.49	(117)	4.119	(2547)	111.8 ± 14.6	113.1 ± 3.5
			100/100	0.52	(124)	0.58	(138)	4.119	(2547)	114.3 ± 16.2	
	9D	Apatite	90/60	0.68	(98)	0.78	(113)	4.119	(2547)	109.1 ± 21.9	110.6 ± 3.8
			50/60	0.78	(94)	0.70	(84)	3.257	(2630)	112.1 ± 23.5	
	C2C25	Apatite	60/60	0.56	(81)	0.62	(89)	4.119	(2547	116.0 ± 23.2	
	T512	Apatite	100/100	0.32	(78)	0.36	(87)	4.119	(2547)	113.8 ± 20.5	
	T512E	Apatite	50/50	0.79	(95)	0.87	(104)	4.119	(2547)	116.1 ± 22.9	
	T512L	Apatite	100/100	0.62	(149)	0.70	(167)	4.119	(2547)	113.4 ± 19.3	
Catalão II	T568V	Apatite	100/100	0.66	(158)	0.77	(184)	3.276	(2630)	87.1 ± 10.1	
Salitre I	172-27	Apatite	50/50	1.43	(171)	1.56	(299)	3.314	(2630)	93.8 ± 11.2	89.8 ± 6.9
			64/64	1.24	(191)	1.48	(227)	3.314	(2630)	85.5 ± 8.2	
	T568Z_2	Apatite	50/50	0.70	(84)	0.80	(96)	3.276	(2630)	88.8 ± 18.3	87.1 ± 3.7
			60/60	0.64	(92)	0.76	(110)	3.276	(2630)	85.4 ± 15.5	
Salitre II	C3C2	Apatite	83/83	1.30	(259)	1.53	(305)	3.065	(1870)	80.8 ± 6.9	82.6 ± 3.7
			70/70	1.36	(163)	1.53	(183)	3.065	(1870)	84.8 ± 10.7	
Serra Negra	T535	Apatite	100/100	0.40	(97(	0.45	(109)	3.065	(1870)	84.4 ± 14.4	79.1 ± 8.7
			100/100	0.31	(75)	0.40	(95)	3.065	(1870)	73.7 ± 15.6	
Tapira	29KI2	Apatite	100/100	0.98	(236)	1.14	(274)	3.046	(1870)	81.7 ± 7.9	
	89I2	Apatite	100/100	0.75	(180)	0.90	(215)	3.046	(1870)	78.6 ± 9.0	

Track densities (ρ) are as measured and are (× 10^5 tr cm^{-2}); numbers of tracks counted (N) shown in parentheses.

periphery of the Paraná and Amazonas basins, and most were emplaced during the Mesozoic. The Alto Paranaíba province contains the economically important Araxá complex and the carbonatite complexes Catalão I, Catalão II, Serra Negra, Salitre I, Salitre II, and Tapira (Fig. 2). These intrusions were emplaced into Proterozoic quartzites, phyllites, and schists of the Araxá, Bambui, and Canastra groups. Fission-track data for this province are reported in Table 1.

Table 2. Fission-track data for Amambay and Concepción provinces.

Location and Sample		Mineral	No. Xryls.	Spontaneous ρ_s	Spontaneous (N_s)	Induced ρ_i	Induced (N_i)	Dosimeter ρ_d	Dosimeter (N_d)	Age (Ma)	Mean Age (Ma)
Arroyo Gasory	T534S	Titanite	16	12.89	(495)	9.38	(180)	3.410	(2630)	146.7 ± 12.8	
	T534S	Apatite	50/50	2.29	(275)	1.74	(209)	3.295	(2630)	133.8 ± 11.6	
			50/50	2.38	(284)	1.80	(216)	3.295	(2630)	134.4 ± 12.9	134.1 ± 2.4
Cerro Apuá	T534F	Apatite	50/50	4.57	(548)	4.03	(483)	3.300	(2630)	115.6 ± 11.6	114.8 ± 2.9
Cerro Guazú	T540E	Apatite	46/50	1.31	(145)	1.17	(140)	3.300	(2630)	114.0 ± 15.8	
Cerro Sarambí	T608u	Apatite	50/50	1.81	(217)	1.56	(187)	3.065	(1870)	110.8 ± 10.8	110.8 ± 2.8
			50/50	1.74	(209)	1.48	(178)	3.065	(1870)	111.5 ± 10.4	
	T608W	Apatite	50/50	4.83	(1159)	5.37	(1289)	3.065	(1870)	85.4 ± 4.6	86.3 ± 2.6
			50/50	5.05	(1213)	5.50	(1320)	3.065	(1870)	87.2 ± 4.4	
Chiriguelo	T456	Apatite	60/60	7.40	(1066)	5.99	(863)	3.300	(2630)	125.7 ± 12.9	
	T557u	Apatite	40/40	2.79	(268)	2.38	(228)	3.276	(2630)	118.9 ± 20.3	

Track densities (ρ) are as measured and are ($\times 10^5$ tr cm^{-2}); numbers of tracks counted (N) shown in parentheses.

Araxá. The geology and niobium mineralization of the Araxá complex have been described by Silva *et al.* (1979) and Paraiso Filho and Fuccio (1982). The complex, a circular plug 4.5 km in diameter, consists predominantly of carbonatite. The central area has a very strongly brecciated core of dolomite carbonatite, with major pyrochlore mineralization. The annulus between the central core and the outer periphery of the complex is composed mostly of carbonatite, with subordinate pyroxenite and glimmerite. In some areas the latter two predominate, but drilling shows that they usually grade into carbonatite. In the NW quadrant of the complex, an apatite-barite rock crops out and has been mined for phosphate.

Only one small outcrop of calcite-dolomite carbonatite occurs along the northern edge of the complex; otherwise, the average depth of lateritic weathering at Araxá is 150 m. Within a major fault zone just southeast of the central core, the laterite extends to a depth of 300 m.

Although perovskite is present at Catalão, Salitre, Serra Negra, and Tapira, the mineral is virtually absent at Araxá. In addition, although some geologists have referred to the Araxá niobium carbonatite ore as a "phoscorite," olivine is rarely found in the outer annulus and has never been found associated with pyrochlore in the central core.

Apatite fission-track ages were determined on a mixed carbonatite/glimmerite rock (84.4 Ma), a phosphate ore rock from the CAMIG pit (81.9 Ma), and a transgressive pyrochlore-mineralized carbonatite (84.8 Ma). The ages are identical within experimental error, indicating simultaneous emplacement of the various units. Previously determined K-Ar biotite ages for glimmerite are 89.4 ± 4.4 and 97.7 ± 4.8 Ma (Hasui and Cordani, 1968). These ages are older than those determined by fission-track geochronology and may indicate either that the glimmerites were emplaced earlier than the carbonatitic phases, which would be in agreement with the observed sequence of emplacement, or that thermal closure for apatite fission tracks did not occur until about 5-13 million years after emplacement of the complex.

Catalão I and II. The geology of Catalão I has been described by Caravalho (1974) and Carvalho and Araujo (1974). Catalão I is almost totally covered by sediment and lateritic material. Outcrops of pyroxenite, altered phoscorite, phosphate-rich calcite carbonatite, and silexite are occasionally found. Drilling has shown that the complex consists of a central carbonatite plug surrounded by an annulus of pyroxenite. The pyroxenite was originally a salite-apatite-magnetite-perovskite rock with some mica. Local areas of perovskite and apatite enrichment provide

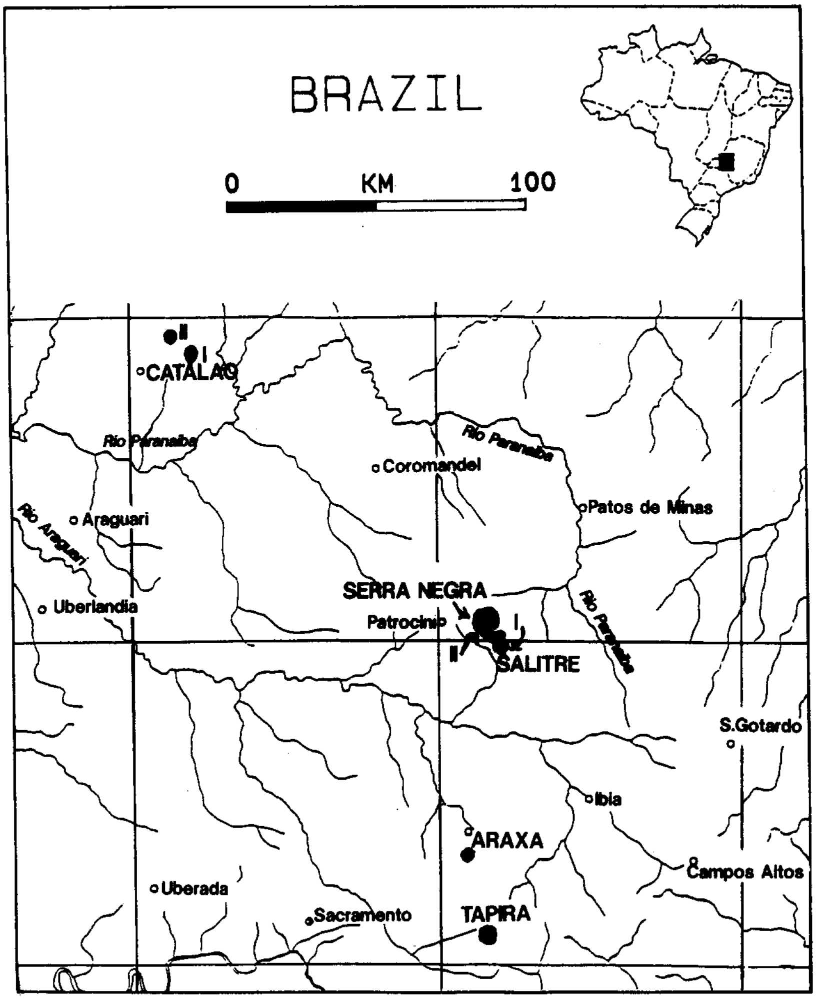

Fig. 2. Location of carbonatite complexes in the Paranaíba province, Brazil.

ore bodies for titanium and phosphate, respectively. The central plug, strongly brecciated and mineralized with pyrochlore, is mined for niobium. Calcite carbonatite bodies within the pyroxenite annulus are not brecciated and contain only minor amounts of niobium as pyrochlore and traces of zirconalite. The pyrochlores from the central plug and outer calcite carbonatite bodies are significantly different in composition. Reaction between carbonatite and pyroxenite resulted in replacement of earlier minerals by phlogopite and biotite, and late hydrothermal carbonate veins transect much of the earlier carbonatite rock.

Catalão II lies in the middle of the same major NW-trending fracture system that contains Catalão I. At Catalão II there is also a secondary fracture system that trends NE; the complex is at the intersection of these two systems. Unlike Catalão I, which is totally discordant to the intruded country rock, Catalão II is concordant to the fractures and fabric. Catalão II consists of calcite carbonatites and orthoclase fenites that form intercalations within the country rock fabric. Areas of significant magnetite-pyrochlore mineralization at Catalão II contain extraordinarily rich concentrations of niobium.

Apatite fission-track ages for pyroxenites and various calcite carbonatite phases at Catalão I give a range of ages from 110.6 to 116.1 Ma, with a mean age of *ca.* 114 Ma. These agree within experimental error and indicate a simultaneity of emplacement for the various units. An apatite fission-track age of 87.1 Ma has been determined for an apatite from Catalão II. Although geographically close, these two intrusions have significantly different geophysical features, and the geochronology indicates that they represent two distinct periods of intrusion. An alkali syenite unit from Catalão I yielded a K-Ar whole-rock age of 85.0 ± 4.2 Ma (Hasui and Cordani, 1968). While this age is significantly younger than the other units dated at Catalão I, it is identical, within experimental error, to the age determined by us for Catalão II. This suggests that the alkali syenite dated by Hasui and Cordani may be related to the intrusion of Catalão II.

Serra Negra and Salitre I and II. A recent account of the geology and mineralogy of these three carbonatite-alkaline igneous plugs can be found in Mariano and Marchetto (1991). The very large circular complex of Serra Negra (65 km^2) is largely composed of a salite pyroxenite (bebedourite). A central buried carbonatite core covered by residuum was suspected to be pyrochlore mineralized but, to date, drilling has revealed only the presence of apatite-calcite carbonatite. Peridotite and dunite are found locally at the contact between the pyroxenite and the country rock. Although the surrounding Precambrian metasediments are strongly silicified, fenitization is sparse or absent.

Two plugs (Salitre I and II) are found on the southeastern edge of the Serra Negra complex. Salitre II is in immediate contact with Serra Negra and consists of bebedourite with only minor thin stringers of carbonatite. Weathered bebedourite float is common in the laterite covering Salitre I, and the predominance of bebedourite in the complex has been confirmed from exploration drilling. Syenitic rocks are rarely found at Salitre I. A phosphate-rich carbonatite body crops out in the NE quadrant of Salitre I, and numerous phonolite, lamprophyre, and rheomorphic fenite dikes crop out as elongate ridges within and peripheral to the complexes. Massive K-dominant fenites are found along the western, southwestern, and southern margin of Salitre I.

An apatite fission-track age of 79.1 Ma has been determined for the Serra Negra apatite-calcite carbonatite. This is a slightly younger age than the K-Ar biotite ages of 83.6 ± 2.5 and 83.8 ± 2.5 Ma determined for the Serra Negra peridotite (Hasui and Cordani, 1968). The geochronology thus suggests that the carbonatite is the younger feature, although the fission-track and K-Ar ages overlap within analytical error. At Salitre I, the sanidine trachyte yields an apatite fission-track age of 89.8 Ma, and the phosphate-rich carbonatite (apatitite) yields an age of 87.1 Ma. The ages are identical within experimental error. An apatite fission-track age of 82.6 Ma was determined for the bebedourite at Salitre II. These ages can be compared with previously determined K-Ar biotite ages of 80.7 ± 4.0 and 84.8 ± 4.2 Ma (Hasui and Cordani, 1968) for the bebedourite at Salitre. Since Hasui and Cordani do not distinguish two separate bodies at Salitre, it is not clear whether both ages were obtained from the same body. Geomorphologic and geophysical evidence (D. A. MacFadyen, personal communication, 1991) suggests Salitre I was an older feature that was disturbed by the subsequent emplacement of Serra Negro and Salitre II. The somewhat older ages for Salitre I, relative to Salitre II and Serra Negra, support this interpretation, although the ages do overlap within analytical error.

Tapira. Descriptions of various aspects of the Tapira complex can be found in Alves (1960), Cruz *et al.* (1976), and Guimaraes *et al.* (1980). The complex is an almost circular intrusion, about 6 km in diameter, which contains a buried central calcite carbonatite core surrounded by an outer annulus composed of bebedourite and glimmerite. A small barren calcite carbonatite crops out in the SW quadrant of the complex. Anatase ore bodies of decalcified perovskite have been delineated in the outer annulus, and phosphate deposits are currently being mined. Bostonite dikes and fenite dikes are found along the margins. Most of the complex is covered by laterite.

Apatite fission-track ages are 81.7 Ma for the bebedourite and 78.6 Ma for the calcite carbonatite, indicating that all of the units were emplaced within a relatively short time. A K-Ar biotite age of 71 ± 4 Ma (Hasui and Cordani, 1968) had been previously determined for the bebedourite. The reason for the significantly younger K-Ar age is not known.

Amambay-Concepción District of Eastern Paraguay

The Amambay and Concepción provinces contain the alkaline complexes of Chiriguelo, Sarambi, and Cerro Guzaú, and the trachyte porphyries of Arroyo Gasory and Cerro Apuá (Fig. 3). The complexes intruded the Precambrian basement and domed the overlying Paleozoic and Mesozoic sedimentary strata. The structural setting is dominated by the NE/SW-trending Ponta Pora High. The intrusions may represent the failed arm of a plume-generated triple junction. The fission-track data for these provinces are reported in Table 2.

Chiriguelo. The complex is essentially circular in shape, with a diameter of about 8 km. The central portion of the complex is overlain by silicified and fenitized Precambrian quartzites and mica schists that are rimmed by Silurian(?) quartzites and outermost Permo-Carboniferous siltstones and sandstones. The eastern and southeastern sections of the complex are overlain by recent Paraná basalt flows. Based on the extension of the domed country-rock ridges and projected thickness of the sediments, the intrusive rocks solidified at a depth of approximately 1.5 km below the present land surface. The complex has a calcite carbonatite core that is intersected by rodbergite and late transgressive carbonatite stringers. The intermediate annulus is an apatite-melanite syenite, and the entire complex is surrounded and partially capped by a massive potassic fenite. Censi *et al.* (1989) give chemical and carbon and oxygen isotopic data for the complex.

A K-Ar biotite age of 128 ± 5 Ma (Geochron Laboratories) has been determined for the biotite-calcite carbonatite, in excellent agreement with the apatite fission-track date of 125.7 Ma determined for the unit. The close agreement between the two ages also supports the geologic inference of a subvolcanic emplacement for the complex, which would lead to rapid cooling of the pluton to temperatures required for the retention of fission tracks in apatite. The transgressive carbonatite yields an apatite fission-track age of 118.9 Ma, suggesting that there was a hiatus in magmatic activity at Chiriguelo.

Cerro Guzaú. This prominent structure in the Province of Amambay consists of a circular plateau of Jurassic Misiones sandstones and coarse conglomerates. The sediments have been silicified, fenitized, and intruded by a radial dike swarm of alkali lamprophyres, shonkinites, and trachyte porphyries (Druecker, 1981). Carbonatite has not been found but is suspected to occur at depth on the basis of geophysics and geochemical anomalies for REE, Nb, Sr, and Ba (Mariano and Druecker, 1985). A K-Ar biotite age of 117 ± 4 Ma (Geochron Laboratories) has been determined for an alkali lamprophyre. A similar apatite

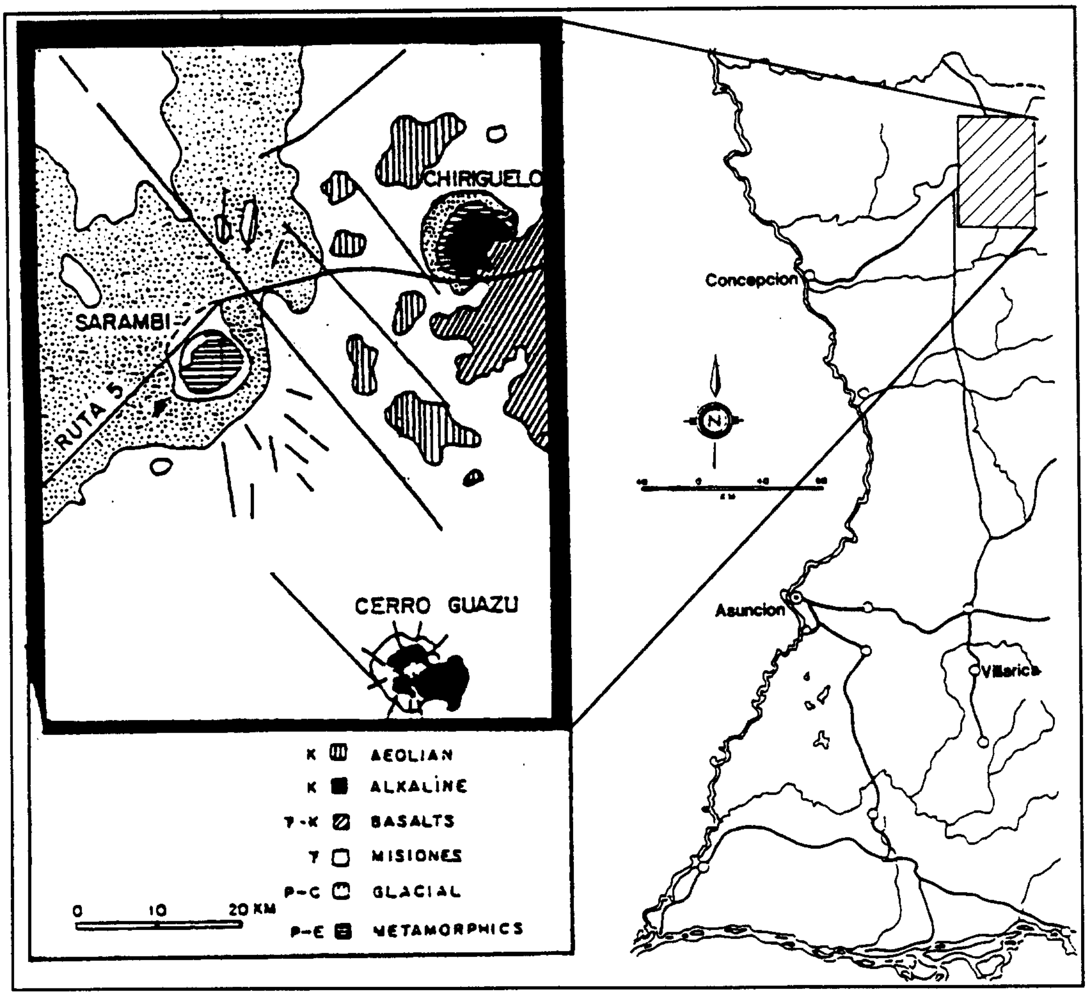

Fig. 3. Location of alkaline and carbonatite complexes in the Amambay District (Amambay and Concepción provinces), Paraguay.

fission-track age of 114.0 Ma was determined for a lamprophyre dike from the complex.

Cerro Sarambi. This complex forms a circular structure about 5 km in diameter composed mostly of pyroxenite, with minor aegirine-nepheline syenite. These rocks are intruded by trachyte and phonolite dikes and thin veins of apatite-magnetite-calcite carbonatite. Massive and rheomorphic fenites are abundant. Apatite fission-track ages of 110.8 Ma and 86.3 Ma have been determined for the host pyroxenite and apatite-magnetite-calcite carbonatite, respectively, thus suggesting a significant hiatus between emplacement of the pyroxenites and formation of the vein apatite-magnetite-calcite carbonatites.

Arroyo Gasory and Cerro Apuá. Arroyo Gasory is a trachyte porphyry dike about 15 km WSW of the Chiriguelo complex. Previous age determinations for this dike (which was misidentified as Cerro Cora, a national monument just outside of the Chiriguelo complex) were 146 ± 8 Ma (K-Ar biotite) and 138 ± 7 Ma (K-Ar whole-rock) (Comte and Hasui, 1971). These ages are in remarkable agreement with the titanite fission-track age of 146.7 Ma and the apatite fission-track age of 134.1 Ma. Given that in both geochronologic systems the older age is associated with the mineral that would have the higher thermal closing temperature, it is reasonable to suggest that these age differences reflect the cooling history of the dike.

Cerro Apuá is an isolated trachyte plug on the edge of Cerro Sarambi. An apatite fission-track age of 114.8 Ma has been determined for the trachyte, and this age is in excellent agreement with that obtained for the pyroxenite at Cerro Sarambi.

DISCUSSION

Alto Paranaíba Province

With the exception of Catalão I, all of the alkaline-carbonatite complexes in this province were emplaced within a relatively short time interval (88-79 Ma), in good agreement with previous age determinations for this province. Where we have data for more than one lithology or event within a single complex, there is no discernible difference in age. In comparing different complexes, however, a fine structure appears in the geochronology. Within the cluster of complexes Salitre I/Salitre II/Serra Negra, Salitre I is found to be the oldest — in agreement with the geologically inferred order of emplacement. The data also suggest two distinct periods of activity, with Salitre II, Serra Negra, and Tapira all being emplaced *ca.* 80 Ma, and Catalão II and Salitre I being emplaced *ca.* 88 Ma.

The new dates for the Catalão I complex yield a much older age of 114 Ma compared to the previously reported K-Ar whole-rock alkali syenite age of 85 Ma. We propose that the previously dated syenite is actually related to the Catalão II complex, which is of similar age.

Amambay-Concepción Provinces

The Cretaceous ages determined for a number of these complexes are correlative with ages reported for some of the southern Brazil carbonatites and alkalic intrusives that border the Paraná Basin in the states of Paraná, Rio Grande do Sul, and São Paulo (White, 1975). These ages, particularly in the case of Chiriguelo and Cerro Guzaú, are also in close agreement with a Rb/Sr age of 120 ± 5 Ma (Umpierre and Halpern, 1971) determined for a syenite from Uruguay which straddles the Paraná Basin.

Although most of the peripheral carbonatite and alkalic complexes are reported to postdate the Paraná basalt flows, some are of about the same age. The flat-lying alkaline basalts that cover most of the eastern and southeastern portions of the Chiriguelo complex apparently belong to renewed alkalic and basaltic activity which occurred at about 110 Ma, following a Barremian hiatus. K/Ar dating of whole-rock basalt samples gave an age span from 119 to 147 Ma, with maximum activity for both basalt flows and diabase dikes occurring between 120 Ma and 130 Ma (Cordani and Vandoros, 1967). A K/Ar biotite age of 151 ± 7 Ma has been determined for a basalt near Chiriguelo (Geochron Laboratories, 1984). These older ages are in good agreement with the K/Ar biotite and titanite fission-track age of *ca.* 147 Ma for the trachyte at Arroyo Gasory, suggesting that emplacement of the trachyte was related to this period of basaltic volcanism.

The ages of the alkaline rocks in Amambay and Concepción provinces vary from 86 Ma to 147 Ma. The bulk of the igneous activity was confined to the period 126-111 Ma. At both Chiriguelo and Cerro Sarambi there is evidence for a hiatus in igneous activity. The age of *ca.* 86 Ma determined for the late-stage apatite-magnetite-calcite carbonatite at Cerro Sarambi is significantly younger than any other ages yet determined for these provinces. Based on this single date, we suggest that, in Amambay and Concepción provinces, a younger period of igneous activity, not yet well defined, was coeval with igneous activity in Paranaíba province.

CONCLUSIONS

This study addresses a number of points concerning the ages of alkaline igneous activity in Brazil and Paraguay and the reliability of the fission-track method in determining these ages.

- In general, the agreement between previously determined K-Ar ages and fission-track ages for the same units is within the experimental error of the K-Ar age. This holds true even for cases in which the fission-track age was determined on apatite separated from grus, relative to a K-Ar age determined on fresh material from the same unit. Given the relatively low temperature required for the annealing of fission tracks in apatite, these observations support the contention that the complexes were emplaced close to the surface and cooled rapidly to temperatures at which fission tracks are retained in apatite.
- The carbonatite complexes dated in this study were generally emplaced either between 90 and 80 Ma or between 135 and 110 Ma, in agreement with ages determined elsewhere in the Paraná Basin for alkaline magmatic activity.
- For most of the carbonatite complexes, igneous activity was confined to a short period of time, and the disparate magmas which formed these complexes must have coexisted in both space and time. The notable exceptions to this generality are Chiriguelo and Cerro Sarambi, where transgressive carbonatite units were emplaced significantly later. These data suggest that it is important to know the geochronology of the various units in a carbonatite complex before attempting to relate them to a single petrogenetic event, and that it should not be assumed that a late-stage mineralized carbonatite is related to the main period of igneous activity.

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REFERENCES

Alves, B. P., 1960. Distrito niobio-titanifero de Tapira. *Departamento Nacional de Produção Mineral, Boletim* **108**, 1-49.

Caravalho, W. T. de, 1974. Aspectos geológicos e petrográficos do complexo ultramáfico-alcalino de Catalão I, GO. *Anais, XXVIII Congresso Brasileiro de Geologia, Porto Alegre* **28**, 107-123.

Caravalho, W. T. de, and Araujo, P. L. de, 1974. Perspectivas de aproveitamento economico do depositos minerais associados ao complexo ultramafico-alcalino do Catalão I, GO. *Anais, XXVIII Congresso Brasileiro de Geologia, Porto Alegre* **28**, 131-139.

Censi, P., Comin-Chiaramonti, P., Demarchi, G., Longinelli, A., and Orue, D., 1989. Geochemistry and C-O isotopes of the Chiriguelo carbonatite, northeastern Paraguay. *Journal of South American Earth Sciences* **2**, 295-303.

Comte, D., and Hasui, Y., 1971. Geochronology of eastern Paraguay by the potassium-argon method. *Revista Brasileira de Geociências* **1**, 33-43.

Cordani, U. G., and Vandoros, P., 1967. Basaltic rocks of the Paraná Basin. In: *Problems in Brazilian Gondwana Geology* (edited by J. J. Bigarella, R. D. Becker, and I. D. Pinto), pp. 207-232. Conselho Nacional de Pesquisás and Instituto de Geologica, Universidade Federal, Curitiba, Brazil.

Cruz, F. F., Chaban, N., Machado, P. T., Townend, R., and Machado, J. E., 1976. Aspects of the superficial phosphorus and titanium deposits of the Tapira carbonatite complex, Minas Gerais, Brazil. *Abstracts of the 25th International Geological Congress, Australia* 1, 209-210.

Dalrymple, G. B., 1979. Critical tables for conversion of K-Ar ages from old to new constants. *Geology* 7, 558-560.

Druecker, M. D., 1981. *Chiriguelo Carbonatite Complex Status Report.* Private report, Anschutz Mining, The Anschutz Corporation, Asunción, Paraguay, 14 p.

Grossi Sad, J. H., and Torres, N., 1968. *Complexos Alcalinos da Região do Alto Paranaíba.* Relatório Anual Serviços, Departamento Nacional Produçao Mineral, Rio de Janeiro, Brazil, 26 p.

Guimaraes, I. G., Amaral, M. A. M., and Garcia, L. R. A., 1980. Uncompahgrito de Tapira, MG. *Anais, XXXI Congresso Brasileira de Geologia, Camboriú* 31, 2050-2058.

Hasui, Y., and Cordani, U. G., 1968. Idades potassio argônio de rochas eruptivas Mesozóicas do Oeste Mineiro e Sul de Goiás. *Anais, XXII Congresso Brasileiro de Geologia* 22, 139-143.

Herz, N., 1977. Timing of spreading in the South Atlantic: Information from Brazilian alkalic rocks. *Bulletin of the Geological Society of America* 88, 101-112.

Hurford, A. J., 1990. International Union of Geological Sciences Subcommission on Geochronology recommendation for the standardization of fission track dating calibration and data reporting. *Nuclear Tracks and Radiation Measurement* 17, 233-236.

Mariano, A. N., and Druecker, M. D., 1985. Alkaline igneous rocks and carbonatites of Paraguay. *Geological Society of America Abstracts with Programs* 17, 166.

Mariano, A. N., and Marchetto, M., 1991. Serra Negra and Salitre — Carbonatite alkaline igneous complex. In: *V International Kimberlite Conference (Araxá, Brazil, 1991), Field Guidebook: II — Cretaceous Intrusions in Western Minas Gerais* (edited by O. H. Leonardos, H. O. A. Meyer, and J. C. Gaspar). Companhia de Pesquisas de Recursos Minerais, Special Publication 3/91, 75-79.

Paraiso Filho, O. de S., and Fuccio, R., 1982. Araxá niobium mine. *Mining Magazine* 146, 134-147.

Rodrigues, C. S., and Santos Lima, P. R. A., 1984. *Carbonatitic Complexes of Brazil.* Companhia Brasileira de Metalurgia e Mineraçao, São Paulo, 3-17.

Silva, A. B. da, Marchetto, M., and Souza, O. M. de, 1979. Geologia do complexo carbonatitico de Araxá (Barreiro), MG. *Mineraçao Metalurgia* 43, 14-18.

Souza Filho, J. G. C., 1974. Prospecção de urânio nas chaminés alcalinas de Serra Negra e Salitre, MG. *Comissão Nacional de Energia Nuclear, Boletim* 9, 1-41.

Steiger, R. H., and Jaeger, E., 1977. Subcommission on Geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters* 36, 359-362.

Stump, E., Fitzgerald, P. G., and Gleadow, A. J. W., 1990. Comparison through fission-track analysis of portions of Australia and Antarctica adjacent prior to continental drift. *Nuclear Tracks and Radiation Measurement* 17, 359-365.

Umpierre, U. M., and Halpern, M., 1971. Edades estronico rubidio en rocas cristalinas del sur de la Republica Oriental del Uruguay. *Revista de la Asociacion Geológica Argentina* 26, 133-151.

Wagner, G. A., 1990. Apatite fission-track dating of the crystalline basement of middle Europe: Concepts and results. *Nuclear Tracks and Radiation Measurement* 17, 277-282.

White, M. G., 1975. *Niobium (Columbium) and Tantalum Resources of Brazil.* U.S. Geological Survey, Open File Report (IR)BR-76, 34 p.

APPENDIX

SAMPLE DESCRIPTIONS AND LOCATIONS

C1B27 Glimmerite: Phlogopite and interstitial dolomite. Accessory minerals: apatite, calcite, pyrite, anatase, baddelyite, and zirconalite. Drill hole 704/3A (depth of 91 m), NW quadrant of the Araxá complex approximately 700 m due south of the Grande Hotel.

TS10F High-grade apatite rock: Fine-grained ovoid apatite forming an equigranular mosaic texture. Void filling by light green euhedral barite and quartz. Open pit phosphate mine (CAMIG pit) in the NW quadrant of the Araxá complex.

T629D Transgressive carbonatite: Major minerals are dolomite and apatite, minor phlogopite, magnetite, and pyrochlore, and accessory calcite, secondary apatite and isokite [$CaMg(PO_4)F$]. Drill core (depth of 209 m) from the center of the Araxá complex.

> ***9A*** Phoscorite: Major minerals are medium-grained granular apatite, altered olivine, and anhedral perovskite. Accessory minerals are magnetite and altered phlogopite. Drill core (depth of 95 m) from southern edge of Catalão I complex.
>
> ***9D*** Dolomitic calcite carbonatite: Medium-grained granulose texture. Dark bands of phlogopite accompanied by anhedral dolomite in calcite. Minor mineral is ovoid apatite. Accessory minerals are magnetite, pyrite, pyrrhotite, and traces of chalcopyrite. Drill core (depth of 30 m) 500 m east of dry lake near the center of the Catalão I complex.

C2C25 Niobium-ore laterite: Laterite essentially composed of magnetite and brown and black ferric iron oxide grains. Colorless equant apatite (~1 mm) occurs as residual grains. Minor and accessory minerals are barite, manganese oxide, bariopyrochlore, plumbopyrochlore, monazite, rhapdophane, and crandellite group minerals. Brazimet niobium ore body in the center of the Catalão I complex.

T512 Dolomite carbonatite-glimmerite contact: Contact between glimmerite and dolomite carbonatite. Coarse-grained anhedral apatite concentated in the glimmerite. Drill core SC1 J4 (depth of 41.4 m) from the Metago area in the eastern part of the Catalão I complex.

T512E Phoscorite: Cumulus masses of magnetite and perovskite in a matrix of granular olivine and clusters of phlogopite. Minor and accessory minerals are apatite, humite, dolomite, calcite, zirconolite, and baddelyite. Drill core SC4 S4 (depth of 29.2 m) from the east side of the Catalão I complex.

T512L Transgressive carbonatite: Dolomite, apatite, phlogopite, bariopyrochlore, and trace baddelyite. Brazimet drill core DDH B450, X-34 (depth of 400.16-405.16 m) from the central part of the Catalão I complex.

T568V Apatitite: Major mineral is apatite, which displays a matted fabric of intergrown plumose fibers. Disseminated magnetite and bariopyrochlore. CBMM exploration poços M-34 in the SW quadrant of the Catalão II complex.

172-27 Sanidine-aegirine fenite: Aegirine-augite and aegirine idioblasts and feldspar porphyroblasts in an aphanitic groundmass of sanidine crystals with accessory titanite and apatite. Dense greenish-grey outcrop along the southwestern edge of Salitre I approximately 250 m due south of the type locality for bebedourite.

$T568Z_2$ Apatitite: The rock is composed chiefly of apatite, with accessory magnetite. Outcrop located in a depression at the edge of Lagoa Campestre in the northern part of Salitre I.

C3C2 Pyroxenite (bebedourite): The rock is medium-grained melanocratic with major anhedral salite and subordinate interstitial perovskite, magnetite, and apatite, and accessory phlogopite. Drill core from the NW quadrant of the Salitre II complex.

T535 Apatite calcite carbonatite: Leucocratic equigranular medium-grained calcio-carbonatite with about 20% apatite as ovoid prisms. Accessory minerals are dolomite, magnetite, phlogopite, humite, rutile, pyrochlore, baddeleyite, pyrrhotite, and pyrite. Drill core (depth of 97 m) from the northeast edge of Lagoa Barriguda, Serra Negra complex.

29K12 Pyroxenite (bebedourite): The major mineral is salite, with accessory magnetite, perovskite, apatite, phlogopite, and calcite. Outcrop located in the SW quadrant of the Tapira complex.

89I2 Calcite carbonatite: Medium-grained rock composed chiefly of granulose calcite, with minor coarse-grained magnetite and medium-grained ovoid apatite and accessory phlogopite and pyrrhotite. Outcrop located along the southwestern edge of the Tapira complex on the left branch of Corrego Cangerana.

T534S Trachyte porphyry: Light greyish-tan porphyritic rock with large colorless K-feldspar phenocrysts and smaller biotite, aegirine-augite, and apatite phenocrysts in an aphanitic groundmass composed chiefly of K-feldspar and plagioclase with accessory apatite, titanite, magnetite, and aegirine-augite. Outcrop located on the Arroyo Gasory adjacent to Route 5 (Cerro Cora topographic sheet).

T534F Trachyte porphyry: Large sanidine phenocrysts and rarer augite, biotite, apatite, and titanite phenocrysts in an aphanitic groundmass of sanidine laths. Accessory minerals are magnetite and calcite, which occurs as small dissemninated patches and fracture fillings. Outcrop from an isolated plug (Cerro Apuá) located 8 km southwest of the Sarambi ring complex.

T540E Alkalic lamprophyre dike: Augite and biotite phenocrysts in a groundmass composed chiefly of sanidine. Accessory minerals are zeolites, magnetite, aegirine, and apatite. Outcrop from the most southerly protuberance of Cerro Guazú.

T608u Pyroxenite: The major mineral is diopside with accessory apatite and calcite. Drill core (depth of 384 m) located at the center of the Sarambi ring complex.

T608E Calcite carbonatite: Coarse-grained calcite carbonatite dike cutting pyroxenite. The major mineral is calcite with accessory biotite, apatite, magnetite, and pyrite. Drill core (depth of 60 m) located in the center of Cerro Sarambi.

T546 Silico-carbonatite: A mixed silicate-carbonate rock consisting of major sanidine, calcite, andradite, and apatite in a groundmass of anhedral sanidine and interstitial calcite. Accessory minerals are phlogopite, barite, and hematite. Outcrop located approximately 1 km north of the agricultural lime quarry (Cantera) in the center of the Chiriguelo complex.

T608E Calcite carbonatite: Coarse-grained calcite carbonatite dike cutting pyroxenite. The major mineral is calcite with accessory biotite, apatite, magnetite, and pyrite. Drill core (depth of 60 m) located in the center of Cerro Sarambi.

T546 Silico-carbonatite: A mixed silicate-carbonate rock consisting of major sanidine, calcite, andradite, and apatite in a groundmass of anhedral sanidine and interstitial calcite. Accessory minerals are phlogopite, barite, and hematite. Outcrop located approximately 1 km north of the agricultural lime quarry (Cantera) in the center of the Chiriguelo complex.