

# THE LUJAVRITE AND KHIBINITE BODIES IN THE POÇOS DE CALDAS ALKALINE MASSIF, SOUTHEASTERN BRAZIL: A STRUCTURAL AND PETROGRAPHIC STUDY

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**RESUMO** OS CORPOS DE LUJAVRITO E KHIBINITO DO COMPLEXO ALCALINO DE POÇOS DE CALDAS, SUDESTE DO BRASIL: UM ESTUDO ESTRUTURAL E PETROGRÁFICO. Dois pequenos corpos de lujavritos e khibinitos, oriental e ocidental, afloram no anel norte do maciço alcalino de Poços de Caldas, SE do Brasil. Mapeamento detalhado revela, no centro da estrutura do corpo ocidental, melhor exposto, um eudialita nefelina sienito de granulação grossa, mesocrático e de aspecto gnáissico (lujavrito, Lu I), com foliação subhorizontal, e variedade mais fina (Lu II) de borda. Como envelope externo, aparecem dois nefelina sienitos (NeS) traquítoides (NeS I e II), circundados por um eudialita NeS grosseiro (khibinito ou NeS III). A estrutura dos dois corpos citados é similar à de um lopolito, com uma seqüência concordante (em parte incompleta no oriental) mostrando as facies Lu I - Lu II - NeS I - NeS II, com mergulhos moderados a fortes na região de contato entre elas; por fora, espalha-se o NeS III. As rochas encaixantes são tinguaítos e um NeS cinzento anterior, NeS IV. Tinguaítos são as primeiras rochas intrusivas (idades de 76-80 Ma), seguidas pela intrusão dos NeS (idades similares), com intrusão do NeS IV anterior à dos lujavritos e facies associadas. A intrusão dos corpos de Lu I-II e NeS I-II foi um processo contínuo, iniciado com a invasão forçada subhorizontal de magma khibinítico. O surgimento de magma subsequente comprimiu a massa magmática inicial, gerando por compactação e extração de líquidos residuais uma capa lujavritica, com estrutura foliada subhorizontal e Lu II na borda. Ao mesmo tempo, ocorreu expansão lateral da câmara magmática. Neste maciço, magmas agpáiticos são sempre intrusões tardias. Uma comparação com outras ocorrências de lujavritos (Ilímaussaq, Lovozero, Pilansberg, Trans-Pecos) sugere que colocação forçada de magmas deve ser o processo que controla a geração das estruturas e texturas de lujavritos.

*Palavras chaves:* Lujavritos - Chibinitos - Nefelina sienitos - Maciços alcalinos

**ABSTRACT** Two small lujavrite-khibinite bodies, an eastern and a western one, are exposed at the northern edge of the alkaline Poços de Caldas massif, southeastern Brazil. Detailed mapping reveals at the center of the better exposed western body a coarse-grained, mesocratic, gneissic-looking eudialyte nepheline syenite (lujavrite) with a strong subhorizontal foliation (Lu I), showing at the contacts a finer-grained border facies (Lu II). Two trachytoid nepheline syenites (NeS I and II) occur as an envelope to the central lujavrites, followed by an outer shell of coarse-grained eudialyte NeS (NeS III or khibinito). The internal structure of both bodies is that of a saucer, with successive foliated shells (in part absent in the eastern body) constituted by Lu I - Lu II - NeS I-NeS II, with rather steep dips at the contacts between the different facies; all are surrounded by the outer NeS III. Country rocks are tinguaítos and a grey NeS (NeS IV). Tinguaítos were the earliest rocks (intruded some 76-80 Ma ago), followed by the coarser rocks, with NeS IV emplaced before the lujavrites and associated types. The emplacement of the lujavrite bodies was a continuous process, initiated with forceful subhorizontal intrusion of strongly agpaitic magmas. Magma upwelling compressed the initial magma batch, generating the lujavrite caps by compaction and liquid extraction, with a foliated subhorizontal structure (Lu I) and an outer shell (Lu II). The intrusion forced at the same time a lateral expansion of the magma chamber. In this massif, agpaitic magmas appear always as late intrusions. A comparison with other occurrences (Ilímaussaq, Lovozero, Pilansberg, the Texan Trans-Pecos province) suggests that emplacement under forceful conditions may be a controlling factor in shaping the final fabric of lujavrites.

*Keywords:* Lujavrites - Khibinites - Nepheline syenites - Alkaline massifs

**INTRODUCTION** The late Cretaceous Poços de Caldas alkaline massif, southeastern Brazil (Fig. 1), with its over 800 km<sup>2</sup>, was first mentioned in early classic petrographic papers (e.g., Derby 1887, Machado 1888). The first geologic map was made available by Ellert, Coutinho and Björnberg (Ellert 1959, Björnberg 1959, cf. also Utsumi et al. 1971, Putzer 1976). Tinguaítos and phonolites (comprising together 80% of outcrops) and nepheline syenites (NeS, 17%) are predominant (Fig. 1). Also observed is a narrow N-S trending irregular trench, close to the western margin of the district, comprising poorly exposed lava flows and predominant pyroclastic rocks (3% of outcrops, showing tuffs, breccias and agglomerates, with fragments of ankarartrites, phenocrustic rocks, etc.). Recently, additional data were presented on the petrography and mineralogy of the nepheline syenites (NeS) (Ulbrich 1983, Ulbrich 1984, Ulbrich et al. 1984, Schorscher & Shea 1992).

Earlier K-Ar geochronological data (Amaral et al. 1967, Bushee 1974) suggested a long magmatic history (from 87 Ma for ankarartrites to 53 Ma for phonolite dikes; data corrected to the 1977 Steiger & Jaeger constants lower these figures by about 2.5%; Sonoki & Garda 1988). Two whole-rock Rb/Sr isochrons were obtained by Kawashita et al. (1984), with ages of 89.8 (±2.8) Ma and an initial Sr<sup>87</sup> / Sr<sup>86</sup> ratio of 0.7050 (±1) (grey NeS and a fluorite-bearing NeS), and 86.3 (±6.0) Ma (i.r., 0.7052 ±1; lujavrites and khibinites). Shea (1992) presents two Rb-Sr isochrons, one based on 4 whole-rock samples of the centrally-located Pedreira NeS type (age of 74.2 ±6.3 Ma, i.r. of 0.70511 ±1), the other a combined mineral and whole-rock isochron (7 data points; age of 77.9 ±3.1 Ma, i.r. of 0.70512 ±1; Ulbrich 1984, Ulbrich & Ulbrich 1992, Chapman et al. 1992; for ages, see especially Shea 1992).

The massif, probably emplaced as a caldera-like structure (Ellert 1959), shows at its present shallow erosion level still significant amounts of engulfed sandstones, mostly attributed to the aeolian Botucatú Formation (Ellert 1959, Björnberg 1959, Oliveira et al. 1984).

A composite intrusion (about 3 km<sup>2</sup>) is found on the topographically prominent Poços de Caldas northern tinguaite rim,

mainly constituted by eudialyte NeS ("lujavrite and khibinite" in Fig. 1). Lujavrites are observed as two disconnected small bodies within the more abundant khibinites.

The present contribution is mainly concerned with a structural study of these two northern lujavrite-khibinite bodies, based on detailed mapping of the several petrographic facies encountered in these outcrops (see inset in Fig. 1).

**PETROGRAPHY AND MINERALOGY** Relevant maps are presented in figures 2 and 3. Two lujavrite types (Lu I and II) were identified, showing transition into one another. Three additional NeS (NeS I, II and III) are found as envelopes to the central lujavrites; all are Na-rich rocks. NeS IV is an earlier K-rich rock. All phaneritic rocks are intrusive into the northern-rim tinguaítos. Macroscopic and microscopic features are depicted in figures 4, 5 and 6; modes are presented in Table 1.

**Macroscopic descriptions** The *type I lujavrite* (Lu I) is a mesocratic, foliated, coarse-grained inequigranular NeS. Feldspars are present as oriented idiomorphic thin plates (up to 2-3 cm in length). Nepheline appears as smaller buff-colored or reddish idiomorphic grains. Aegirine occurs as thin mm-sized needles forming wavy sheaves but without a pronounced lineation. The rock structure is that of an augen or flaser gneiss (cf. Shand 1947, also Sorensen 1974b, p. 401). Bright reddish-pink to pinkish purple eudialyte, a main constituent, appears as irregularly distributed eudialyte-rich patches (sizes varying from one to 4-5 cm); the individual grains are anhedral to subhedral.

The *type-II lujavrite* (Lu II) is medium-grained and more parallel-textured than Lu I; eudialyte is usually a minor component.

*NeS I* is a leucocratic fine- to medium-grained rock with a trachytoid texture; aegirines are isolated, euhedral, mm-sized prismatic to acicular grains. Accessories are eudialyte, fibrous aggregates of golden-brown astrophyllite (plus some lamprophyllite) and felty masses of a whitish acicular mineral (rinkite?).

*NeS II* is a coarser-grained equivalent of NeS I, with less eudialyte and other accessories.

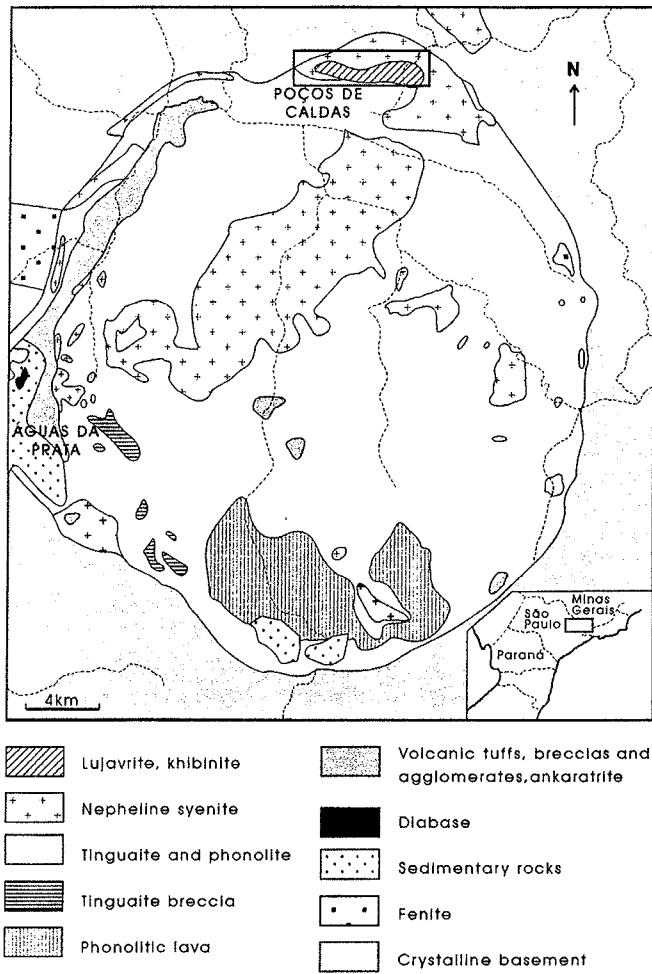


Figure 1 - Geologic map of the Poços de Caldas massif, states of São Paulo (SP) and Minas Gerais (MG), southeastern Brazil, after Ellert 1959. The area shown in figure 2a is outlined.

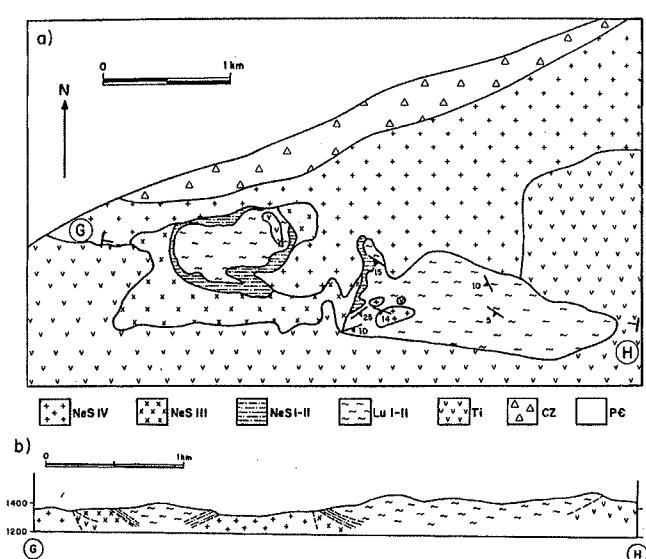


Figure 2 - a) Map of the two lujavrite occurrences, northern border of the massif (cf. Fig. 1). Contacts are approximate or inferred. CZ: contact zone, mainly supracrustal migmatitic-granulitic rocks of the Caconde Complex, cut by massive, fine-grained tinguaite dikes, veins, and lenses. Lu: lujavrite; NeS: nepheline syenites (for facies, see text); PC: Precambrian Caconde Complex; Ti: tinguaites. b) Geological section along line GH, based on maps of figures 2a and 3a.

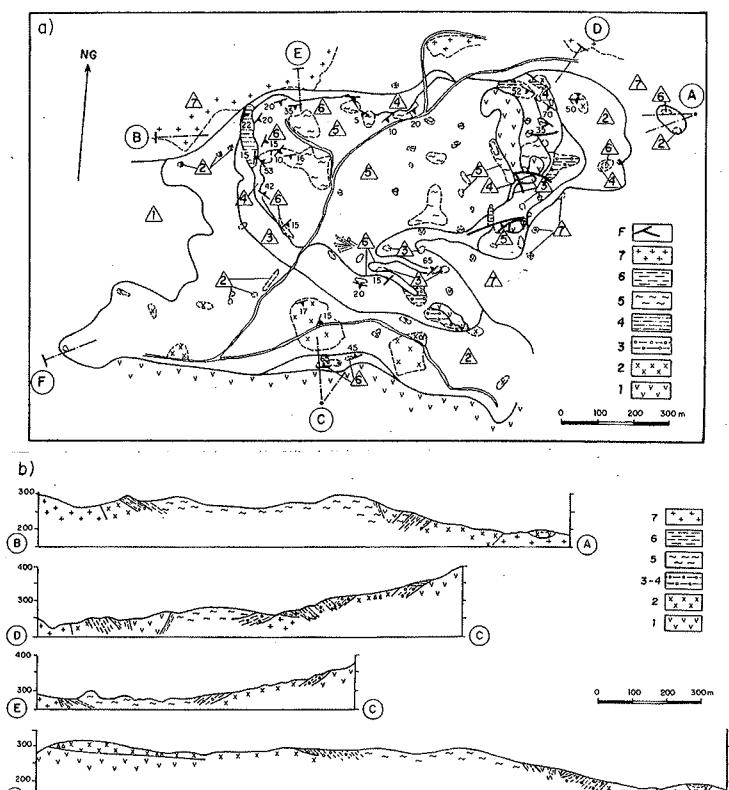


Figure 3 - (a) - Detailed map of western lujavrite body, based on a 1:5000 plane-table survey. Dirt roads and trails marked with conventional symbols. Actual outcrops outlined by light dashed lines. Heavy continuous lines are observed or approximate contacts. Triangles identify areas with many tinguaite xenoliths. Legend: 1: tinguaite; 2: khibinite, NeS III; 3: coarser trachytoid NeS II; 4: fine-grained trachytoid NeS I; 5: coarse lujavrite, Lu I; 6: fine-grained lujavrite, Lu II; 7: NeS IV; F: faults. (b) - Geological sections across the western lujavrite body. Base for vertical scale is an arbitrary altitude of 300 m at the initial plane-table station (marked as heavy dot; actual altitude: 1350 m). Legends as in Fig. 3a (3-4: both NeS I and II). The three segments of lujavrites and NeS I-II in profile CD are probably connected as parts of an eroded sheet; dips of contacts for this sheet, in the southern part of CD, have been exaggerated.

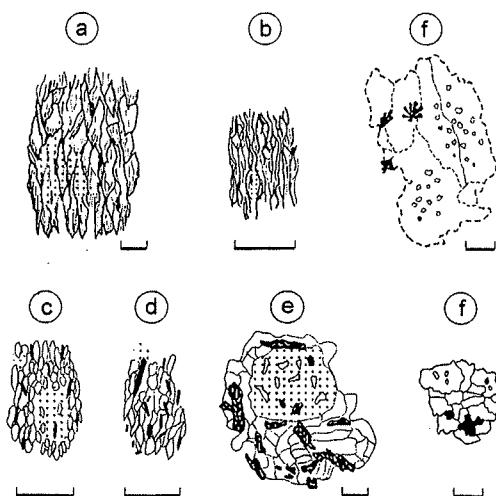


Figure 4 - Macroscopic aspect of the different phaneritic rock types. Aegirine in black, eudialyte-rich patches identified by dots, dominant feldspar and subordinate nepheline with no ornament. Bar represents one cm. a: Lu I; b: Lu II; c: NeS I; d: NeS II; e: NeS III (khibinite); f: two varieties of NeS IV.

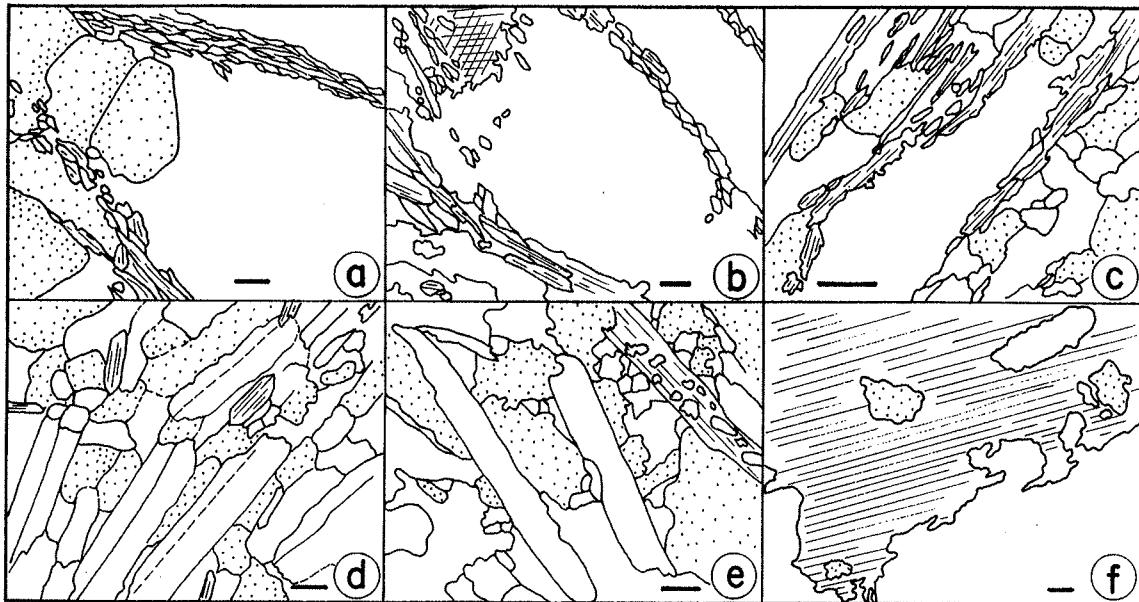


Figure 5 - Microscopic aspects of mapped facies. Bar represents 0.2 mm. Dashes: aegirine; dots: nepheline; blank: alkali feldspar; a, b: eye-like felsic crystals or aggregates in Lu I, surrounded by continuous aegirine sheafs; in b, a large amphibole plate encloses aegirine needles; c: Lu II, more parallel textured and leucocratic than Lu I; d: medium-grained trachytoid texture of NeS I, with some small euhedral aegirine prisms; e: medium to coarse-grained trachytoid texture in NeS II; aegirine is already partly poikilitic; f: large poikilitic grain of aegirine II in NeS III, enclosing smaller nephelines and alkali feldspars. Drawings from photographs.

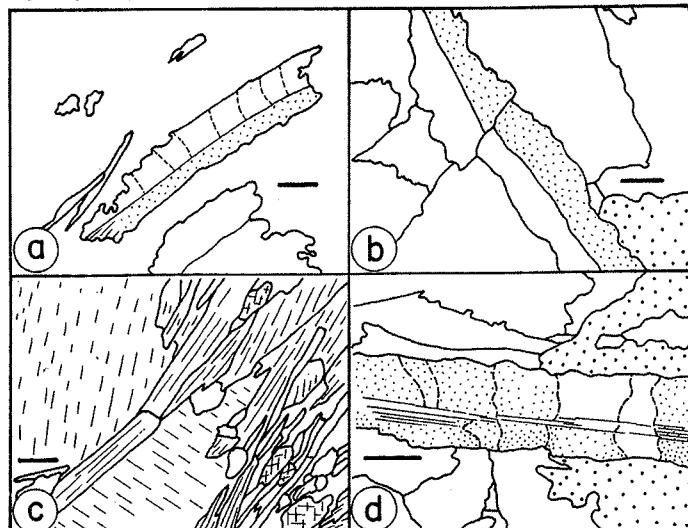


Figure 6 - Deformation features in NeS and lujavrites. Bar represents 0.2 mm. Larger dots: nepheline; blanks, dots or short dashes: K-feldspar or albite; long dashes: aegirine. a: bent crystals of alkali feldspar in Lu I, with incipient mortar structure, in a matrix of eudialyte, catapleite and aegirine (not represented as single phases); b: a blade-like alkali feldspar; broken and partly annealed at one of its ends (in NeS III); c: a long broken aegirine needle in Lu I (center of figure); d: albite crystal with incipient mortar structure, in NeS I (outlined domains with marked differences in extinction). Drawn from photographs.

NeS III is a khibinite (Johannsen 1938, p.107-108, Gerasimovsky et al. 1974, p.214 ff). Textures are usually massive, sometimes foliated. Subidiomorphic whitish laths of K-feldspar and small nepheline grains form a foyaitic fabric which includes large (up to 1-3 cm) subidiomorphic poikilitic aegirines, with jagged borders and irregular terminal outlines. Eudialyte is concentrated in cm-sized conspicuous patches. Strongly foliated varieties were also observed locally; they are either almost massive and hololeucocratic, or show a faint banding marked by an alternation of felsic and subordinate mafic layers.

NeS IV is a leucocratic grey massive rock, mostly coarse- to very coarse-grained. Subhedral K-feldspars (up to 3-4 cm) poikilitically encloses round millimetric grains of nepheline (similar to the rischorrites, but without symplectitic intergrowths; Gerasimovsky et al.

1974, p.214). Irregular to acicular aegirine and platy biotites occur as isolated grains or aggregates. Astrophyllite and pink eudialyte are observed as accessories in samples close to the contact with khibinites; these minerals are late metasomatic phases, crystallizing from fluids derived from khibinite magmas, adding volatiles together with Na, Fe and Zr to the NeS IV (cf. also Gualda 1998, Gualda & Vlach 1996).

Pegmatite veins are found in Lu I, as irregular patches or lenses, rarely over 1 or 2 m in length, and in NeS III as dikelets within fractures (lengths of a few m to tens of m, thickness of up to 25 cm).

Tinguaites (i.e., fine-grained to aphanitic greenish-grey equivalents of phonolites) are usually massive, aphyric or with some sanidine or nepheline phenocrysts. Tinguait xenoliths, observed in all NeS, vary from small cm-sized specimens to blocks of mappable dimensions (see Fig. 3).

**Microscopic descriptions and mineral chemistry** Some microscopic details of these rocks are shown in figure 5. Data on mineral chemistry are quoted in Table 2 (Ulbrich 1983, 1993, for rock chemistry, see Ulbrich 1984).

Lu I is, as all described NeS in this paper, a hypersolvus rock. Nepheline is distinctly euhedral or subhedral, usually much smaller than K-feldspar. It is a meso-potassic variety (1.0 to 2.0 K atoms per formula). Aegirine occurs as pleochroic, slightly zoned needles and slender prisms, with growth faces parallel to those of the felsic minerals. Frequently, the borders of microcline crystals are crowded with aegirine needles, leaving the central part of the grain with an eye-like appearance (Fig. 5). Minor arfvedsonite (about 1 %) is found as larger anhedral plates with inclusions of euhedral aegirine. Eudialyte-eucolite, restricted to the patchy areas, appears as interstitial grains typically with an irregular sector-zoning; it is frequently altered to catapleite and other unidentified minerals. Main alteration phases of felsic minerals are analcime, natrolite and cancrinite (Table 1).

Lu II (Table 1) is usually albite-bearing. The albite is very fresh, with irregular borders; its orientation, in general, cuts at a low angle the planar structure of the rock. Some minor arfvedsonite is observed as aegirine replacement. Another important mafic mineral is eudialyte. Accessory phases are astrophyllite, lamprophyllite, a rinkite-like mineral, pectolite, normandite and in minute proportions several unidentified minerals (cf. data in Gualda, 1998).

The textures of khibinites (NeS III; Table 1) are partly foyaitic, partly hypidiomorphic inequigranular; K-feldspars are observed as primary euhedral laths, as irregular plates, and also as interstitial grains and overgrowths. Nepheline shows larger compositional variations than in lujavrites (Table 2). Aegirine is observed as variety I (subordinate, slightly pleochroic, occurring as small euhedral prisms), the predominant variety II (typical large poikilitic grains, with sector

Table 1 - Modal composition of lujavrites and associated rocks, Poços de Caldas.

Facies	Lu I	Lu I	Lu II	NeS I	NeS II	NeS III	NeS IV	NeS IV	NeS IV
Sample number	P46 (2)	P10/5 (2)	P161/134 (2)	P163 (1)	P164 (1)	P47/173 (2)	P205/177 (coarse) (3)	P49d (medium) (1)	P131 (medium) (1)
K feldspar	38.2	33.8	46.0	49.3	49.2	59.0	59.1	64.4	58.0
Albite			0.8	1.0	2.2				
Nepheline <sup>1</sup>	24.8	17.2	24.9	27.7	30.2	18.6	25.1	27.0	27.4
Natrolite <sup>2</sup>	tr	11.5	tr		0.5				2.6
Analcime <sup>3</sup>	tr		8.8	8.5	7.0	tr			0.4
Zeolites <sup>4</sup>	tr			tr		tr			
Sodalite	tr					tr			
Cancrinite			tr	tr			4.5	0.2	
Na-pyroxene	27.3	27.4	17.1	8.6	5.8	10.1	8.7	5.6	7.6
Amphibole <sup>5</sup>	0.7	0.8					0.7	tr.	0.2
Biotite			<0.1	tr	tr	tr		tr	
Rinkite mineral									
Lamprophyllite <sup>6</sup>				<0.1		tr	0.9	tr	
Eudialyte <sup>7</sup>	7.6	3.7	1.6	4.1	0.9	7.9			
Catapleiite	tr	3.8							
Opaques	tr								0.9
Others <sup>8</sup>	4.4	1.5	0.8	0.8	4.3	4.2	0.7	3.0	2.9

1: some alteration included; 2: alteration of Kf/Ne; 3: mostly alteration of Ne; 4: analcime + natrolite; 5: mostly arfvedsonite;

6: lamprophyllite and astrophyllite; 7: eudialyte-eucolyte; 8: sphene, fluorite, unidentified species, also opaques.

In parenthesis, number of counted thin sections.

Table 2 - Textures, color index and mineral chemistry of lujavrites and associated rocks, Poços de Caldas.

	Lujavrite I (Lu I)	Lujavrite II (Lu II)	NeS I	NeS II	NeS III (khibinites)	NeS IV (grey Nes)
Texture Grain size Color Index	"Gneissic" fabric Coarse to medium >33	Parallel-textured Medium to fine ~10-25	Trachytoid Fine-medium ~10-15	Trachytoid Medium <12	Massive (foyaitic) Coarse-medium 15-25	Massive (foyaitic) Coarse to medium <11
KF:Ne ratio KF Or:Ab:An	≤2:1 86-95:13-5:~0.2	≤2:1 84-88:16-12:<0.2	≤2:1 84-86:14-15.5:<0.2	<2:1 As in NeS I	~2:1 * 88-99:13-1:<0.2	>2:1 94-98:6-1:<0.2 up to Or 100
Fe2O3 %	0.54-0.6	1.5-2.0%	>99: <1	>99: <1	As in NeS I	
Albite Ab:An						
Ne Ne:Ks:Qz Fe2O3 %	70-73:25-23:3-5 0.4-0.6	74:19-21:6-7 1.5-2.0	73-74:19-21:5-8 0.9-3.3	As in NeS I As in NeS I	72-74:21-27:1-5 0.3-2.5	73:24-26:1-3 0.5-2.0
Aegirine Di:Hd:Ac	C 6-9:12-16:68-75 B 1-4:2-9:73-88	C 8-12:17-22:62-68 B 6-9:8-14:69-78	C 10:17:65 B 5:11-15:73-78	C 8-11:11-18:63-71 B 5:11-15:73-78	0.2-2.4:81-85 (no color) to 4-6:13-21:62- 70 (green)**	0.5-8:15:70-76***
Arfvedsonite MnO % TiO2 % Biotite MnO % TiO2 %	3.4-6.0 up to 1.5	As in Lu I			As in Lu I	2.0-5.0 2.3-4.1

C: core, B: border of pyroxenes. KF: K feldspar; Ne: nepheline. Ne, Ks, Qz: nepheline, kalsilite and excess quartz components in Ne (weight %). Di, Hd, Ac: diopside, hedenbergite and acmite components in aegirine (mol %; Ti, Al-Na, etc. components not included). For references, see text. \* (NeS III): macroscopically, usually < 2: 1; \*\* (NeS III) colorless and colored refer to zones in sector-zoned main pyroxene (type II, see text). \*\*\* (NeS IV): medium-green aegirines (lighter colored aegirines have different composition, cf. Ulbrich 1983).

and irregular oscillatory zoning; Fig. 5) and the hydrothermal late aegirine variety III (strongly pleochroic, parallel or radiating fibers). Sporadically, arfvedsonite replaces aegirine. Eudialyte is sector-zoned and interstitial to the main minerals (although partly idiomorphic) and partially altered to catapleiite. Analysis of eudialyte and other rare silicates can be found in Gualda & Vlach (1996). A few grains of small (0.2 mm) euhedral sodalite are enclosed within K-feldspar. The most frequent accessory minerals are a rinkite mineral, acicular astrophyllite and anhedral to subhedral sphene, a late strongly colored violet fluorite, and several unidentified rare-metal silicates. Alteration is widespread: interstitial cancrinite, replacing both feldspar and

nepheline, and analcime and platy natrolite are secondary minerals.

NeS I and NeS II are very similar trachytoid rocks (Table 1; Fig. 5). Nephelines show a large *qz* number (Table 2). The aegirines are usually idiomorphic prisms; in NeS II, the largest aegirine prisms are filled with inclusions (transition to NeS III). Laths of albite are present in both rocks. Eudialyte is less frequent in NeS II. Additional phases in NeS I are astrophyllite and a rinkite mineral, together with some unidentified subordinate species. Secondary analcime and natrolite are frequent. Some analcime is probably a primary mineral (for other minerals, cf. also Gualda, 1998).

NeS IV shows a K-feldspar/nepheline ratio usually well over 2:1. K-

feldspar encloses small euhedral to subhedral nepheline (Fig. 4); nepheline is also in part interstitial. Mafic minerals are mainly clusters of zoned aegirine with minor biotite (Fig. 4); biotites are irregularly zoned (Fe biotites with a strong yellowish-brownish pleochroism, Mg biotites with a yellowish uniform color).

**Deformation** Signs of deformation are observed in NeS I, II and III, and especially in lujavrites, but are restricted to individual grains and do not affect the rock as a whole (see broken or bent minerals in Fig. 6).

**Order of crystallization and the fluid-rich nature of the magmas** The observed textures show that in these agpaitic rocks nepheline is the first main mineral to crystallize, either together with K feldspar, or shortly before it. Aegirines, also mostly magmatic minerals, crystallize later; the exception are the smaller euhedral type-I aegirines in khibinites and the pyroxene prisms in NeS I and II, which apparently crystallized early in the magmas. The frequently observed face-to-face contact between these three minerals suggests the coexistence of all three phases at a late, but still magmatic stage. They were probably drawn together as "cumulates" by dynamic processes. Interstitial growth of aegirine and feldspar is important only in khibinites and to some extent in coarse lujavrites. It is the result of either intercumulus crystallization (e.g., feldspar borders in NeS III) or, as in the case of fibrous aegirines, of late-magmatic to deuteritic addition of material, with metasomatic introduction of Fe, Na, F, etc. Other important mafic minerals (eudialytites in all NeS; arfvedsonite as an accessory phase in Lu I) are late and in part reaction-replacement phases (arfvedsonite). Albite laths are found only in Lu II, NeS I and NeS II, and were formed by exsolution, reordering and recrystallization of K-feldspars, aided probably by the addition of Na.

This sequence of formation corresponds to the "agpaitic order of crystallization" in nepheline syenites, with formation of early nepheline and K-feldspar and late pyroxene, in contrast to the "miaskitic order" with early mafic minerals (after Kogarko & Gulyaeva 1965, as cited in Kogarko 1974).

The original magmas were very mobile and probably rich in several volatiles, later concentrated in deuteritic fluid phases, a feature reflected in the composition of some minerals (F in fluorite and arfvedsonite, Cl in eudialyte,  $H_2O$  in alteration minerals,  $CO_2$  also in some cancrinites; cf. also Sorensen 1974a, Kogarko 1974, Sorensen & Larsen 1978).

**Twining patterns of K-feldspars** The K-feldspars in the described NeS show a typical triclinic "multiple twinning" (Ulbrich, 1983, 1993), previously described in some other NeS (Mackenzie 1954, Smith & McLaren 1983). The pattern resembles that of a "chessboard" albite twinning. Several twinning types are recognized, characterized by increasing Al-Si ordering (Ulbrich 1983, 1993): a) in *incipient twinning*, only small cloudy veins and patches are twinned, irregularly distributed in an otherwise monoclinic K-feldspar; b) in *poor twinning*, most of the grain is taken over by the turbid twinned areas, with subordinate clean monoclinic patches; c) in *good twinning*, the whole K-feldspar is twinned and turbid; d) the next step is a *very good twinning*, in which the entire crystal is clear, with well-developed twin individuals or domains (akin to the "tilted microclines" of Smith & McLaren 1983). Several of these twinning patterns can coexist in any rock, or even in a thin section, but one of them is usually the predominant type.

The twinning pattern is, in general, well-developed along the strained areas of the K-feldspar host that surround both albite laths and the microperthitic albite, although it is not restricted to these areas. The coarser Lu I and NeS III show predominantly the better developed twinning ("type b"); incipient ("type a") and "type b" twinning are mostly found in the finer-grained Lu II, NeS I and II, together with albite laths, formed by exsolution-recrystallization of their K-feldspar host. Good twinning ("type c") is also found in NeS IV (Ulbrich, 1993).

**Geothermometry** The nepheline and the nepheline-feldspar re-equilibration geothermometers (Hamilton & McKenzie 1960, Hamilton 1961, Powell & Powell 1977) yield several estimates for the magmatic crystallization temperatures of the Poços de Caldas rocks, for a  $H_2O$  pressure up to about 1 kb (Ulbrich 1983, 1985, 1993). Experimental figures (Sood 1981) show that lujavrite magmas are very

cold, with a solidus close to  $400^\circ C$  (1 kb  $H_2O$  pressure), or even below it, although the liquidus is near  $850^\circ C$  (with K-feldspar as the liquidus phase); temperatures for khibinitic magmas are probably quite similar. Miaskitic magmas, on the other hand, crystallize completely at about  $620^\circ C$  (1 kb), with a liquidus temperature around  $820^\circ C$ . For Lu II and NeS I-II, the recorded magmatic re-equilibration temperatures (RT) between the two felsic minerals are  $580$ - $600^\circ C$ , and around  $540$ - $550^\circ C$  for the coarser-grained Lu I and khibinites, or even lower. NeS IV yields  $\sim 500^\circ C$  as its lowest RT.

**STRUCTURE** A sketch map and geologic sections of the two lujavrite outcrops are shown in figure 2.

**Western body** Lu I is the facies found at the center of this body, passing into the border facies Lu II (Fig. 3a, 3b). Two small sheets of projecting Lu II can be found along the S contact, and some meter-sized Lu II outcrops appear within tinguites, spatially unconnected to the main Lu I (Fig. 3a). Lu II thickness varies from about 2-3 m to as much as 20 m (profiles BA and EC, Fig. 3b). In one instance, a few Lu I veins cut the Lu II foliation at a very low angle (Fig. 7a). NeS I and NeS II form an outer shell to the lujavrites, with very rapid passage of one into the other; NeS I is from 4 to 15-20 m thick, NeS II is up to 50 m thick (Fig. 3b). NeS II grades rapidly into khibinite. NeS I and NeS II structures are concordant with the Lu II foliations.

The shell-like feature of the structure is emphasized by the sequence Lu I - Lu II - NeS I - NeS II, with NeS III on the outside; some facies may be missing (see sections in Fig. 3b). NeS III, not in direct contact with lujavrites at the present level of exposure, probably thins out at the root zone (section FA, Fig. 3b).

The planar structures of Lu I go from subhorizontal to the moderate or even steep concordant dips of the Lu II and NeS I-II foliations (Fig. 3a). Observations along some profiles (e.g., line FA, Fig. 3b) indicate that the successive sheets are flatter towards the outside (so, NeS III wedges out towards the lujavrites and may in fact be very thin, or even

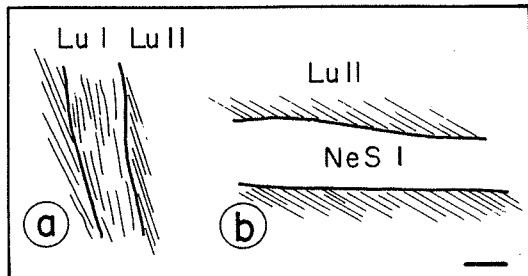


Figure 7 - (a) - Lu I vein cutting Lu II foliation at a slight angle (outcrop at a Lu I patch, separated from the main western body by a small fault; Fig. 3a); (b) - NeS I cutting as a small dikelet the Lu II foliation (outcrop at western end of eastern lujavrite body; Fig. 2a). Scale bar represents 5 cm. Drawn from photographs.

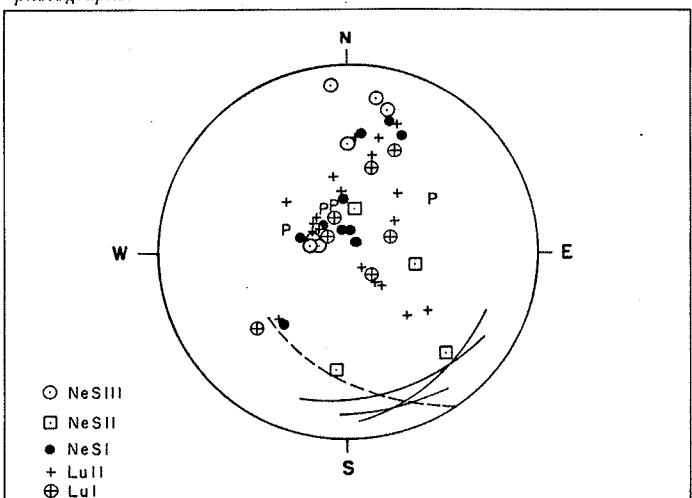


Figure 8 - Pole diagram of fluidal structures (Schmidt's net, lower hemisphere). Full and dashed greater circles represent the position of pegmatite dikes (P) in NeS III, intruded along two conjugate fracture planes.

absent, below them). As a result, the lujavrites and associated rocks may have a maximum thickness of about 80 to 100 m at the root zone (see section FA, Fig. 3b). The structure is that of a flat asymmetric saucer, with its major axis trending E-W and steeper dips of foliations to the E (Fig. 3a). Poles of foliation emphasize the overall concordant attitudes (Fig. 8). Pegmatite veins within NeS III are preferentially located along two conjugate fracture systems (Fig. 8).

Foliated and banded structures within khibinites are developed only locally, with a thickness varying from decimeters to several meters and extensions of up to 10 m; rather abruptly, massive khibinites take their place. On the other hand, the structural attitude of these foliations shows no general relationship with the overall geometry of the entire body. A minor banded and foliated leuco-syenite structure (Fig. 9) is found at the western margin of this body, intrusive into NeS IV (see the NeS III-IV contact in Fig. 3a) this foliated NeS III is surrounded, and in part clearly invaded, by massive khibinite, which is also intrusive into NeS IV. These observations suggest that the khibinite fluid-rich magmas were very mobile and subjected to local controls that generated foliated structures (e.g., in minor convection cells), in part destroyed and invaded by subsequent remobilization of the remaining liquid portions of the magma chamber.

The present structural interpretation for these lujavrite bodies differs from that proposed by Bushee (1974), who mapped all the cited NeS as varieties of a single rock type, with the exception of the lujavrites.

**Eastern body** The eastern lujavrite body measures about 2 x 0.75 km. The area is deeply weathered and covered mostly by talus, vegetation and coffee plantations. To the N, NE and S, the lujavrites are in contact with tinguaite and NeS IV (see also map in Bushee, 1974), showing planar subhorizontal structures (dips up to 10-15°). Lujavrite outcrops are missing along the southern lujavrite-tinguaite contact, but the straight trace suggests that it is probably vertical. Lu II is observed only along the irregular western edge of this body, accompanied on the outside by NeS I and NeS II and finally by khibinites. In a few exposures on this western edge the relationships indicate intrusion of NeS I into Lu II (Fig. 7b).

**AGE RELATIONSHIPS** Tinguaite crystallized as the oldest rocks, since they are present as xenoliths in lujavrites and in the rest of the NeS (including NeS IV).

In the western body, the five aigaïtic facies (Lu I-II, NeS I-II-III) are related to each other in a predictable shell-like structural pattern, constituting a single intrusive unit. NeS III is also intrusive into the miaskitic to intermediate NeS IV. In some cases, NeS I-II present a cross-cutting relationship in contacts with Lu II (Fig. 7b) and Lu I is also seen as veins that cut the Lu II foliation (Fig. 7a); these features are interpreted as the equivalent of "synplutonic" dikes. The sequence of intrusion is thus tinguaite  $\rightarrow$  NeS IV  $\rightarrow$  lujavrites and other aigaïtic facies. The same pattern can also be applied to the eastern lujavrite body.

**THE STRUCTURAL RELATIONSHIP BETWEEN THE EASTERN AND WESTERN LUJAVRITE BODIES** The lujavrite in the eastern body seems to lie directly in contact with the tinguaite that formed the floor of the former magma chamber. The

western body shows around its central lujavrite a well-developed "halo" of khibinites (NeS III), which however thins out under the lujavrites (e.g., profile FA in Fig. 3b).

The two lujavrite bodies are not directly connected at the present level of erosion (Fig. 2), and they probably crystallized in different parts of the same magma chamber or even in two unconnected separate small magma chambers. In any case, the parental magmas are khibinitic and are probably related to the other aigaïtic Poços de Caldas intrusions showing eudialyte as their identifying mineral (e.g., Ulbrich & Ulbrich 1992). All these aigaïtic magmas clearly originate at depth and were emplaced as late separate intrusions, as shown by geologic relationships.

#### MECHANISM OF EMPLACEMENT

In the Poços de Caldas occurrences, the mechanism of emplacement has to explain the following aspects (Ulbrich 1983, Ulbrich 1984):

- the structural relationship between all five facies of lujavrites and khibinites and the origin of the magmatic foliations, as well as the sequence of intrusion-mobilization (cf. Figs. 3, 7);
- the lack, or relative paucity, of eudialyte, aegirine and other mafic minerals in NeS I and II;
- the strong indications of recrystallization and reordering shown in all five facies (e.g., the different twin patterns and Al-Si ordering in K-feldspars; albite laths only in Lu I, NeS I and II; etc.).

The actual structures at their emplacement site cannot be explained in terms of simple *in-situ* crystal settling controlled by density currents or gravity (e.g., inclined structures in Lu II, NeS I and II; Figs. 2, 3).

The proposed emplacement mechanism is envisaged as a continuous process during the injection of strongly aigaïtic, fluid-rich khibinitic magmas (not mushes, see Deformation, above) that combines forceful emplacement with compaction and the formation of a cap of crystallizing lujavrite, all the while accompanied by lateral spreading and enlargement of the original magma chamber (Fig. 10a, b, c). The initially mostly liquid khibinitic magma entered through a central channel, under a local stress regime leading to sill formation (s<sub>3</sub> vertical, Fig. 10a), and was trapped under a crystallized but still very hot tinguaite cover. This magma was enriched in volatiles and also in Na, Fe, Mn, and some rare metals, leading to conditions whereby K-feldspar (and nepheline) were the liquidus phases, with somewhat later magmatic crystallization of the rather abundant mafic minerals (aegirine, also eudialyte). Around this initial blob, a contact envelope was formed, not cooler but certainly more viscous than the core, on account of some volatile loss. In the inside, volatiles were held concentrated, together with the elements they could transport (Fe, Zr, Na, rare metals). The kinetic conditions for the crystallization of a coarser Lu I at the core of the magma blob were thus created, in contrast to the marginal Lu II.

The khibinitic magma continued its intrusion, under and alongside the lujavrite cap, in contact with tinguaite to the S (with NeS IV, to the N and W). The effect is threefold: a) a mostly lateral expansion and significant enlargement of the original magma chamber; b) a forceful but slow horizontal flattening of the crystallizing lujavrite cap (now a mush) together with its compaction, and c) the formation of Lu II as well as NeS I-II as a more viscous magmatic contact envelope around Lu I. The compaction is certainly coupled with the migration and loss of interstitial magmas, together with the rearrangement of the crystallizing minerals into oriented patterns, both in the more viscous envelope as well as in the central lujavrites (Lu I; Fig. 10B).

The re-equilibration temperatures RT, taken as indications of the lower crystallization ranges, show that Lu I and probably also NeS III (RT about 500-540 °C) were still at least partly liquid under conditions where the volatile-depleted Lu II and NeS I-II (RT of 580-600 °C) had already crystallized (cf. references, above). These contact facies were thus subjected to an additional "cooking" by the cooling central Lu I and the surrounding khibinites, and exposed to the passage of some percolating deuterium fluids. These conditions favoured the exsolution of albite (both as microperthites and laths) in Lu II and NeS I-II by reconstitution of their K-feldspars, probably with Na addition by percolating fluids (some comments on the behavior of interstitial magmas are put forward in Gualda, 1998).

The conversion of disordered K-feldspars to microcline in Lu I and NeS III started under solidus conditions at a lower temperature (cf. Geothermometry) than in Lu II and NeS I-II; there is no indication that

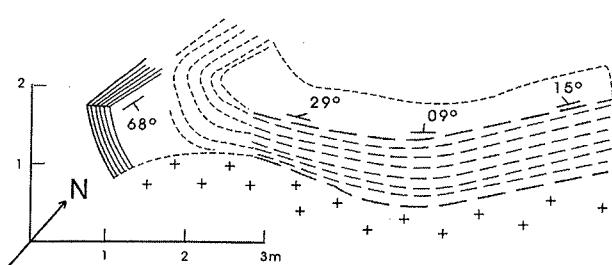


Figure 9 - Banded and laminated leuco-syenite outcrop, within khibinites (intrusive into NeS IV), at the western contact of the western khibinite body (cf. Fig. 3a).

microcline formed at a magmatic stage in the coarse rocks. It is not clear, however, why the multiple twinning is better developed in the coarser-grained rocks, while Lu II and NeS I-II show mostly incipient twinning. The exsolution of albite from the original monoclinic alkali feldspar in Lu II and NeS I-II may not favor the concomitant or later "microclinization" process, or perhaps the incipient twinning is the type that is achieved at higher temperatures in these contact facies, later to be stopped simply by unfavourable kinetic conditions.

The initial upwelling of the magma occurred along a curved or straight vertical fracture path (Fig. 2a), possibly representing the equivalent of a late ring fracture, before spreading laterally into the present emplacement site.

The whole process took place under a lithostatic and maximum  $H_2O$  pressures of up to 1 kb (Ulbrich 1984). The overall initial intrusion temperatures ( $> 650$  or  $> 700^\circ C$ ; Sood, 1981) were certainly higher than the recorded geothermometric RT figures; the passage from magmas into mushes occurred mainly at the emplacement site. These conditions place the *in situ* crystallizing "mushes" into the field of ductile behavior, thus making it easier to produce melt extraction, compaction, and structural re-arrangement of already formed minerals. Brittle deformation (Fig. 6) is kept at a minimum.

It is tempting, but probably misleading, to compare the cited stratigraphy with the one that appears at Ilímaussaq (Sorensen 1970, Ferguson 1970, Paslick et al. 1993). The Poços de Caldas khübinites would then correspond, as the lowermost unit, to the Ilímaussaq bottom kakortokites, the lujavrites representing the middle horizon. But there are no direct or indirect structural or mineralogical indications that a rock such as the Ilímaussaq upper naujaite (=sodalite NeS) flotation unit ever existed on top of the Poços de Caldas lujavrites: on the one hand, the differences in geological setting and thickness are very large between the two occurrences (e.g., Larsen & Sorensen 1987, Bailey & Gwozdz 1994), while sodalite, on the other, is a rare mineral in the Poços de Caldas NeS.

**A PETROGRAPHIC AND STRUCTURAL COMPARISON WITH ROCKS FROM OTHER OCCURRENCES** The Lovozero lujavrites, with an age of 290 Ma, are more leucocratic (as little as 15% mafics; Fig. 11) and some are rich in amphibole (black lujavrites); the main accessory phases are lamprophyllite, murmanite, loparite, ramsayite, rinkite-rinkolite, villiaumite, sphene and apatite, and sodalite is also an essential primary mineral (Vlasov et al. 1966, Sorensen 1970). The Ilímaussaq lujavrites, age of 1130 Ma, are divided into green (aegirine) and black (amphibole) varieties, and albite and sodalite as important minerals; also cited are strennstrupine, aenigmatite, monazite, lovozerite, ussingite, villiaumite, pyrochlore, and others (Sorensen 1970, Ferguson 1970, Paslick et al. 1993, Blaxland et al. 1976, 1978). Minor minerals found in the Diablo Plateau lujavrite, belonging to the Trans-Pecos Cenozoic alkalic province of Texas and Arizona (ages of 35 Ma; Potter 1996), are aenigmatite, biotite and fayalite (Barker et al. 1977, Barker 1987).

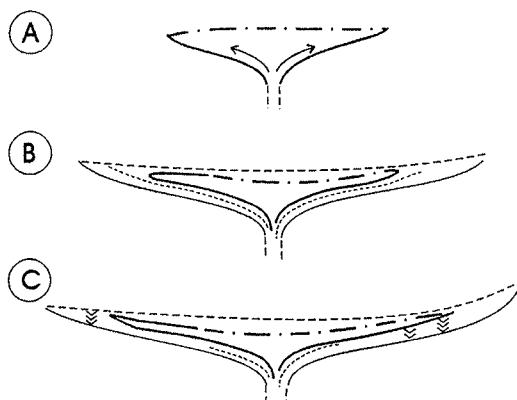


Figure 10 - A schematic representation of the sequential mechanism of intrusion, western lujavrite body. The black lines indicate the position of the Lu II envelope with a Lu I core, surrounded by spreading khübinitite magma. Outlined throughs represent the sites of smaller convection cells, generating igneous foliation. For explanation, see text.

Eudialyte may be absent from some lujavrites, or present only in minor amounts (e.g., Shand 1929, Vlasov et al. 1966). The average Ilímaussaq kakortokite is similar to the Poços de Caldas lujavrite (cf. Ferguson 1970; Table 1, Fig. 11).

The type khübinitite from Khibina (Johannsen 1938; age of 365 Ma, cited in Zaitsev 1996) is modally as variable as the Poços de Caldas equivalent rocks, especially in their KF-Ne ratios; some Khibina specimens may be poor in eudialyte, while others show biotite, alkali amphibole and aenigmatite (e.g., Sorensen 1970).

Similarities, as well as differences, are found in the structural setting. In cross-sections, the Lovozero lujavrites are depicted as a funnel-shaped structure with subhorizontal fluidal foliation, dipping gently to moderately towards the center; they are separated on structural grounds into two units, considered to be late intrusions (Sorensen 1970, Gerasimovsky et al. 1974). The Ilímaussaq lujavrite is located between the bottom layered kakortokites and the naujaite flotation cumulate, and has been interpreted as the re-injected residue formed from a large aegiritic magma batch after the extraction of the naujaite and kakortokite components (Ferguson & Pulvertaft 1963). Cumulate processes have also been proposed to interpret the formation of the Ilímaussaq lujavrites (Upton 1974, p.231, Larsen & Sorensen 1987), to the extent that the basal aegirine lujavrites are defined as orthocumulates (Bailey & Gwozdz 1994); some geologic relationships suggest that compaction must have played a significant role in controlling texture and structure at their final emplacement site (Ferguson & Pulvertaft 1963, Sorensen 1974a, p.44). The Pilansberg lujavrite (age of 1250 Ma) is restricted to some localized outcrops within the ring of "green foyaite" (Shand 1929, p.112); newer work by Retief (cited in Mathias 1974, p.196) shows that these rocks constitute moderately to steeply dipping sheets. The Trans-Pecos (SW Texas) lujavrites, on the other hand, appear within small alkaline intrusions in SW Texas, intermittently injected as a magmatic mush, since early lujavrite foliations are disturbed by later ones (Barker et al. 1977), at pressures probably lower than those registered for the other lujavrite occurrences.

The Texas occurrence suggests that magmas akin in composition to lujavrites may have existed and were emplaced either as mushes (as claimed by Barker et al. 1977) or, alternatively, as more liquid mixtures (e.g., Larsen & Sorensen 1987, Bailey & Gwozdz 1994), with residual melt extracted during a later compaction episode. In Poços de Caldas, a more complex intrusion mechanism for the formation of these rocks is favored (Fig. 10). The information on other occurrences (Ilímaussaq, Lovozero, Pilansberg) can be reinterpreted, suggesting that magma emplacement coupled with a compaction episode was probably the main responsible factor determining the final lujavrite fabric.

**Acknowledgements** The authors thank the Brazilian agencies FAPESP and CNPq for support for field and laboratory studies, and E. Bagnoli for help during mapping. To two anonymous referees of RBG for the critical review and suggestions to the manuscript.

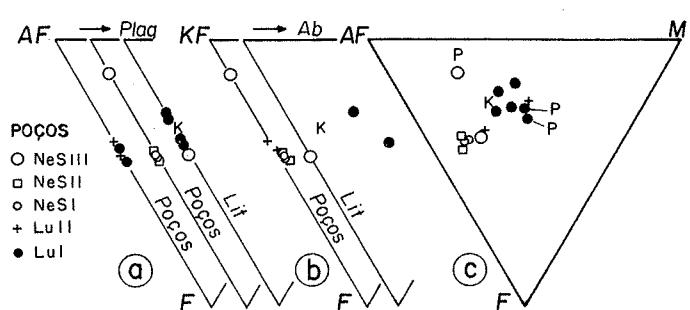


Figure 11 - Modal composition of lujavrites and associated rocks from Poços de Caldas and other localities (data from: Table 1; Johannsen 1938, Troeger 1935, Ferguson 1970). Heavy dots: lujavrites; circles: khübinites (NeS III) (specimens from Poços de Caldas rocks and other places, cf. cited literature). Ab: albite; AF: alkali feldspar; F: feldspatoids; K: kakortokite; KF: potash feldspar; M: mafic minerals. In c, Lu I and NeS III from Poços de Caldas are identified by the letter P. Lit: data from literature.

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Manuscrito A-1086  
Recebido em 10 de abril de 1999  
Revisão dos autores em 30 de março de 2000  
Revisão aceita em 14 de abril de 2000