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Part II

THE POÇOS DE CALDAS ALKALINE MASSIF

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Acknowledgements:

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THE GENERAL GEOLOGIC OUTLINE

Regional basement rocks

The Cretaceous Poços de Caldas alkaline massif (~80 Ma), one of the largest of its kind, covers over 800 km^2 and crops out as a roughly circular mass, almost entirely composed by nepheline syenites and phonolites. It appears as one of several dozen alkaline occurrences, mostly crowded around the western and eastern margins of the Paraná Basin, filled with Devonian to Cretaceous sediments and the very thick (up to 1000 m) basaltic lava flows and subvolcanic intrusions of the Cretaceous Serra Geral Formation (~130 Ma; cf. Fig. 5).

The Precambrian basement at the limit between the states of São Paulo and Minas Gerais can be broadly grouped into three well-defined tectono-stratigraphic units: 1) the large discontinuous Socorro-Guaxupé Nappe; 2) the Alto Rio Grande Belt of folded supracrustal rocks; 3) the reworked Archean basement adjacent to, and part of, the São Francisco Craton (Fig. 5).

The *Socorro-Guaxupé Nappe*, which may have been attached to the southernmost portion of the Brasilia folded Belt (general SE-NW direction), represents a large slice of crust transported during the Neoproterozoic in an easterly direction, over the São Francisco Craton. It is divided into two separate, but possibly related segments: to the N, the *Guaxupé block* with a triangular shape, its base covered by the sediments of the Paraná Basin, and the *Socorro structure*, to the south (Fig. 5). The stratigraphic units that have been recognized within the Guaxupé block are the complexes Caconde (supracrustal quartzose gneisses), Alfenas-Guaxupé (assorted granulites of igneous origin), Varginha (high-grade gneisses and paragranulites), and Pinhal (subdivided into migmatitic and deformed granitic facies). The nappe structures were intruded by a series of igneous rocks belonging to the Brasiliano cycle (~800-450 Ma), making up several deformed and undeformed igneous suites: syenites (e.g., Pedra Branca: 613±3 Ma), pink granites with rapakivi affinities (610-586±10 Ma), minor monzonites-monzodiorites (e.g., Piracaia: 577±2 Ma), porphyritic granites, small bodies of anatectic peraluminous granites (624±2 Ma), mangeritic-charnockitic rocks (625±7 Ma) and calc-alkaline potassic granites (610-595±10-12 Ma; cf.Figs. 5, 6 [2,3]).

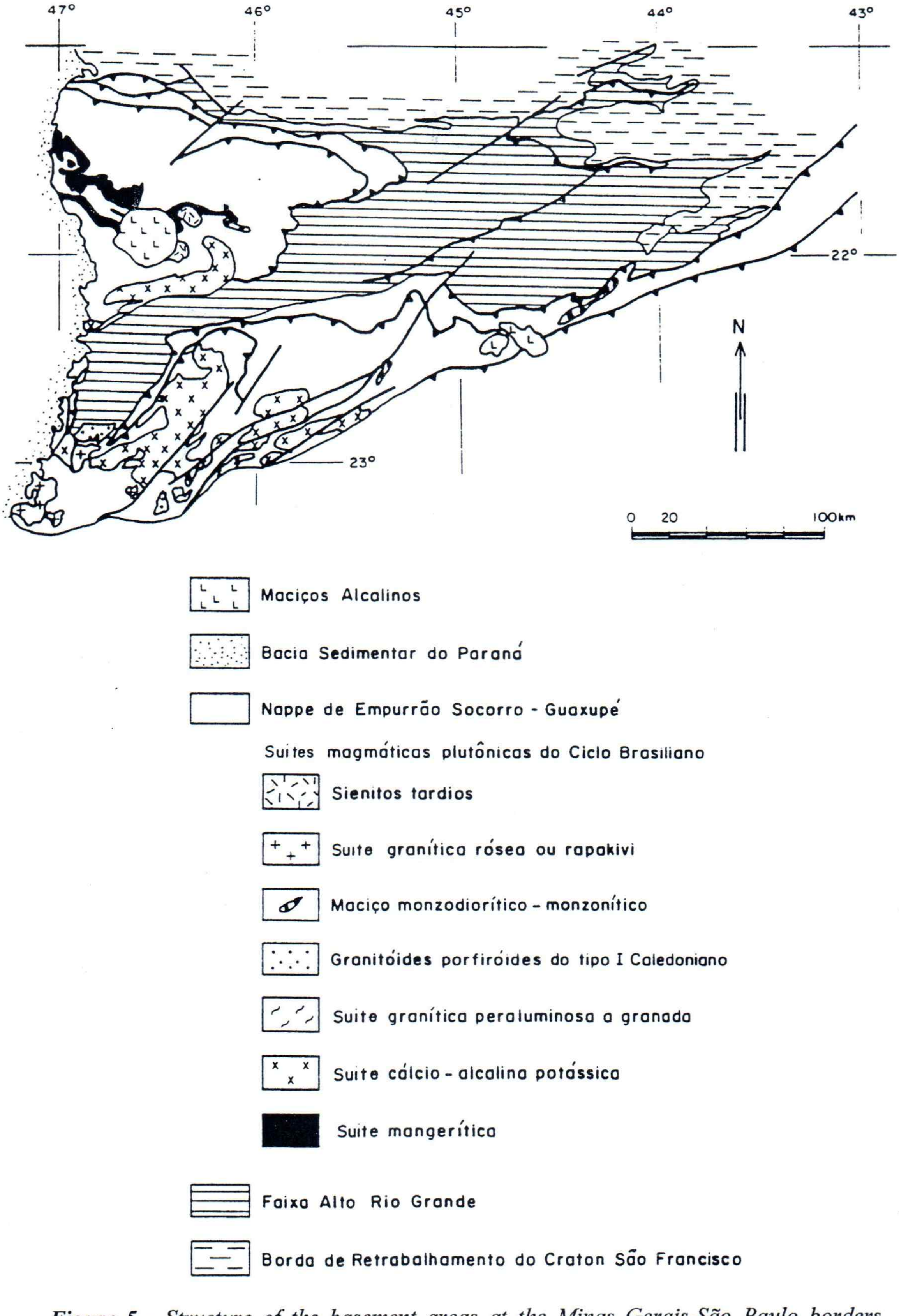

Figure 5 *- Structure of the basement areas at the Minas Gerais-São Paulo borders. Source: [1].For comments, see text.*

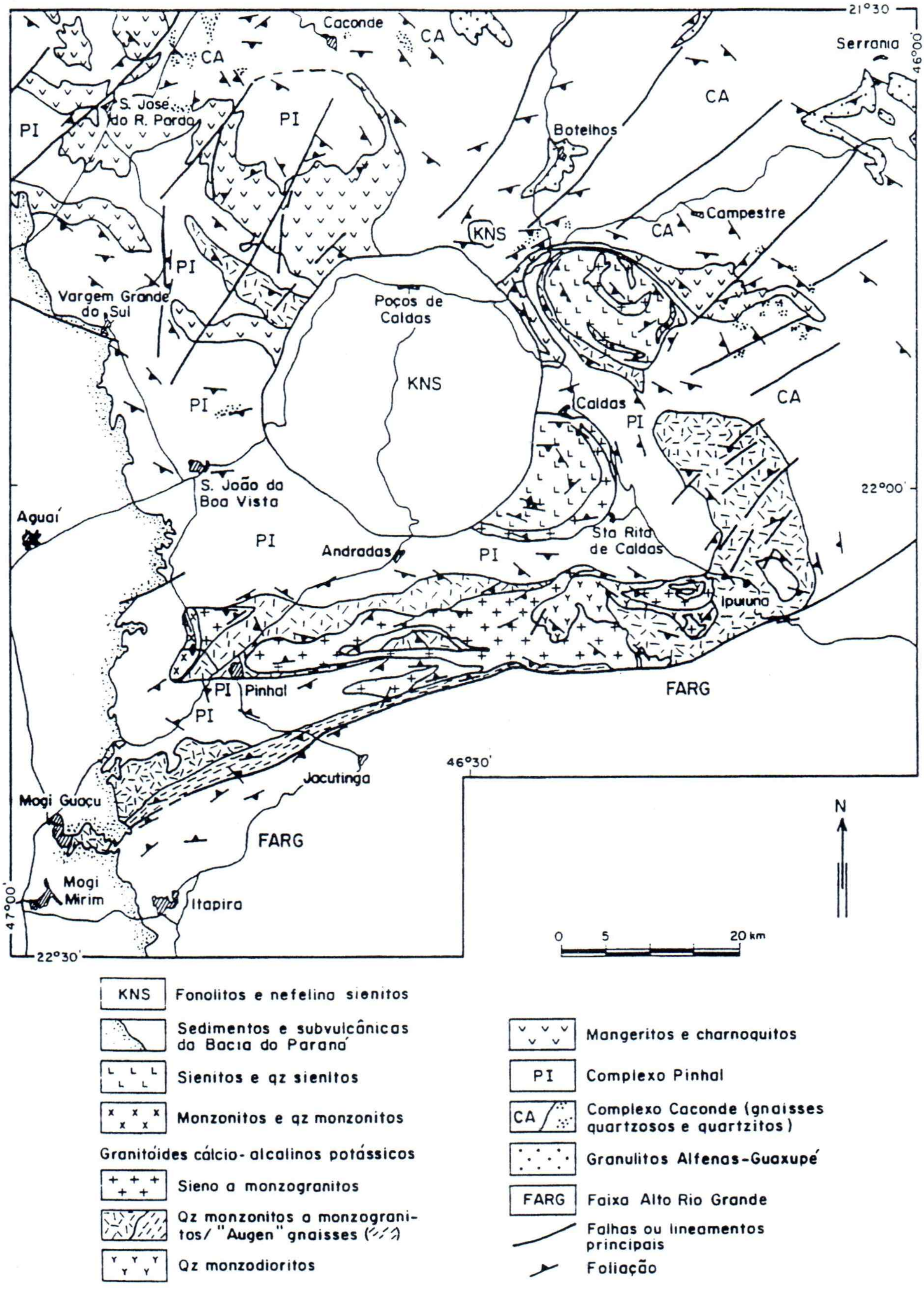

Figure 6 *- The location of the Poços de Caldas massif within the Guaxupé block, with outlined basement units. Source:* [1] *. See text.*

The *Alto Rio Grande Belt* is formed almost entirely by supracrustal strongly deformed and recrystallized units: the complexes Andrelândia (medium-grade schists and gneisses, sedimentation age less than 1.2 Ga) and Itapira (high-grade gneisses and quartzites), with some minor outcrops, to the N of the Guaxupé block, of the São João del Rei Complex (low-grade phyllites and schists); in certain areas, the Silvianópolis Complex (migmatitic gneisses, reworked during the Transamazonic cycle, ca. 1.8-2.2 Ga) crops out as the basement to the Andrelândia Complex.

The areas to the N and E of the Guaxupé block are made up of *reworked Precambrian units* of the São Francisco Craton. The Barbacena Group (granite-greenstone terrranes, ages over 2 Ga) is considered part of the Craton itself, while the Campos Gerais Complex (highly deformed older granitic gneisses and greenstones, which may grade into rocks of the São Francisco Craton, together with some tectonically intermingled younger schists and gneisses) separates the Guaxupé block from the nearby Passos nappe structure (to the N of the Guaxupé block, not represented in Fig. 5)[1-3] .

Regional structural outline

The basement areas are cut by several linear features, interpreted for the most part as older, in part reactivated fault surfaces. The main directions are NE and NW, the two most commonly observed trends in the basement regions in SE Brazil. A block structure with a general ENE trend has been observed on Landsat images, limited by faults that define structural "lows" and "highs" (Fig. 7). The intersection of the NE and NW structures may define "zones of weakness", forming possible channels for the intrusion of the alkaline intrusions (Fig.7).

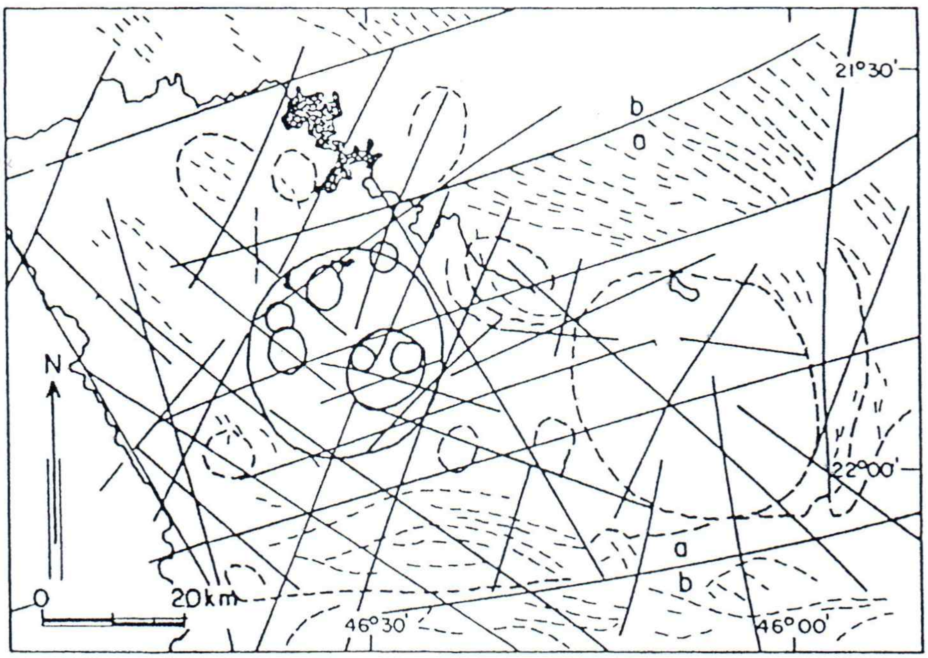

Figure 7 *- Structural outline in the basement rocks of the Guaxupé block and surrounding areas, as interpreted from Landsat images [4,5] . The NE-NW fault trend may define a zone of weakness that controls the emplacement of the large Poços de Caldas intrusion (circular outline; circular structures within the massif are also outlined). Other circular structures, indicated by dashed lines; are however devoid of Phanerozoic magmatic activity.*

Geomorphologic features

The basement rocks crop out as a rather strongly dissected plateau with an irregular topography. The highest elevations, over 1400 or even over 1600 m, are found along some ridges of basement rocks (e.g., the Ranges or Serras de Pau d'Alho, Mirante, etc.; Fig. 8), but prevailing altitudes are usually between 900 and 1300 m. The Paraná Basin, on the other hand, is a depressed area, with elevations almost always less than 900 m (Fig. 8). The Poços de Caldas massif stands out in this landscape as a marked topographic high, with an outer ring composed by phonolites (the so-called "ring dike" [7]) especially to the N and S, with elevations over 1400 m and even over 1600 m. To the SE of the Poços de Caldas structure, a marked semicircular structure (elevations over 1600 m) indicates the presence of the Pedra Branca syenite. Large areas around the Poços de Caldas massif are at heights between 1100 and 900 m (Fig. 8). This cursory examination of the topographic features strongly suggests that the relief is caused mainly by differential weathering and erosion, in part possibly enhanced by the presence of faults and joint systems in the basement areas. No indication can be found that a regional doming of basement rocks during the Cretaceous accompanied the emplacement of the Poços de Caldas massif.

GENERAL GEOLOGY OF THE POÇOS DE CALDAS MASSIF

Geologic map

A simplified structural and petrographic outline of the Poços de Caldas massif is presented in Figure 9. Dark-grey to greenish-grey tinguaites (aphyric to porphyritic microgranular subvolcanic phonolites) and vesicular to massive purple-colored phonolites are the predominant rocks; the main minerals are K-feldspar (sanidine or orthoclase), fresh to slightly altered nepheline and greenish to colorless pyroxenes (aegirine to Na-augite), with lesser amounts of a variety of accessory phases. Nepheline syenites (NeS) are also found, with the same mineralogy as the finer-grained rocks; they are mostly inequigranular, coarse- to medium-grained, and cover about 17% of outcrops. Earlier sandstones, the most conspicuous ones belonging to the Botucatú Formation and showing large-scale cross-bedding, are incorporated as large enclaves; a few diabase outcrops are considered preserved intrusive rocks belonging to the basaltic Serra Geral Formation of the Paraná basin. Volcanoclastic rocks are found as agglomerates, lapilli and tuffs, usually heavily weathered; the most conspicuous strip is found along the Vale do Quartel, a depressed region at the W margin of the massif. Most of the larger fragments in the agglomerates represent ultramafic to mafic rocks, petrographically unrelated to the prevailing NeS and phonolites of the district. Ultramafic rocks are also found as dikes within the Osamu Utsumi mine pit (cf. below, "Mineralization") and to the NW, a few km outside of the district, as small carbonatite-lamprophyre dikes and pods within regional granulites and gneisses, together with some tinguaite dikes (Minas Pedras quarry). Another occurrence pointing to the existence of carbonatite magmas is the presence, within the district, of a large patch with a high REE-Th anomaly, associated with several very conspicuous magnetite dikes (Morro do Ferro, Fig. 9; for rock descriptions, see [5, 7-9]).

1 Serra do Boqueirão
2 Serra da Fumaça
3 Serra do Marinho
4 Serra do Mirante
5 Serra da Fartura
6 Serra do Picadão
7 Serra da Pedra Branca
8 Serra do Pau d'Alho
9 Serra de Poços de Caldas
10 Serra de São Domingos
11 Morro do Cristo Redentor (1637 m)
12 Serra do Selado
13 Serrote do Maranhão
14 Serra do Gavião
15 Serra do Caracol
16 Serra da Forquilha
17 Morro do Ferro (1491 m)
18 Morro do Taquari (1352 m)
19 Morro Grande (1554 m)
20 Morro do Mel
21 Morro do Serrote (1497 m)

Figure 8 *- Topographic features within the Poços de Caldas massif and surrounding basement areas. Source:* [5, 6]

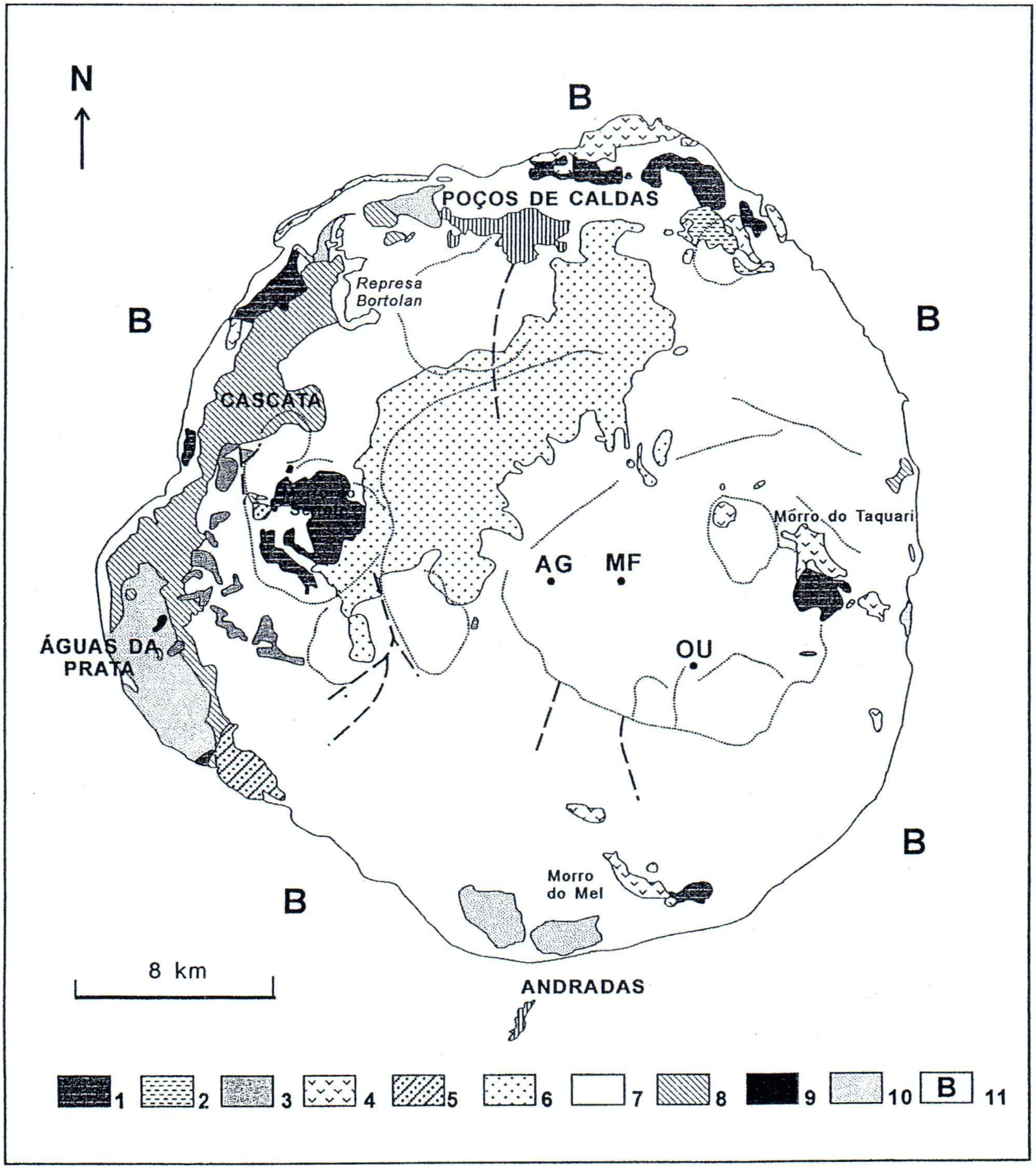

Figure 9 *- Simplified geologic map of the Poços de Caldas massif. 1: agpaitic nepheline syenites (NeS); 2: NeS with pseudoleucites; 3: porphyritic NeS; 4: grey NeS; 5: biotite-bearing NeS; 6: NeS, Pedreira facies; 7: tinguaites and phonolites, undifferentiated; 8: volcanoclastic deposits (to the W, Vale do Quartel strip); 9: diabase; 10: sandstones and related sediments; 11: B: undifferentiated basement rocks (cf. also Fig. II.2). AG: Campo do Agostinho; MF: Morro do Ferro; OU: Osamu Utsumi open pit. Faults as heavy lines, "circular structures" as dotted lines. Map by H. Ulbrich. Source:* [5].

All NeS are intrusive within the finer-grained rocks, which are frequently also incorporated as enclaves in NeS (in some cases, with structures showing commingling relationships); contacts between the two rock types, where observed, are always sharp. Several facies of NeS can be defined, recognized by variations in their grain size, texture, color, and characteristic accessory minerals. These facies are divided into agpaitic or miaskitic-intermediate varieties, on account of the presence (or absence) of rare metal silicates (usually Na-bearing, with no Al, together with cations such as Ba, Ca, Sr, U, Th, REE, Zr, Mn, etc.) of which eudialyte, in Poços de Caldas, is the most conspicuous one, even becoming a rock-forming minerals in lujavrites and khibinites (respectively, foliated eudialyte mela-NeS, with needle-like aegirine, and massive to laminated eudialyte NeS with prismatic aegirine. Biotite is present in significant amounts only in one NeS facies (cf. Fig. 9). The largest single NeS facies is the Pedreira intermediate type (over 80 km^2 of exposures), with a typical patchy texture; it crops out as an elongated mushroom-shaped body (Fig. 10).

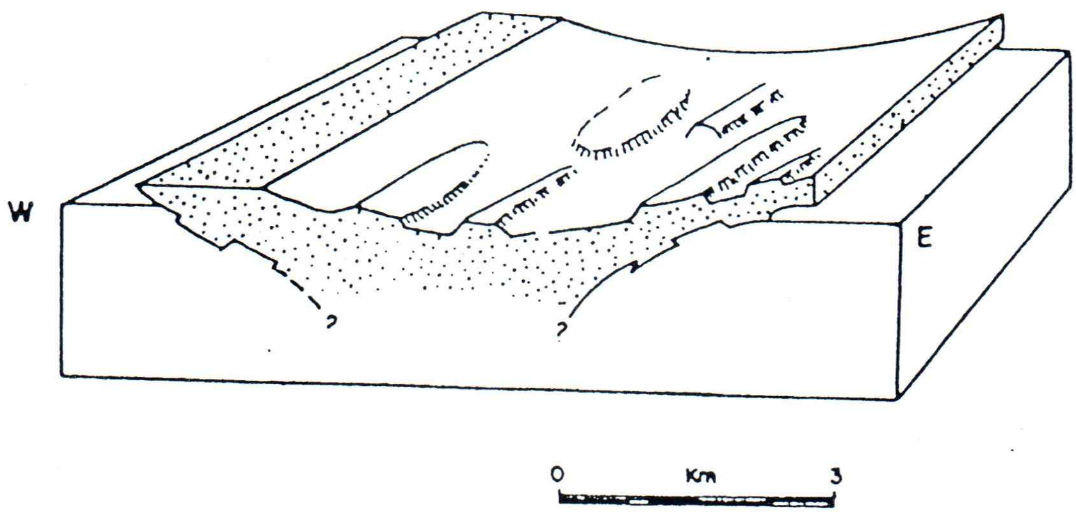

***Figure 10** - Shape of the large Pedreira facies of NeS. For location, see Fig. 9. Source:* [5].

The northernmost agpaitic NeS (Fig. 9) are found as two small, unconnected bodies with a marked stratified structure of magmatic origin, composed entirely by eudialyte-bearing NeS. The smallest of the two, to the W, has the better outcrops, showing at the center a coarse lujavrite (Lu I), surrounded by a thin rim of a finer-grained variety (Lu II) and two NeS with a trachytoid (oriented) texture (NeS I and NeS II, the last one somewhat coarser and with less eudialyte); the structure is completed by an outer apron of khibinites (NeS III), with prismatic poikilitic aegirines and eudialyte-rich patches. The foliations are subhorizontal at the center (with Lu I) and show steeper dips at the margin (Lu II, NeS I and NeS II) (cf. Fig. 11). The eastern of the two bodies, with poor outcrops, shows a similar petrographic zonation.

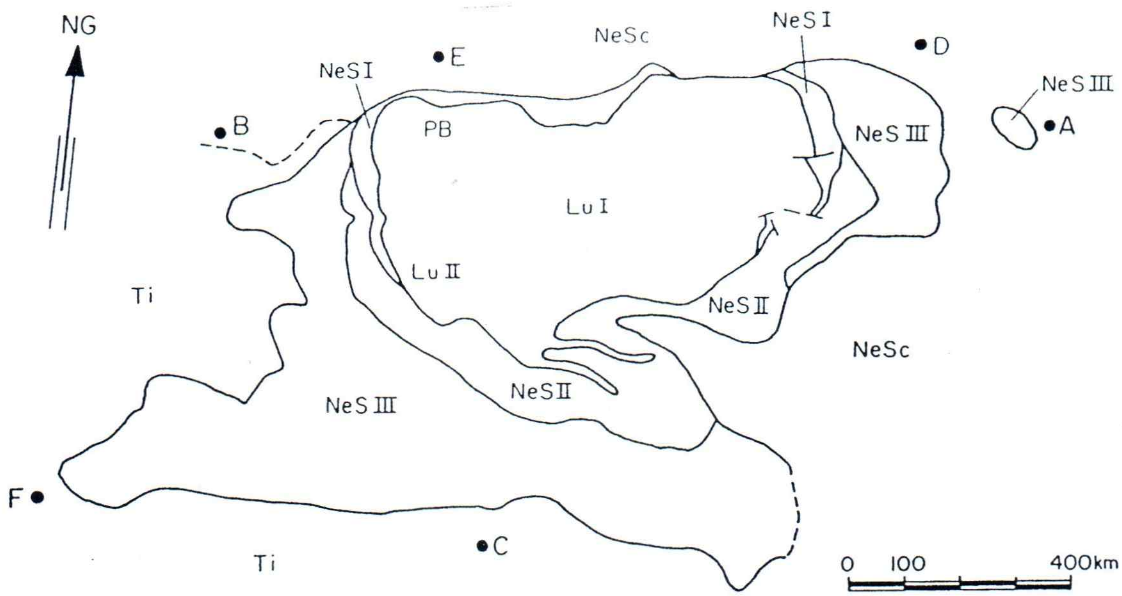

***Figure 11** - Geologic map of the W lujavrite-khibinite body, northern rim, Poços de Caldas (see location in Fig. 9). Plane-table map by H. Ulbrich. Source: [5] . Lu I and Lu II: coarse-grained and finer-grained lujavrites. NeS I, II and III: the two trachytoid NeS and khibinite (NeS III). NeSc: grey NeS. Ti: tinguaite. PB: Pedra Balão, the "balloon rock", a local landmark.*

Geologic observations and textures indicate that most of the phonolites and subvolcanic tinguaites were the first rocks to be emplaced, later to be followed by discrete and separate intrusions of NeS; the presence of commingling features in some NeS bodies indicates that the last ones were intruded into still hot and partly fluid tinguaites. Field observations show that the less differentiated miaskitic to intermediate NeS in the district are older than the more differentiated agpaitic varieties (e.g., khibinites of the western lujavrite body are intrusive into grey NeS and tinguaites; Fig. 9). A few phonolitic dikes cut NeS. The ultramafic-mafic dikes and volcanoclastic Vale do Quartel rocks are mostly later than the feldspathic phonolitic-syenitic event in Poços de Caldas, as suggested by the presence of fragments of NeS within agglomerates and by geologic observations (e.g., linear geometry of the Vale do Quartel; lack of evidence that the flanking tinguaites intruded the volcanoclastic rocks). Other ultramafic occurrences, such as the dikes in the Minas Pedras quarry and Osamu Utsumi mine, are also considered somewhat younger than the associated phonolitic-tinguaitic and syenitic rocks.

Structural setting

Topographically, the tinguaites that form the contact areas stand out to the N, W and S as higher rims, probaly representing the remnants of true ring dikes (cf. also Fig. 8). No faults were observed cutting these rim areas, contrary to interpretations expressed by other authors. Marked "photo-lineations", observed on aereal photographs and images, are considered by many authors as faults, but may have originated as erosion lines along joint systems, brecciated zones, etc. A few "circular structures" are also present within the massif, representing either true structures or, in part, the result of erosional activity within regions with different petrographic types and/or alteration; the largest is the "eastern-central structure" with a diameter of about 10 km (cf. below, "Hydrothermal alteration").

Ellert in 1959 [7] considered that Poços de Caldas represents a caldera, with interior areas that were depressed by collapse, at the same times allowing for the intrusion of peripheral ring dikes. This interpretation is based mostly on geomorphic features, since a lack of good outcrops makes it difficult to find corroborating structural evidence. There is no doubt, however, that the rim of the massif is an area of weakness, since most of the smaller NeS intrusions are located within this region, or close to it, where they appear as elongated bodies, parallel to the rim. At the NW contact, a fluorite-bearing grey NeS is emplaced as a true discontinuous ring dike (Fig. 9).

Petrography

The supracrustal *phonolites* are aphanitic rocks with a purplish color, usually more altered than others, showing frequently elongated vesicles. *Tinguaites* are the subvolcanic fine-grained equivalents, mostly aphyric or with small and infrequent sanidine and nepheline phenocrysts; their color is a characteristic greenish-grey to greenish-black. The most common assemblage is made up of K-feldspar (sanidine or otrhoclase), fresh or partially altered nepheline, and greenish pyroxene (Na-augite to aegirine), strongly to weakly pleochroic, together with several opaque phases, sphene, etc.; textures are usually "tinguaitic", with feldspar laths, nephelines as squares and irregular grains, and pyroxenes as disoriented needles [5]. Other tinguaite varieties show, in addition, some albite laths and several acessory minerals such as rare-metal silicates (e.g., astrophyllite $(K_2,Na_2,Ca)(Fe,Mn)_4(Ti,Zr)[OH,Si_2O_7]_2)$, rare eudialyte and/or villiaumite, etc. A remarkable variety of tinguaite shows large (2-5 cm) to very large (> 5 cm) idiomorphic pseudoleucite crystals (= nepheline-K feldspar intergrowth), isolated or as clusters of several phenocrysts, often accompanied by cm-sized sanidines and some larger pyroxenes, all set in a fine-grained to aphanitic matrix with K feldspar, nepheline and pyroxene; they appear as dikes or pods in several parts of the district. Most of the pseudoleucite dikes are intrusive into tinguaites, but some also cut NeS (e.g., in the Osamu Utsumi open pit). Tinguaites can also be divided into agpaitic and intermediate-miaskitic varieties, although this division is mostly observed only in thin sections.

Nepheline syenites are varied. The predominant minerals are always K-feldspar (orthoclase to maximum microcline [10]), partially altered nepheline, and pyroxene (egirine to Na-augite). The most common texture shows an unoriented web of tabular K-feldspars enclosing smaller feldspars and the other minerals (foyaitic texture [11]; "ditroitic" textures, with more stubby K-feldspars, are less frequent). The agpaitic NeS are characterized by enrichment in several rare metals (such as Mn, Zr, Ti, REE, U, Th, etc.; cf. references in [12]), thus showing a variety of accessory minerals, of which eudialyte, $Na_6Ca_3(Ca,Mn)_{<2}(Zr,Nb)_{<2}[Cl_{0.5}.Si_3O_9.Si_9O_{25}(OH)_2]$, is the most common of them all, sometimes even constituting a rock-forming mineral. Biotite, a typical miaskitic mafic mineral, is rather rare in Poços de Caldas, only present as a significant phase in one NeS facies (Fig. 9); the typical mafic mineral of the Poços de Caldas intermediate to miaskitic NeS is a Na-augite to aegirine-augite. The most agpaitic rocks are the Na-rich lujavrites and khibinites found in some small bodies along the N rim and in other areas of the massif (Fig. 9); in both rocks, eudialyte is a rock-forming phase. A single body of NeS is characterized by showing mostly rounded pseudoleucite. K-rich agpaitic rocks were not found in Poços de Caldas (wadeite $K_2ZrSi_3O_9$, for instance, is a very rare mineral in the district; leucite, although cited in the literature, may actually correspond to pseudoleucite intergrowths).

The larger blocks in the Vale do Quartel are constituted by fragments of lavas, with clinopyroxene phenocrysts in an altered aphanitic matrix, which also shows vesicles (cf. descriptions in [5,7]). A fresh mica lamprophyre dike at the Osamu Utsumi mine shows brownish phlogopite both as phenocrysts and in the matrix, together with olivine, clinopyroxene, calcite (in part primary) and other acessory minerals [9,13,14]. The Minas Pedras dikes and pods are constituted by massive to banded lamprophyres (with phlogopite, Ca-pyroxene, calcite and several acessory minerals), carbonatite veins with calcite and micas, and a phlogopite-biotite pyroxenite with clinopyroxene phenocrysts [15-17].

Hydrothermal alteration

Large areas of the massif were affected by hydrothermal alteration. Original magmatic textures and structures are preserved, but the primary mineralogy is entirely substituted by a hydrothermal assemblage. The color is a typical buff to greyish-bege to blue-grey in the *reduced* rock with the "unaltered" hydrothermal minerals, but more yellowish-brownish in the incipiently weathered (*=oxidized*) type. The hydrothermal K-feldspar, without losing its textural identitity, is chemically and structurally reconstituted, passing to almost pure $KAlSi_3O_8$, while very fine-grained sericite completely replaces nepheline. Pyrite is the main Fe phase in the reduced rock, present as pervasively distributed little cubes and also in veins and along fractures; the mineral passes into goethite, other Fe hydroxides and hematite in the oxidized horizons. The primary mafic minerals are converted into illite, carbonates and Fe hydroxides. Kaolinite is less frequent in the reduced rocks, appearing only as minor aggregates or in veinlets; the mineral is much more common in the oxidized rock. Geochemically, the hydrothermal alteration leaches out principally Ca, Na and Mg, with concomitant introduction of K, H_2O and CO_2, hence the local name "potassic rock" ("rocha potássica"); the material is now used, although still in a limited way, to produce fertilizer.

The distribution of the "potassic rock" is outlined on the Poços de Caldas map produced by the CNEN(Comissão Nacional de Energia Nuclear)-Nuclebrás geologists (Fig. 12). The "potassic rock" passes in a gradational way into the completely weathered equivalent, with the destruction of the primary textures and a very significant increase in the amounts of kaolinite, gibbsite, and amorphous and crystalline Fe- and Mn-hydroxides, while illite and K-feldspar tend to disappear [5,6,20].

The alteration event is (somewhat) later than the emplacement of the magmatic rocks, since tinguaites and phonolites, as well as NeS, are affected by hydrothermal alteration. The large "eastern-central circular structure"(Figs. 9, 12), with over 100 km^2 of outcrop surface, is almost entirely converted into "potassic rock". In this area, the rock is also strongly cracked by myriad of fractures, to such an extent that it is difficult to sample larger pieces; especially affected by fractures are tinguaites. This alteration pattern suggests that the hydrothermal alteration is intimately associated with a concomitant heavy fracturing of the country rock, enhancing the pervasive flow of H_2O-rich fluids through the rock fabric. This model indicates that the hydrothermal alteration and the associated ore bodies are strongly connected to the emplacement of the local magmas; therefore, radiometric ages of the fresh rocks and the hydrothermally altered variety, if accurate, should overlap.

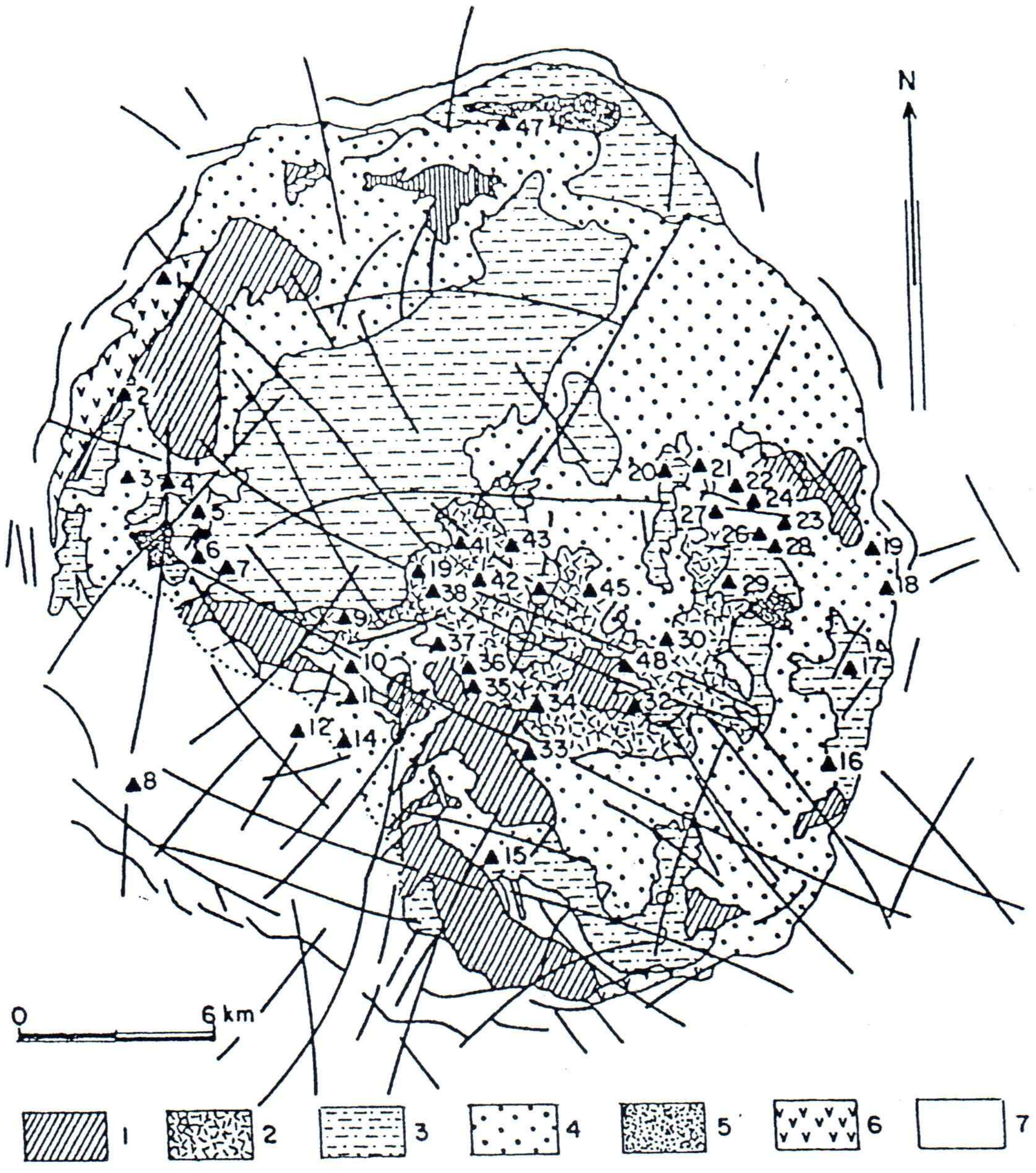

Figure 12 - Geologic map of the Poços de Caldas massif by geologists of the Brazilian CNEN, Nuclear Energy Comission (before 1974), with ammendments by Nuclebrás geologists, shown to outline the presence of the "potassic rock" formed by hydrothermal alteration. 1: aphanitic phonolite; 2: potassic rock; 3: nepheline syenite; 4: microgranular phonolites (tinguaites); 5: lujavrites and khibinites; 6: pyoclastic rocks; 7: unmapped areas. Triangles and numbers refer to mineralized occurrences (mainly caldasites, U-Th sites). For references, cf. [5,18,19].

The relationship between mineralization, hydrothermal alteration, and intrusive phenomena is well-depicted in and around the "eastern-central circular structure", which possibly represents the site of emplacement of late subvolcanic intrusions. The envisaged model is as follows. While cooling, the subvolcanic magma bodies generated a second-boiling process with production of overpressure, thus triggering pervasive fracturing and a marked increase in permeability, which in turn allowed the flow of interstitial fluids and strong chemical interaction with the host rock. The result is a very thorough hydrothermal alteration with accompanying mineralizations (cf. literature for porphyry coppers in [21]).

Mineralizations

Several typical ores are found in intimate association with hydrothermal alteration (Fig. 12). One ore-forming process is characterized by the generation of caldasite, an intergrowth of zircon $ZrSiO_4$ with baddeleyite ZrO_2, usually emplaced within vertical veins. Poços de Caldas is the type locality for caldasite, which is found on the ground as heavy, cm- to mm-sized grey pebbles; in some unusual cases, meter-sized irregular to angular blocks of caldasite are preserved, representing the original shape of the material in the mother vein, unearthed by erosion and prospectors. The Poços de Caldas caldasite is remarkable for its unusually high U-content. Caldasite was heavily mined by prospectors up to the seventies. The second hydrothermal ore in Poços de Caldas is that represented by the U-Zr-Mo assemblage, typically associated with breccias; the two most important examples are the one at Campo Agostinho, a linear mineralized breccia, and the breccia pipe that gave rise to the Osamu Utsumi open pit mine (cf. Fig. 9). A map of the open pit is presented in Figure 13. Uranium and REE minerals are found in the breccias and in the oxidized potassic rock; the mineralization was certainly polyphasic, depositing minerals such as pitchblende (colloform to massive UO_2), uraninite (cubic UO_2), brannerite ($UTiO_6$) and monazite (Ce,REE)(PO_4), as well as zircon and other minerals; molibdenite MoS seems to be the only true primary Mo phase present in the mine. Several secondary minerals were also described, mainly assorted phosphates, among them bluish Mo-coquimbite $(Mo,Al,Fe)_2(SO_4)_3.9H_2O$ and other ill-defined Mo species. Significant mineral changes, such as the deposition of secondary pitchblende, occur along the redox front, separating the reduced assemblage from the oxidized one [20].

Another unusual occurrence at Morro do Ferro, within tinguaites converted into "potassic rock", shows discontinuous magnetite dikes within a superficial patch with a remarkable Th-REE anomaly; it has been interpreted as the site of a strongly altered and weathered carbonatite intrusion [9,20,22] . On textural grounds, several minerals were recognized as primary phases, among them bastnaeseite (Ce,La,REE)(CO_3)F, thorite $ThSiO_4$, monazite (REE)PO_4, pyrochlore $(Na,Ca)_2(Nb,Ti,Ta)_2(OH,F,O)$ and zircon, while others are considered secondary, such as cerianite $(Ce,Th,U)O_2$, thorianite $(Th,U)O_2$, Nd lanthanide $(La,Nd)_2(CO_3)_3.8H_2O$, and several others [22] .

The single most important material of economic interest in Poços de Caldas is of course bauxite, developed by weathering on top of both NeS and tinguaites. Two varieties are distinguished: the rim or ridge bauxites, on the steeper hills, richer in Al, and the plateau bauxites on the plains, found mostly within the massif, in areas with a smoother topography. The main laterite minerals are gibbsite, kaolinite, halloysite and goethite company (for more data, see [23]). One of the largest Al-smelting facilities in Brazil is located in Poços de Caldas, operated by the Alcoa.

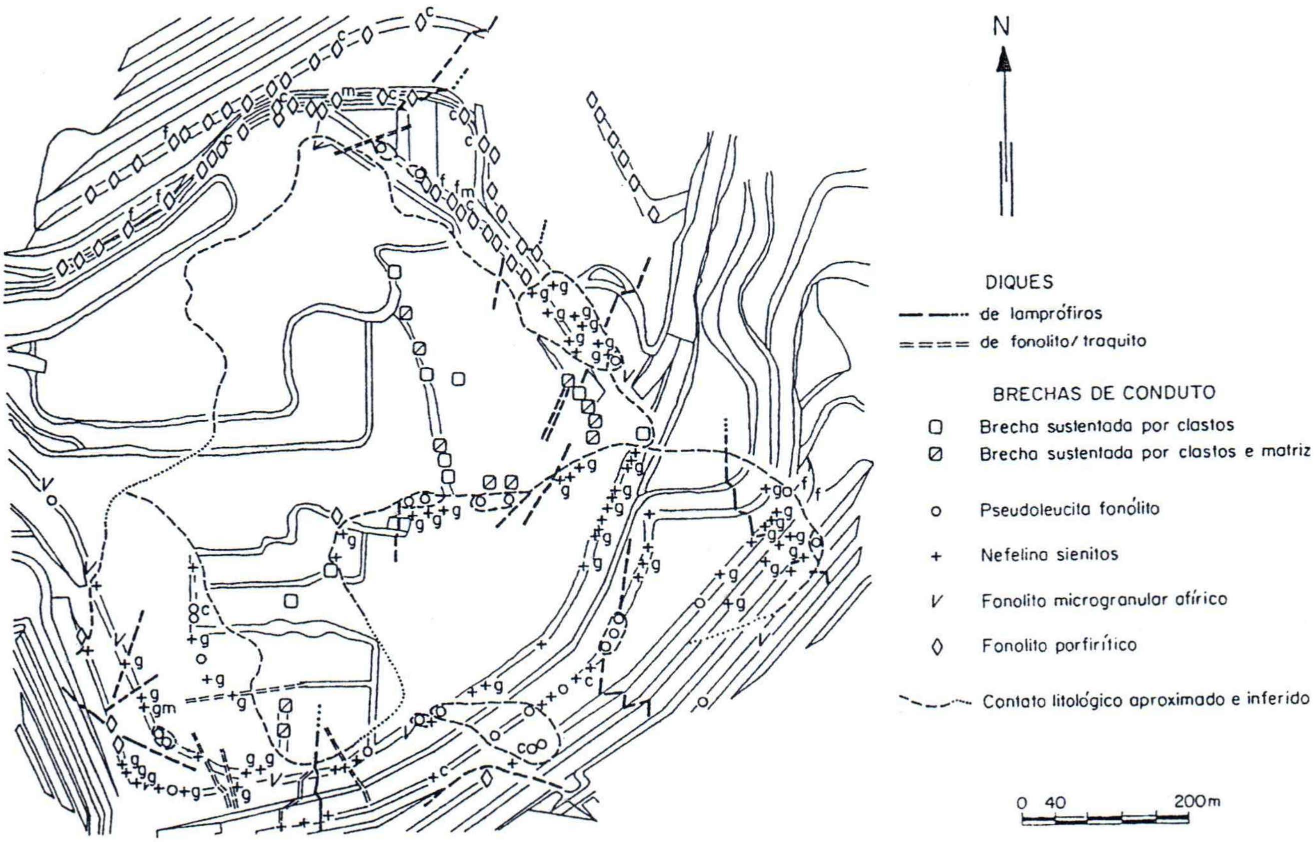

Figure 13 - Geologic map of the Osamu utsumi open pit. Indicated are the dike rocks (biotite lamprophyres and phonolites/trachytes), conduit breccias (both clast- and clast-matrix supported), pseudoleucite phonolites, NeS, and aphyric and porphyritic phonolites (=tinguaites). C= craquelée, "cracked" rock; f: fragmentation breccia (with non-rotated angular fragments); g: coarse- to very coarse grain size; m: myarolitic cavities. Geology by H.Ulbrich, topographic base by Nuclebrás (1982-1983) (cf. also [6,18,20] ; for mineralogy, cf. text and [6,20])

Geochemistry

Both NeS and phonolites are intermediate rocks, very similar as far as major and minor elements are concerned, but with significant variations in the abundance of trace elements (therefore, agpaitic, intermediate, and miaskitic varieties). On the whole, the Poços de Caldas alkaline rocks are relatively enriched in K, Mn and Sr, when compared with other alkaline districts of the world. Typically, most rocks show K_2O > 6 weigth %, and may reach >12% in certain grey NeS of the northern rim; for most rocks, the K_2O/Na_2O ratio (weight %) is over 1, while only a few agpaitic rocks show an excess of Na_2O over K_2O (foremost, among them, lujavrites and khibinites). The agpaitic rocks are typically peralkaline, with increased amounts of Zr (mostly between 500 and 4000 ppm), Mn (usually above 0,20 %, up to 0,55%) U (up to 2000 ppm), Nb (over 300-500 ppm), Th, and REE. The intermediate to miaskitic varieties are usually moderately peralkaline to metaluminous. The district is unusually enriched in Sr, most rocks showing over 700 ppm, with the highest values observed in some miaskitic-intermediate varieties (over 5000-6000 ppm; e.g., the Pedreira NeS); Ba contents (up to 1000 ppm) show a general positive correlation with Sr. Normative K-feldspar, albite and nepheline of these rocks plot in and around the undersaturated valley in the quartz-nepheline-leucite phase diagram, between the ternary eutectic points at H_2O-pressures between 1 and 5 Kb (corresponding to a minimum depth of roughly 3 km). Some geochemical and isotopic data suggest that at least some subvolcanic phonolites (tinguaites) belong to different genetic lineages than the NeS and the volcanic phonolites (H.Ulbrich, unpublished data; cf. also [9]).

Petrogenetic interpretations indicate that the feldspar-rich Poços de Caldas rocks derived from mantle melts, probably initiated with the generation of ultrabasic to basic magmas, with differentiation by removal of clinopyroxenes and/or olivines (cf., for instance, [24,25]). The agpaitic rocks can be derived from the more miaskitic-intermediate varieties by removal of K-feldspar and nepheline.

The more ultrabasic varieties, at least in part associated with carbonatites (cf. Petrography, above), are genetically different rocks, representing mantle melts coming from different depths and/or different protoliths. Chemical data [13,17,20] show similarities between the Osamu Utusumi and Minas Pedras ultrabasic occurrences: they are potassic to ultrapotassic rocks, with high contents of Ti and of several incompatible elements, and present a low mg number, mostly less than 0.60. The basic-ultrabasic magmas are probably the evolved liquids of more primitive parents, and are also broadly similar to the potassic basic-ultrabasic rocks of the Paranaiba and Serra do Mar provinces [24,25].

As indicated by some isotopic data, the felsic and basic-ultrabasic magmatisms are not clearly related. The initial $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotope ratios (for T= 79 Ma; cf. Ages, below) of the ultrabasic rocks are more primitive than those of the phonolites and syenites; the respective ε parameters vary between $(-0.2) < \varepsilon Nd < (0.4)$ and $(-1.5) < \varepsilon Sr < (3.0)$ for the first rocks and between $(-3.0) < \varepsilon Nd < (-4.6)$ and $(6.5) < \varepsilon Sr < (11.0)$ for the latter [14,15,16] . These values suggest that the ultrabasic magmas derived from more primitive, and possibly carbonated, lithospheric mantle sources, but it is also possible that the initial isotopic characteristics of the more felsic rocks were changed by an added crustal contribution. The thermal driving mechanism that triggered the two contrasted magmatisms has been attributed by some authors to the passage of the Trindade mantle plume [25,26] .

Ages

The first K-Ar ages for alkaline rocks in southern Brazil, and also for Poços de Caldas, show a variation between 78 and 89 Ma (for the agglomerates in the Vale do Quartel) to 54 Ma (tinguaite dikes); most NeS (including a lujavrite) show K-Ar ages between 61-63 Ma, most tinguaites and phonolites between 64 and 82 Ma [27,28,29]. The total age span of these dates is over 34 Ma, and can hardly be accurate; in part, it contradicts geologic observations (e.g., commingled tinguaite within NeS; coexistence of NeS and tinguaites, to be explained by cooling of NeS magmas within still hot tinguaites, at rather shallow depths; etc.). New data were obtained by Rb-Sr geochronology: an age of 83 (±21) Ma, initial ratio of 0.7052 (±3) for the lujavrites and khibinites and of 88 (±8) Ma, i.r. 0.7051 (±2) for the northern-rim grey NeS [30]. Better data yielded a Rb-Sr isochron age of 79 (±7) Ma, i.r. 0.70511 (±1) for the Pedreira NeS, and of 77 (±3), i.r., 0.7052 (±2) for a hydrothermally altered NeS from a borehole in the Utsumi mine [23]. The unaltered phlogopite lamprophyre outcropping at the Osamu Utsumi mine yields phlogopite ^{40}Ar-^{39}Ar ages of 75.7 (0.6) and 76.2 (1.6) Ma (phenocrysts and groudmass, respectively) [14].

Combining the best ages with geologic observations, the following sequence can be considered. Most tinguaites erupted at about 79 Ma, followed by the intrusion of most NeS magmas, which acquired their coarser texture by cooling within still very hot, and in part liquid, tinguaites; the agpaitic NeS are somewhat later than the intermediate-miaskitic ones. The district-wide hydrothermal mineralization, together with the most important U-Mo-Zr breccia mineralization, is closely related to the intrusive episodes, and should show ages of around 78-79 Ma. The subordinate basic-ultrabasic magmatism is represented by the Utsumi lamprophyres, the Morro do Ferro occurrences, the Minas Pedras silico-carbonatitic dikes and pods and, most importantly, by the Vale do Quartel lavas, agglomerates and tuffs. The Ar-Ar age of 76 Ma shown by the Utsumi dike may represent the true age of this basic-ultrabasic magmatism.

Further evidence is provided by paleomagnetic studies [31]. About 70 samples from the Poços de Caldas syenitic-phonolitic rocks show reverse polarity, while the three succesfully analysed samples taken from the Vale do Quartel rocks, regarded as fragments from lava flows, present normal magnetization. The ages here proposed of around 79 Ma for the syenitic-phonolitic magma emplacement would place the eruption of these rocks erupted into the 33r Campanian reverse polarity episode (between 83 Ma and 78.8 Ma), while the somewhat younger basic-ultrabasic magmatism probably invaded during the 33n Campanian normal polarity event (< 78.8 Ma; for polarity ages, cf. [32]).

FIELD TRIP STOPS

The localities worth visiting, within easy reach of buses or cars, are indicated in Figure 14. Some comments follow.

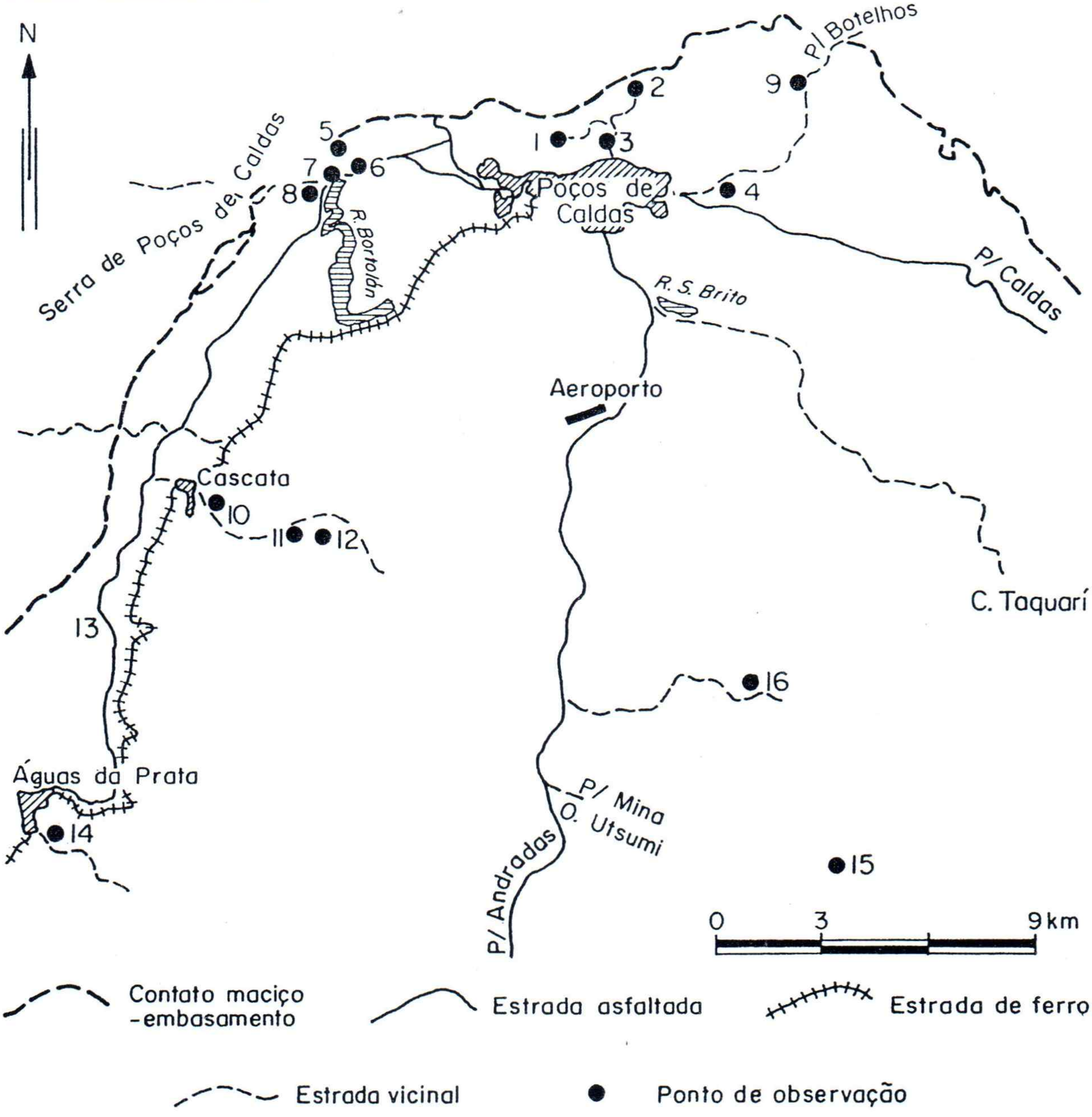

Figure 14 - Geologic points of interest in Poços de Caldas. Localities 1, 2, etc.

Locality 1

Statue of Jesus Christ, on top of the Serra de São Domingos, north of the locality of Poços de Caldas, accesible by a paved road and also by cable car. The ridge is formed by typical aegirine tinguaites. This site allows a panoramic view to the S, showing the marked western and southern ridges, the eastern contact and, outside of the Poços de Caldas massif, the crescent-shaped Pedra Branca syenitic massif (altitudes over 1600 m).

Locality 2

The "balloon rock", Pedra Balão, a local tourist point, located on the outside of the northern tinguaite ridge. Access by paved road. The balloon rock and the surrounding blocks are coarse-grained lujavrites, surrounded by shells of trachytoid NeS and rimmed, on the outside, by khibinites. It is the westernmost of two contiguous lujavrite-khibinite bodies. The nearby ridge limits the Poços de Caldas massif, to the N, and is made up by grey NeS. Aegirine tinguaites limit this lujavrite body to the W, S and E (cf. Figs. 9 and 11).

Locality 3

Breccia strip cutting the northern tinguaite ring. Outcrops along the paved road to the Christ statue. Structurally an agmatite (cm. to dm.-sized fragments in a tinguaitic matrix with sanidine and nepheline phenocrysts) or a tinguaite with xenoliths. Some fragments are syenitic to pyroxenitic in composition, others are fine-grained to aphanitic lavas.

Locality 4

The abandoned Prefeitura "pedreira"(quarry), on a side road cutting the northern rim, along the paved Poços de Caldas-Caldas road. Abandoned quarry cut into the inequigranular intermediate Pedreira NeS, with a typical spotty appearance. Observed are also pegmatoid segregations and cm to dm-sized vugs, filled with a secondary mineralogy (fluorite, analcime $NaAlSi_2O_6.H_2O$, pyrite, kutnahorite $CaMn(CO_3)_2$, calcite, white to yellow natrolite $Na_2Al_2Si_3O_{10}.2H_2O$, ilmenite and various Mn and Fe oxides-hidroxides); quartz crystals were found in only one vug sample. A phonolite dike, with sanidine phenocrysts, cuts the NeS. Conspicuous are also the several joint systems. Compare the cited secondary mineralogy with the one found at the Bortolán quarry in tinguaites (locality 8). *Comment*: permission to visit the quarry is granted by the Poços de Caldas "prefeitura" (municipal authorities).

Locality 5

Paved road, cutting the incomplete ring dike (Fig. 9), formed by the "fluorite NeS" facies type. A variety of the grey NeS cropping out mainly along the northern and eastern flanks of Poços de Caldas, it shows conspicuously fluorite as a secondary mineral, together with some pyrite.

Locality 6

Sand quarry cut into sandstones of the Triassic Botucatú Formation, showing typical large-scale cross-bedding of eolian origin. The siliceous cement, which holds together the sandstones elsewhere (e.g., at the "Veú das Noivas", a small cascade close-by) has been leached out in this sand quarry, possibly by the action of interstitial acid waters (superimposed bogs, now eroded away?).

Locality 7

Paved road, Águas da Prata-Poços de Caldas, a few hundred meters from locality 6. Breccia with alochthonous fragments, mainly constituted by basement rocks and xenocrysts (quartz, microcline), in a greenish matrix with secondary minerals (pyroxene needles, fluorite).

Locality 8

The abandoned Bortolán quarry cut into agpaitic tinguaites of the western rim. This fine-grained rock shows irregularly distributed mm. to cm.-sized xenomorphic pseudoleucites (nepheline-K feldspar intergrowth, more granular at the center, with a radial texture at the border), frequently also observed in tinguaites in the whole district. Conspicuous are pegmatoid veins (aegirine, K feldspar, natrolite) and vugs of various sizes (cm. to dm.) filled with several secondary minerals (both fibrous and prismatic aegirine, K feldspar, analcime, natrolite, rinkite, calcite, fluorite, villiaumite NaF, strontianite $SrCO_3$, fibrous palygorskite $(Mg,Al)_2[OH,Si_4O_{10}].2H_2O$ $+2H_2O$, apophyllite $KCa_4(Si_4O_{10})2F.8H_2O$, Mn oxides-hydroxides and minerals of the hainite group $\{Na_2Ca[Ti(OH)_2(Si_2O7)_2]\}\{Ca_3(Ca,Mn,Fe,Ce)\}F_2$,.[33]). Several joint systems are observed, in part coated with secondary minerals (K feldspar, smectites, kaolinite, etc.).

Locality 9

Blocks of the Botelhos khibinite, along an unpaved road that cuts the northern rim in direction to the locality of Botelhos. This agpaitic NeS is inequigranular, presenting eudialyte and the typical prismatic-poikilitic pyroxenes of the Poços de Caldas khibinites.

Locality 10

Outcrops of the porphyritic NeS facies, along an unpaved road that leads to the Morro do Serrote, within the massif (immediataly after crossing a small river; cf. triangular shape of this small NeS body in Fig. 9). *Comment*: larger vehicles, such as buses, can reach this point, but not localities 11 and 12, especially during the rainy season (september-november to march-april).

Locality 11

Pseudoleucite dikes at the Morro do Serrote. Same road as before, winding its way along the western flank of the Morro do Serrote, close to the contact of tinguaites with the Serrote NeS (cf. Fig. 9). These dikes appear with a "pinch- and swell" structure, and show large to very large (up to 10-15 cm) pseudoleucites of the euhedral type, with well-developed trapezohedral faces, set in a aphanitic to fine-grained matrix. More often than not, the pseudoleucites are observed as clusters of phenocrysts, associated with some large (2-5 cm) sanidines and prismatic aegirines; nepheline and K feldspar show a granular habit at the center, and a "palisade" texture at the border, with K-feldspar oriented perpendicular to the outline of the phenocryst. An altered, violet-coloured phonolite is found a few hundreds meters to the S, along a depressed and more weathered area, showing K-feldspar and typical reddish-violet rounded phenocrysts that resemble analcime, actually converted into a microcrystalline intergrowth of nepheline and K-feldspar.

Locality 12

Same road as before, at the contact of the Serrote eudyalite NeS with tinguaite. The Morro do Serrote, entirely underlain by this NeS, is interpreted as the root zone of a volcano (?): it lies at the center of one of the "circular structures" (cf. Fig. 9, and [5]).

Locality 13

Several points along the Vale do Quartel, with volcanic blocks and road cuts, beginning somewhat to the S of the locality of Cascata and almost up to the entrance to Águas da Prata. The larger blocks are somewhat altered, showing mostly pyroxene phenocrysts and irregular to elongated vesicles and amygdules; some cuts (e.g., found along the rail track) expose what are interpreted as in-situ lava flows. The flanking rocks are constitued by aegirine tinguaites, with some minor bodies of the porphyritic variety of NeS (cf. Fig. 9). A monolith at the Fonte Paiol, a mineral water facility, showing about 100 m of borehole samples, displays the large variety of lavas and breccias that constitute the Vale do Quartel rocks; minimum thickness of this volcanoclastic strip is 450 m. *Comment*: the entrance to the Fonte Paiol can be found along the paved road, a few km N of Águas da Prata.

Locality 14

An unpaved east-groing road, its road cuts presenting an alternation of m-sized massive sandstone with laminated siltstone beds . These rocks may belong to the Aquidauana Formation (considered by some as the equivalent of the basal Upper Carboniferous Itararé Subgroup). The limit of the Poços de Caldas massif, at Águas da Prata, shows a conspicuous small belly-like outgrowth to the SW, interpreted as the "Águas da Prata structure", possibly representing a cognate smaller intrusion of tinguaites, still capped by sandstontes [5] .

Locality 15

The abandoned open pit Osamu Utsumi mine, the largest ore occurrence within the "central-eastern circular structure". Access by the paved road Poços de Caldas-Andradas, within the massif, and then by a secondary paved road to the mine. Hydrothermally altered "potassic rocks" are predominant. The structural-textural varieties of rocks to be observed are: tinguaites, pseudoleucite tinguaites, NeS (unidentified facies, possibly of the Pedreira type), lilac biotite lamprophyres, breccias at the center of the mine, all of them altered. NeS and especially tinguaites are strongly fragmented ("craquelée"). The open pit is capped by weathered rock with no structure. Both the oxidized and reduced varieties of the hydrothermally altered rocks are clearly observed, respectively with reddish-yellowish and bege-greyish colors: presence or absence of pyrite defines either the reduced or the oxidized type. The oxidation-reduction front is clearly marked along the banks of the open pit. A local factory was used for the manufacture of yellow cake up to the eighties; the facilities are now used for Th and REE separation using monazite sands as raw material. *Comments*: permission to visit the mine is granted by its owner INB, Industrias Nucleares do Brasil, with offices on the road Poços de Caldas-Andradas.

Locality 16

The Morro do Ferro ("iron mountain"), with access from an unpaved road that leads to the paved Andradas-Poços de Caldas road. Altered tinguaites ("potassic rocks") are predominant at the Morro do Ferro, showing a set of magnetite dikes (some up to 5 m in thickness, with lenghts of up to 500 m). Part of the Morro is covered by a patch of weathered material, enriched in Th and REE, incorporated into microcrystalline minerals. *Comments*: the unpaved road may be impassable for larger vehicles during the rainy season.

REFERENCES

[1] Haddad R.C. 1995. O batólito granitóide Pinhal-Ipuiúna (SP-MG): um exemplo do magmatismo cálcio-alcalino potássico neoproterozóico no sudeste brasileiro. Doctor's thesis, Instituto de Geociências, University of São Paulo, 270 p (unpublished).

[2] Haddad R.C., Janasi V.A. & Ulbrich H.H.G.J. 1997. Caracterização geoquímica preliminar dos granitóides aflorantes na vizinhança do batólito Pinhal-Ipuiúna (SP-MG). Revista Brasileira de Geociências, 27, 129-138.

[3] Janasi V.A. 1999. Petrogênese de granitos crustais na Nappe de empurrão Socorro-Guaxupé (SP-MG): uma contribuição da geoquímica elemental e isotópica. Habilitation thesis, Instituto de Geociências, University of São Paulo, 302 p (unpublished).

[4] Paradella W.R. & Almeida Filho R. 1976. Condicionamento das mineralizações radioativas no Planalto de Poços de Caldas baseado em imagens MSS do Landsat. In: Congresso Brasileiro de Geologia, 29, Ouro Preto, 1976, Anais ... Ouro Preto, SBG, v. 3, 181-190.

[5] Ulbrich H.H.G.J. & Ulbrich M.N.C. 1992. O maciço alcalino de Poços de Caldas, MG-SP: características petrográficas e estruturais. In: Congresso Brasileiro de Geologia, 37, São Paulo, Roteiro de Excursões...São Paulo, SBG, v.5, 64 p.

[6] Garda G.M. 1990. A alteração hidrotermal no contexto da evolução geológica do maciço alcalino de Poços de Caldas, MG-SP. Master's thesis, Instituto de Geociências, University of São Paulo, 213 p. (unpublished).

[7] Ellert R. 1959. Contribuição à geologia do maciço alcalino de Poços de Caldas. Boletim da Faculdade de Filosofia, Ciências e Letras, USP, no. 237, Geologia no. 18, 5-63.

[8] Björnberg A.J.S. 1959. Rochas clásticas do Planalto de Poços de Caldas. Faculdade de Filosofia, Ciências e Letras, USP, Boletim 237, Geologia 18, 65-123.

[9] Schorscher H.D. & Shea M.E. 1992. The regional geology of the Poços de Caldas alkaline complex: mineralogy and geochemistry of selected nepheline syenites and phonolites. Journal of Geochemical Exploration 45, 25-51.

[10] Ulbrich M.N.C. 1993. Mineralogy of nepheline syenites from the Poços de Caldas alkaline massif, SE Brazil: chemistry, X-ray data and microtextures of feldspars. Revista Brasileira de Geociências, 23, 388-399.

[11] Johannsen A. 1938. A descriptive petrography of the Igneous Rocks. Vol. IV: Feldspathoidal rocks. Peridotites and Perknites. University of Chicago Press, Chicago, 523 p.

[12] Sorensen H. (editor). 1974. Alkaline Rocks. Wiley, London, 622 p.

[13] Schorscher H.D., Garda G.M., Shea M.E. & Waber N. 1991. Lamprophyre dikes form the Utsumi uranium mine, Poços de Caldas (MG), Brazil. In: International Symposium on Mafic Dykes, São Paulo, 1991. Extended Abastracts... São Paulo, 116-124.

[14] Shea M.E. 1992. Isotopic geochemical characterization of selected nepheline syenites and phonolites from the Poços de Caldas alkaline complex, Minas Gerais, Brazil. Journal of Geochemical Exploration 45, 173-214.

[15] Vlach S.R.F., Ulbrich M.N.C. Ulbrich H.H.G.J. & Gualda G.A.R. 1996. Rochas de afinidades alnoíticas e sílico-carbonatíticas periféricas ao maciço alcalino de Poços de Caldas (MG-SP). In: Congresso Brasileiro de Geologia, 39, Salvador, 1996, Anais...Salvador, SBG, v. 2, 128-130.

[16] Vlach S.R.F., Ulbrich H.H.,G.J. & Ulbrich M.N.C. 1998. Isótopos radiogênicos (Sr, Nd) e estáveis (C, O) de rochas máfico-ultramáficas potássicas da região de Poços de Caldas, MG-SP: inferências

sobre a natureza do manto litosférico mesozóico. In: Congresso Brasileiro de Geologia, 40, Belo Horizonte, 1998, Anais ... Belo Horizonte, SBG, p.475.

[17] Ulbrich M.N.C., Vlach S.R.F. & Ulbrich H.H.G.J. 1998. Geoquímica dos diques de rochas máfico-ultramáficas potássicas periféricas ao maciço de Poços de Caldas, (MG-SP). In: Congresso Brasileiro de Geologia, 40, Belo Horizonte, 1998, Anais ... Belo Horizonte, SBG, p.469.

[18] Oliveira A.G. 1974. Mineralização de urânio e molibdênio no Planalto de Poços de Caldas, MG. In: Congresso Brasileiro de Geologia, 28, Porto Alegre, Anais... Porto Alegre, SBG, v.1, 207-221.

[19] Utsumi O., Oliveira A.G., Parisi C.A. Williams D.D. 1971. Roteiro de escursões: Poços de Caldas. In: Congresso Brasileiro de Geologia, 25, São Paulo, 1971, Roteiro de Excursões, Boletim Especial ... São Paulo, SBG, v.2, 7-13.

[20] Waber N., Schorscher H.D. & Peters Tj. 1992. Hydrothermal and supergene uranium mineralization at the Osamu Utsumi mine, Poços de Caldas, Minas Gerais, Brazil. Journal of Geochemical Exploration 45, 53-112.

[21] Sawkins F.J. 1990. Metal Deposits in Relation to Plate Tectonics. 2d. edition, Springer, Berlin, 461 p.

[22] Waber N. 1992. The supergene thorium and rare-earth element deposit at Morro do Ferro, Poços de Caldas, Minas Gerais, Brazil. Journal of Geochemical Exploration 45, 113-157.

[23] Schulman A., Carvalho A. & Valeton I. 1997. Bauxite of Poços de Caldas. In: A. Carvalho, B.Boulangé, A.J. Melfi & Y. Lucas (editors): Brazilian Bauxites. USP/Fapesp/Orstom, São Paulo, 229-254.

[24] Gibson S.A., Thompson R.N., Dickin A.P., Leonardos O.H. 1996. High Ti- and low-Ti mafic potassic magmas: key to plume-lithospheric interactions and continental flood-basalt genesis. Earth and Planetary Sciences Letters 141, 325-341.

[25] Thompson R.N., Gibson S.A., Mitchell J.G., Dickin A.P., Leonardos O.H., Brod J.A., Greenwood J.C. 1998. Migrating Cretaceous-Eocene magmatism in the Serra do Mar alkaline province, SE Brazil: melts from the deflected Trindade mantle plume? Journal of Petrology 39, 1493-1526.

[26] Thomaz Filho A. & Rodrigues A.L. 1999. O alinhamento de rochas alcalinas Poços de Caldas-Cabo Frio (RJ) e sua continuidade na Cadéia Vitória-Trindade. Revista Brasileira de Geociências 29, 189-194.

[27] Amaral G., Bushee J., Cordani U.G., Kawashita K. & Reynolds J.H. 1967. Potassium-argon ages of alkaline rocks from southern Brazil. Geochimica et Cosmochimica Acta 31, 117-142.

[28] Bushee J. 1971. Geochronological and petrographic studies of alkaline rocks from southern Brazil. Ph.D. thesis, Department of Geology and Geophysics, UC Berkeley, 145 p. (unpublished).

[29] Sonoki I.K. & Garda G.M. 1988. Idades K-Ar de rochas alcalinas do Brasil meridional e Paraguai oriental: compilação e adaptação às novas constantes de decaimento. Boletim IG-USP, Série Científica 19, 63-85.

[30] Kawashita K., Mahiques M.M. & Ulbrich H.H. 1984. Idades Rb/Sr de nefelina sienitos do Anel Norte do maciço alcalino de Poços de Caldas, MG-SP. In: Congresso Brasileiro de Geologia, 33, Rio de Janeiro, 1984, Resumos... Rio de Janeiro, SBG, 244-245.

[31] Montes Lauar C.R., Pacca I.G., Melfi A.J. Kawashita K. 1995. Late Cretaceous alkaline complexes, southeastern Brazil: paleomagnetism and geochronology. Earth and Planetary Sciences Letters 134, 425-440.

[32] Cande S.C. & Kent D.V. 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. Journal of Geophysical Research 97, 13917-13951.

[33] Atencio D., Coutinho J.M.V., Ulbrich M.N.C., Vlach S.R.F., Rastsvetaeva R.K. & Puschcharovsky D.Y. 1999. Hainite from Poços de Caldas, Minas Gerais, Brazil. Canadian Mineralogist 37, 91-98.