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MINERALOGY OF NEPHELINE SYENITES FROM THE POÇOS DE CALDAS ALKALINE MASSIF, SE BRAZIL: CHEMISTRY, X-RAY DATA AND MICROTEXTURES OF FELDSPARS

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RESUMO MINERALOGIA DE NEFELINA SIENITOS DO MACIÇO ALCALINO DE POÇOS DE CALDAS, SE DO BRASIL: QUÍMICA, DADOS DE RAIOS X E MICROTEXTURAS DOS FELDSPATOS. Os nefelina sienitos (NeS) do Maciço Alcalino de Poços de Caldas ocorrem principalmente como corpos pequenos de rochas miasquíticas intermediárias ou agpaíticas. Na maioria dos NeS, os feldspatos são muito ricos em potássio (Or > 80 - 85) sendo ora ortoclásio, ora microclínio com alto ordenamento estrutural. O microclínio mostra um tipo de geminação múltipla que lembra a da albita *chess-board*, aparecendo em áreas turvas de cristais monoclínicos límpidos ou ocupando todo o grão (geminação incipiente, pobre, boa); as micropertitas, quando presentes, aparecem nas áreas geminadas. Em alguns NeS, os feldspatos potássicos são limpos, estão totalmente geminados e possuem lamelas de geminação de maior tamanho (geminação muito boa). Em algumas fácies petrográficas, ocorre albita secundária (albita tabular) inclusa nos cristais de feldspato potássico ou bordejando-os. Na maior intrusão miasquítica da região, a dos *NeS da Pedreira*, os feldspatos potássicos são mais ricos em Na, Ca e Sr; são muito turvos e apresentam "geminação difusa", que lembra a geminação "em grade". Os difratogramas de raios X mostram uma mistura de ortoclásio e microclínio intermediário. As temperaturas obtidas por geotermometria indicam que houve reequilíbrio entre feldspato e nefelina no estado *subsolidus*, particularmente nos casos em que o feldspato potássico apresenta geminação boa ou muito boa. As microtexturas dos feldspatos potássicos são o resultado de um processo contínuo de recristalização de grãos inicialmente não-geminados, controlado por fluidos magmáticos tardios. As áreas turvas representam, provavelmente, regiões com abundantes microporos que facilitariam a circulação dos fluidos. A composição da fase fluida, e a dos próprios feldspatos, pode ter grande influência no desenvolvimento dos vários tipos de geminação observados. A albita tabular e a pertítica podem resultar da redistribuição do sódio por fluidos deutéricos.

Palavras-chave: Geminações de feldspatos alcalinos, inversão ortoclásio-microclínio, recristalização de feldspatos alcalinos, albita secundária, processos deutéricos.

ABSTRACT Nepheline syenites (NeS) of the Poços de Caldas Alkaline Massif constitute mostly small bodies of miaskitic-intermediate or agpaitic rocks. The alkali feldspars of most NeS are highly potassic (OR > 80-85) and are either orthoclase or highly ordered microcline. The microcline shows a multiple twinning that resembles that of "chess-board" albite. This twinning may appear in isolated turbid spots in otherwise clean monoclinic crystals or occupy the whole grain (incipient, poor, good twinning); microperthites, when present, occur in the twinned areas. In some NeS the K-feldspars are clean, wholly twinned with larger twin lamellae (very good twinning). Secondary albite (tabular albite) is seen in some facies either included in, or bordering, the K-feldspars. In the singlemost important NeS intrusion, the *Pedreira NeS*, the alkali feldspars are richer in Na, Ca and Sr, very turbid and show a "diffuse twinning" resembling a cross-hatched pattern. The X-ray diffractograms show a mixture of orthoclase and intermediate microcline. Estimated geothermometric temperatures indicate subsolidus reequilibration between feldspar and nepheline, particularly when the K-feldspars show good or very good twinning. The microtextures of the K-feldspars are the result of a continuous process of recrystallization of non-twinned earlier crystals, controlled by late magmatic fluids. The turbid patches probably represent regions of abundant micropores facilitating fluid circulation. The twinning styles of the K-feldspars may be due to the composition of the fluid phase and of the feldspars. Sodium redistribution by deuteric fluids may have produced the secondary and perthitic albite.

Keywords: Orthoclase-microcline inversion, recrystallization of alkali feldspars, secondary albite, deuteric processes.

INTRODUCTION

Alkali feldspars are the most important modal felsic minerals in nepheline syenites. In leucocratic rocks, the chemical composition of the magmatic feldspars, in terms of total Na and K contents, appears to be directly related to the bulk chemistry of the rocks. Textural features, on the other hand, give valuable information on crystallization conditions and/or late or post-magmatic events; most cited in this connection are microtextures such as the exsolution of the sodic phase, crystallographic characteristics related to the structural state of the mineral, and the recognition of primary and secondary feldspars.

Studies of exsolution and orthoclase-microcline inversion are numerous in the literature (see McLaren 1984, Parsons & Brown 1984, Smith & Brown 1988, and references therein). However, most detailed studies deal with feldspars of granitic rocks, in which the structural changes produced at the orthoclase-microcline inversion become optically visible as the familiar cross-hatched pattern. The microclines of many nepheline syenites, on the other hand, show a totally different microtexture, here denominated "multiple twinning". It resembles optically a chess-board pattern.

The multiple twinning can be found only in restricted turbid areas of an otherwise clean and optically homogeneous crystal, or occupy the whole feldspar grain. This special twinning, shown in many photomicrographs depicting feldspars of nepheline syenites, has been recognized and described by several authors (Mackenzie 1954, Retief 1962, Vlasov *et al.* 1966, Czigan 1969, Sorensen 1974, Smith & McLaren 1983). The work of Mackenzie (1954) shows a partially twinned potassium feldspar from a nepheline syenite pegmatite from the Bearpaw Mountains,

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demonstrating the coexistence of orthoclase and almost maximum microcline in the same crystal. Smith & McLaren (1983) used TEM methods to study what they called "tiled microclines" (i.e., wholly twinned perthitic K-feldspars) from a nepheline syenite from the Ilímaussaq Complex. The authors show that on a TEM scale these microclines are constituted by "misoriented domains with no obvious crystallographic relationship to neighboring domains".

There is a strong suggestion that these textural and structural changes are produced during deuteric or hydrothermal alteration of the rocks. Parsons (1978, 1980) emphasized the importance of alkali-rich solutions in promoting perthite coarsening and Si-Al ordering in K-feldspars. Several studies (e.g., Christoffersen & Schedl 1980, Brown *et al.* 1983, Worden *et al.* 1990, Waldron & Parsons 1992) combined chemical, optical and TEM features defining K-feldspars in igneous rocks to emphasize the origin of several perthitic microtextures and other morphological characteristics as a result of a complex series of thermal events that triggered both dry and fluid controlled late-stage exsolution and recrystallization . One of the outcomes was the discovery that turbid feldspars are permeated by interconnected micropores, which enhance fluid-mineral interactions and may thus explain exsolution, recrystallization and metasomatic changes (e.g., Walker 1990, Worden *et al.* 1990, Finch & Walker 1991, Waldron & Parsons 1992).

A complete understanding of the particular twinning style of the K-feldspars in nepheline syenites depends on detailed work on a submicroscopic scale . Nevertheless, there is also a need for more information integrating optical features, X-ray data and chemical composition of feldspars, with or without multiple twinning, in groups of well-known alkaline rocks belonging to a single massif. It is the aim of this paper to present results covering the mentioned aspects, found in a variety of nepheline syenites in the Poços de Caldas alkaline massif.

GEOLOGICAL SETTING AND PETROGRAPHY

The Late Cretaceous Poços de Caldas Alkaline Massif (Fig. 1) is constituted almost entirely by intrusive phonolites (78%) and nepheline syenites (14%). Phonolitic lavas (5%) and pyroclastic rocks (3%; tuffs, agglomerates and breccias, partly showing clasts of porphyritic and amygdaloidal lavas) are subordinate and appear as more restricted outcrops (cf. Ellert 1959, Ellert *et al.* 1959).

Most nepheline syenite (NeS), unevenly distributed within the massif, are concentrated along the northern rim areas and in the district's northwestern and central parts (Fig. 2).

The NeS are found as intrusive bodies, mostly within phonolites. Contacts are always sharp, sometimes showing rounded enclaves of finer-grained rocks, reminiscent of "commingling" structures and thus suggesting a rapid succession of intrusions. The NeS appear frequently as dike-like stuctures or as irregular masses with vertical contacts. Many other bodies, however, are emplaced as subhorizontal sheets, possibly as the upper extensions of mushroom-shaped intrusions; conspicuous among them are the small bodies with *lujaurites* and *khibinites* (Fig. 1). Most of the individual NeS intrusions are small (0.1 to 0.9 km^2); only a few cover larger areas, including the singlemost important body, the *Pedreira NeS* (± 80 km$_2$).

Detailed mapping of the Poços de Caldas NeS showed a large variety of facies, mainly identified by differences in texture, grain size, contents of mafic minerals and appearance of accessory rare-metal silicates (RMS), such as rinkite, eudialyte etc. (Ulbrich 1984).

About 40 faciological varieties of NeS, constituting 28 individual bodies, have been recognized in the district (Ulbrich 1984). Many bodies are composed of two or more facies. The most remarkable example is given by the two small composite *lujaurite-khibinite* bodies in the northern rim, showing a concentric arrangement of five different NeS (Fig. 3), with the following sequence: **a.** a central coarse-grained lujaurite (*Lu I*) with subhorizontal foliation which gradually changes to a maximum dip of about 40-60° towards the periphery, followed by a narrow band of a medium-grained border lujaurite (*Lu II*); **b.** an outer incomplete ring of two leucocratric NeS with trachytoid texture (fine-grained, *NeS I*, and medium-grained, *NeS II*); **c.** an external irregular area of a massive, non-homogeneous coarse-grained khibinite. The five facies constitute an emplacement unit: all foliated facies (from *Lu I* through to *NeS I* and *NeS II*) have structures adapted, in a concentric fashion, to those of the neighbouring facies, and thus the entire body presents a shell-like structure (Ulbrich 1984, Ulbrich & Ulbrich 1992).

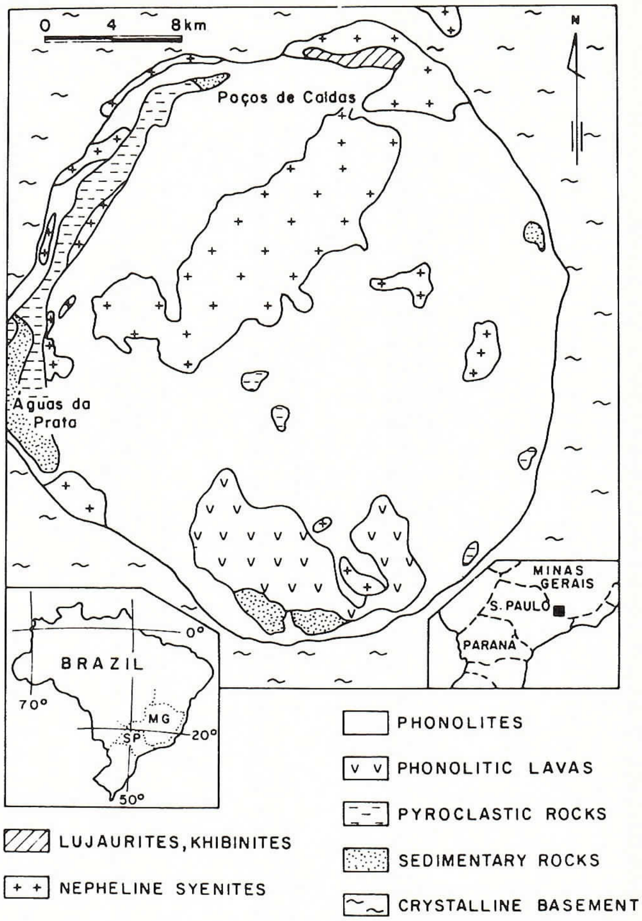


Figure 1 – Geologic sketch map of the Poços de Caldas Alkaline Massif (after Ellert et al. *1959, simplified)*

Figura 1 – Mapa geológico esquemático do Maciço Alcalino de Poços de Caldas (Ellert et al. 1959, simplificado)

The presence of RMS, distinctive of peralkaline agpaitic NeS, allows a convenient field and petrologic grouping of the Poços de Caldas NeS into agpaitic, intermediate and miaskitic varieties.

Predominant among the NeS are miaskitic and intermediate facies (84%) over the agpaitic ones (16%). Field observations in a few selected areas show that the agpaitic types are the latest intrusions, following the emplacement of the miaskitic and intermediate varieties (Ulbrich 1984).

Late hydrothermal alteration strongly affected some areas within the massif, mainly in the central and eastern parts, to such an extent that over 100 km^2 were almost totally

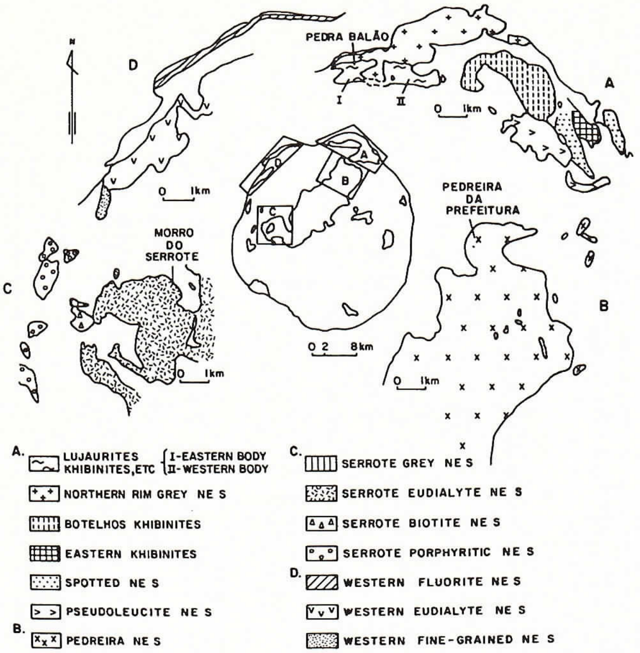


Figure 2 – Nepheline syenites (NeS) in the Poços de Caldas massif. Details referring to areas A, B, C and D are shown (Ulbrich 1983, Ulbrich and Ulbrich 1992); central reference map is from Ellert et al. *(1959)*

Figura 2 – Nefelina sienitos (NeS) do Maciço de Poços de Caldas. Mostra-se, em detalhe, as áreas A, B, C e D. O mapa de referência, no centro da figura, é de Ellert *et al.* (1959)

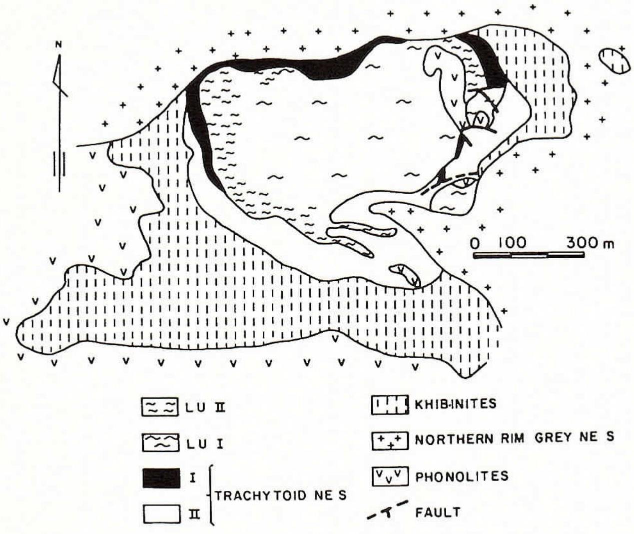


Figure 3 – Detailed map of the westernmost lujaurite-khibinite body (Ulbrich 1983, Ulbrich & Ulbrich 1992). See text for description.

Figura 3 – Mapa de detalhe do corpo de lujauritos-chibinitos ocidentais (Ulbrich 1983, Ulbrich & Ulbrich, 1992). Para descrição, ver texto

altered. The primary mineralogy, with no textural change, is then converted into illite (replacing nepheline), iron oxides, clays and chlorites (altering mafic minerals) and reconstituted K-feldspar. This pervasive alteration is clearly related with late mineralizations. On a more limited scale, hydrothermal alteration affected most rocks of the alkaline district, but it usually goes unnoticed, even in thin section observations (for more details, cf. Ulbrich 1984, Garda 1990, Chapman *et al.* 1992, Ulbrich & Ulbrich 1992).

NEPHELINE SYENITES

Petrography Most rocks in the district are massive, mainly leucocratic to hololeucocratic, with a hipidiomorphic, inequigranular to graded texture of a foyaitic type (i.e. lathlike non-oriented feldspars as predominant textural feature); rocks with more equidimensional feldspars are less frequent. Porphyritic types, such as the *Serrote porphyritic NeS* (Fig. 2), are distinctive constituents of some small bodies, and show centimetric, idiomorphic, platy feldspars in a hipidiomorphic medium- to fine-grained matrix. The presence of rounded centimetric to decimetric pseudoleucites, set in a medium-grained hipidiomorphic matrix, is the characteristic feature of the *pseudoleucite NeS* (Fig. 2). Banded varieties are recognized in some bodies; in the *Botelhos khibinite* (Fig. 2), banded rocks are found in the central part of the intrusion with alternating feldspar and pyroxene cm-sized layers, partly resembling the structure shown by the Ilimaussaq kakortokites (Sørensen 1970). *Lujaurites* are the only strongly foliated NeS; although undeformed, they show the characteristic macroscopic appearance of a "crystalline gneiss" (Shand 1949), due to the strong planar orientation of feldspar laths and acicular to prismatic pyroxenes.

Varieties with a trachytoid texture are rare; the best examples are the already mentioned leucocratic to hololeucocratic *trachytoid NeS I* and *II*, which accompany the *lujaurites* (Fig. 3), where the rock foliation is given by the planar orientation of feldspar laths and pyroxene prisms.

Mineralogy The essential mineralogy of the rocks is simple (Ulbrich 1983, Ulbrich *et al.* 1984). Potassium feldspar (K-feldspar), nepheline, sodic pyroxene and sometimes eudialyte (e.g., in the *lujaurites* and *khibinites* of the *lujaurite-khibinite* bodies) make up 95 - 98% of the rocks. Variations in modal composition of different NeS facies are shown in table 1.

The K-felspars present Or > 80 in most rocks except in the *Pedreira NeS*, where they are richer in Na and Ca and also in trace elements (Sr, Ba). The nephelines are of the mediopotassic variety (1.0 to 2.0 K atoms per formula unit; Deer *et al.* 1966); those of coarser-grained rocks have slight excess silica (Qz < 5%), with data clustering around the Mohorocewicz-Buerger convergence field (Tilley 1954). The nephelines of fine-grained NeS, generally found as border facies, are typically Qz-rich (5% or more of excess silica). In most NeS the pyroxenes are slightly zoned from Na-rich aegirine-augite cores to aegirine rims. Strongly zoned pyroxenes occur in the medium to coarse grained *Pedreira NeS* and the *spotted NeS* (Fig. 2); the composition varies from soda-augite, in the partially resorbed cores of the crystals, to Na-rich aegirine-augite or aegirine at the borders. Small amounts (less than 4%) of other felsic minerals (albite, analcime, sodalite) are only found in some facies.

Eudialyte is a distinctive agpaitic rare-metal silicate in Poços de Caldas, appearing in almost all agpaitic rocks of the massif, in varying amounts (0.2 - 12%, Tab. 1). It is accompanied by other Na-bearing RMS (lamprophyllite, rinkite, etc) and occasionally by Mg-arfvedsonite (< 1%) and fibrous aegirine, composing the suite of mafic late-stage minerals in these rocks. The miaskitic to intermediate NeS have less than 5% of any of the following phases: titanite, fluorite, magnetite, apatite, biotite.

Chemistry The chemical data presented in table 2 (selected from Ulbrich 1984) illustrate the variations in major and trace element contents of the NeS.

Most NeS are peralkaline rocks (Na+K/Al > 1.0). The peralkalinity index varies from ± 1.0 in the miaskitic *Pedreira NeS* to ± 1.35 in the agpaitic *lujaurites*. A remarkable chemical feature resides in the moderate to high K_2O content

Table 1 – Modal composition of selected nepheline syenites
Tabela 1 – Composição modal de nefelina sienitos selecionados

Body	lujaurite- khibinite		western eudialyte NeS	Pedreira NeS		Serrote porphyritic NeS	western fluorite NeS
Facies	Lu I	khibinite	coarse-grained	medium grained	coarse grained		
Sample n°	46	47 173	513 531	386	235 236	658	525
K-feldspar	38.2	59.0	54.4	45.7	55.2	55.6	65.7
Nepheline	24.8	18.6[a]	31.3[a]	35.6	31.7[b]	35.8[a]	32.4
Analcime[1]	tr		tr		0.4		
Sodalite[1]		0.2					
Pyroxene	27.3	10.1	11.0	16.1	10.1	8.1	
Amphibole	0.7						
Biotite						1.2	
Titanite + fluorite+ Opaques	tr	0.2	0.6	1.2	3.0	0.5	0.7
Eudialyte	7.6	7.9	1.4				
Other RMS[2]	1.4	4.0	1.3				

1. interstitial grains; **2.** rare metal silicates: lamprophyllite, rinkite etc.; ***a,b.*** nepheline partially altered to: ***a.*** natrolite, or analcime plus natrolite, ***b.*** mainly cancrinite

Table 2 – Chemical composition of selected nepheline syenites
Tabela 2 – Composição química de nefelina sienitos selecionados

Body	lujaurite-khibinite		western eudialyte NeS	Pedreira NeS		Serrote porphyritic NeS	western fluorite NeS
Facies	Lu I	khibinite	coarse-grained	medium grained	coarse grained		
Sample n°	223	47	512	386	38	658	525
SiO_2	53.2	54.1	54.6	54.3	54.4	54.8	55.1
TiO_2	0.62	0.77	0.43	0.85	0.80	0.32	0.23
AL_2O_3	15.0	15.9	16.6	19.7	19.1	21.1	20.3
Fe_2O_3	8.4	5.6	4.9	3.1	2.8	2.4	1.8
FeO	1.15	0.50	1.01	1.15	1.45	0.72	0.72
MnO	0.48	0.31	0.52	0.18	0.26	0.13	0.08
MgO	0.42	0.21	0.27	0.43	0.46	0.16	0.06
CaO	2.1	2.1	1.6	1.9	1.6	1.1	0.48
Na_2O	8.1	7.6	8.1	6.5	4.3	6.8	5.5
K_2O	6.3	8.8	7.6	8.7	9.3	9.2	13.0
LOI	3.34	2.96	3.68	2.0	5.15	2.5	2.29
P_2O_5	<0.05	0.06	0.05	0.13	0.11	<0.05	<0.05
TOTAL	99.16	98.91	99.36	98.94	99.73	99.28	99.61
F (ppm)	710	3250	3250	1650	1040	850	2750
Cl	380	310	140	1480	70	<20	<20
S %	0.04	0.26	0.03	0.10	0.05	0.02	0.21
Rb (ppm)	230	300	240	180	230	170	560
Sr	2410	740	1020	2500	1970	820	370
Zr	3500	1900	1200	720	760	460	500
Nb	310	340	380	160	230	140	83
Pb	220	184	126	80	42	70	58
Ba	220	460	130	560	320	64	78
Y	31	180	35	66	47	54	10

LOI - loss on ignition; data in Ulbrich (1984) of the NeS and in the high negative correlation between Na_2O and K_2O of some rock facies (Ulbrich 1984). Miaskitic NeS commonly show $Na_2O/K_2O < 1$ (mol proportions). Most agpaitic and intermediate rocks have a slight to marked molecular excess of Na_2O over K_2O.

Trace elements, like Zr and Nb, are lower in miaskitic rocks (Zr = 300 - 800 ppm, Nb = 60 - 230 ppm) than in the agpaitic *lujaurites* and *khibinites* (Zr = 800 - 3.200 ppm, Nb = 130 - 660 ppm). Sr, on the other hand, can be as high as 4.150 ppm in some *Pedreira NeS* rocks, with an average of 2.500 ppm, while intermediate and agpaitic NeS have Sr contents varying from 400 to 3.050 ppm. No rare K and/or Sr-bearing minerals have been so far identified in miaskitic rocks; these elements are apparently entirely taken up by alkali feldspar and other common minerals (Tab. 2 and 3).

K-FELDSPAR AND ALBITE

Texture K-feldspar is the only primary feldspar of the NeS. Some agpaitic and miaskitic facies show small amounts (up to 2.5%) of fresh sodium feldspar laths (tabular albite), twinned on the Albite and Albite-Carlsbad laws. The albite laths appear very frequently enclosed within K-feldspar, haphazardly oriented. In other cases they protrude sideways into surrounding feldspars. Occasionally, this tabular albite is found as smaller grains adjacent to larger K-feldspars, and always subparallel to their (010) elongation. The textural and chemical features (see below) indicate that albite is a late stage mineral in all the Poços de Caldas NeS.

The K-feldspars occur mostly as laths or plates, flattened on (010), a typical habit in many nepheline syenites (Sørensen 1974). The mineral shows Carlsbad and Baveno twins;

Table 3 – Chemical composition of selected feldspars

Tabela 3 – Composição química de feldspatos selecionados

Body	lujaurite-khibinite				western eudialyte NeS	northern rim gray NeS	Pedreira NeS				western fluorite NeS	spotted NeS
Facies	Lu I	Lu II	khibinite		medium-coarse grained		fine grained		coarse grained			
Sample nº	46	217	169		512	432	238		384		525	541
	K-feldspars											Albite
			c	b			c	b	c	b		
SiO_2	64.3	64.8	65.0	64.6	64.2	64.8	65.3	64.4	65.3	65.0	64.3	68.6
Al_2O_3	18.0	18.2	18.2	18.1	18.4	18.0	19.4	19.7	18.4	18.4	17.9	19.3
Fe_2O_3	0.54	0.76	0.44	0.44	0.03	0.20	0.46	0.58	0.59	0.63	0.40	
CaO	0.03	0.02	0.03	0.03		0.04	0.36	0.08	0.07	0.08	0.02	
SrO							1.38	0.33	0.27	0.23		
Na_2O	1.05	1.65	1.88	0.78	0.08	0.68	4.76	2.91	3.23	2.41	0.71	11.9
K_2O	15.8	14.5	14.6	15.4	16.5	16.1	9.04	12.9	12.3	13.7	15.8	0.24
Total	99.72	99.93	100.15	99.35	99.21	99.82	100.70	100.90	100.16	100.45	99.13	100.04
Si	11.946	11.951	11.965	11.995	11.972	12.011	11.806	11.739	11.938	11.920	11.995	11.995
Al	3.951	3.958	3.946	3.965	4.048	3.933	4.135	4.229	3.971	3.970	3.940	3.983
Fe	0.076	0.105	0.061	0.062	0.005	0.028	0.063	0.079	0.081	0.087	0.056	
Ca	0.006	0.004	0.006	0.006		0.008	0.069	0.016	0.014	0.016	0.004	
Sr							0.145	0.035	0.028	0.025		
Na	0.378	0.590	0.672	0.280	0.030	0.245	1.669	1.030	1.147	0.858	0.258	4.016
K	3.744	3.415	3.435	3.650	3.924	3.813	2.084	2.988	2.858	3.209	3.765	0.054
Or	91.1	85.9	84.3	93.1	99.3	94.1	53.5	74.5	71.7	79.0	93.9	1.4
Ab	8.7	14.0	15.5	6.7	0.7	5.7	40.4	24.1	27.1	19.9	6.0	98.6
An	0.2	0.1	0.2	0.2		0.2	6.1[a]	1.4[a]	1.2[a]	1.1[a]	0.1	

RMS - rare metal silicates (eudialyte, lamprophyllite etc.); **c, b.** center and border of grains; **a.** An = $(Ca,Sr)Al_2Si_2O_8$; data in Ulbrich (1983) the former occur in all rock types while the latter, restricted to agpaitic rocks, are dominant in some facies (e.g. *Serrote eudialyte NeS*, Fig. 2).

Besides these simple twins, all feldspars except those of the *Pedreira NeS* show a triclinic multiple twinning which resembles a chess-board pattern. This microtexture, here called "multiple twinning", may be observed only in some portions of the feldspar laths, or in the whole crystal (see detailed descriptions below, "Multiple Twinning"). Partially or totally twinned grains can coexist with untwinned K-feldspars in the same thin section; in some rocks, all grains are twinned.

The K-feldspars may have microperthites of the rod and string varieties. The albite lamellae occur only in the multiple twinned areas of the host feldspars.

The *spotted NeS* feldspars contain larger amounts of albite, as vein and patch-checkered perthites in all K-feldspar grains; tabular albite, positioned as laths marginal to the K-feldspars, present the same optical orientation as the albite in the perthites.

Chemistry Electron microprobe analysis of K-feldspar and albite were carried out on a 3-channel A.R.L. microprobe (wavelenght dispersion) at the University of São Paulo, Brazil. Well-characterized silicate minerals (orthoclase, Crystal Bay bytownite, Tiburon albite and eutectic $SiO_2.SrO$) were used as standards. Operating conditions included a 15KV accelerating potential with 0.2 - 0.3 mA sample current and 15 - 20 µm beam diameter. The correction procedure of Bence & Albee (1968) was used for data reduction.

The K-feldspar analyses were performed, whenever possible, on fresh-looking homogeneous crystals. In samples with both twinned and untwinned grains, the latter were chosen for analysis.

Selected chemical analyses of K-feldspars and albite are presented in table 3. The K-feldspars are either chemically homogeneous or weakly zoned with Na-richer centers; they have moderate to low Fe contents and trace amounts of Ca. The K-feldspars of the *Pedreira NeS* show marked zoning, with higher core contentrations of Na, Ca and Sr, particularly in the fine-grained facies (Tab. 3); trace amounts of Ba were also detected in these feldspars.

The tabular albite (Ab_{98-100}) has the same composition as the lamellae in microperthites.

OPTICAL STUDIES

Multiple twinning This microtexture has been mentioned and described in the literature (Mackenzie 1954, Retief 1962, Vlasov *et al.* 1966, Czigan 1969, Sørensen 1974, Smith & McLaren 1983) always in connection with feldspars of nepheline syenites. Under the microscope it appears as "an intricate penetration twinning according to the albite law" (Sørensen 1974). The TEM studies of Smith & McLaren (1983) in microclines of an Ilímaussaq NeS showed that, although symmetrical orientation around (010) is a proeminent feature, the twinning is indeed a very complex microtexture. The feldspars studied by Smith & McLaren 1983, named by them "tiled microclines", are identical to the ones shown in Figure 4d (cf., below).

The textural aspects and other optical data of multiple twinned K-feldspars from 130 thin sections are summarized below. Four typical cases are recognized, which may coexist in the same sample (see discussion below and in the next item):

a. *Crystals with incipient twinning* (Plate 1-a). Vein and patch-like areas of finely to very finely twinned K-feldspars in otherwise optically homogeneous crystals. The twinned areas are easily recognized in plane-polarized light by their cloudy appearance and brownish colour; observed under high magnification, these areas show abundant fluid and tiny acicular inclusions. Optical examination suggests twinning according to the albite law, with a conspicuously developed (010) twin plane. The (010) and (001) cleavage planes seem to be continuous through the whole grain (cf., Mackenzie 1954). Microperthites, when present, concentrate in these twinned areas. The optically homogeneous untwinned areas are clean monoclinic K-feldspars; 2Vα varies from 23 to 55° (average 40°) in different nepheline syenite samples, with the optical axial plane normal to (010) . The K-feldspars with lower axial angles show uniform extinction while those with 2Vα = 40 - 55° commonly exhibit undulatory extinction.

b. *Crystals with poor twinning.* It includes all cases in which most of the crystal shows multiple twinning, with only minor areas or islands of clean monoclinic K-feldspar (Plate 1-b). The twinned turbid areas are similar to those described above. Axial angles vary between 60 and 65°.

c. *Crystals with good twinning.* The whole crystal is turbid and exhibits multiple twinning (Plate 1-c). The twinning is generally continuous through the grain; occasionally, the crystal is a mosaic of 2 or 3 multiple-twinned domains joined by irregular contacts.

d. *Crystals with very good twinning* ("tiled microclines" of Smith & McLaren 1983). The whole crystal is again completely twinned but the twin individuals (tiles) are larger and can be easily identified even with low magnification (Plate 1-d). The feldspars are totally clean. Perthites and acicular to irregularly-shaped mineral inclusions may be seen but the myriads of tiny inclusions of brownish colour are absent. The size of the twinning individuals and the freshness of the crystals facilitate optical observations; the axial angle values vary from 76 to 84°.

Diffuse twinning The feldspars of the *Pedreira NeS* exhibit a very poorly defined "diffuse twinning"; it can be mistaken as an irregular to undulatory extinction. Optical recognition and description is seriously hampered because the feldspar grains are, in the medium to coarse grained rocks, very cloudy, filled with tiny fluid and crystalline inclusions; observations in somewhat clearer crystals show that the diffuse twinning resembles a cross-hatched pattern. 2Vα varies from 54 -56° in the cores of the crystals to 44-46° at the borders.

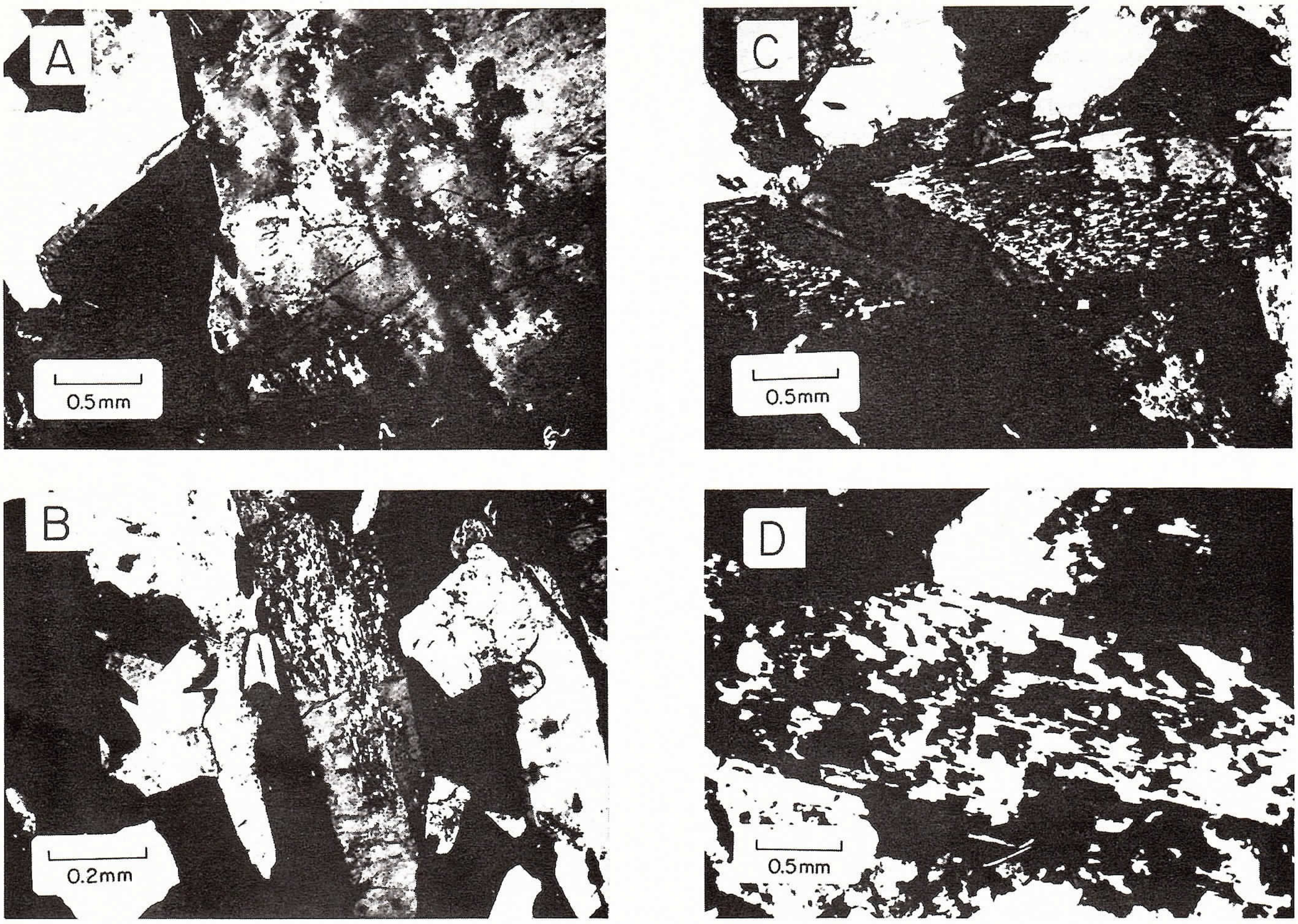
In fine-grained rocks, the K-feldspars are clean and untwinned.

X-ray Powder diffraction Twenty nine K-feldspar powder-patterns were obtained from medium to coarse grained NeS. The K-feldspar grains were separated manually from crushed material; heavy liquids and magnetic separation were used to obtain purer samples in some cases (e.g., in Lu I). Nepheline or zeolite inclusions were removed to a great extent by attack with 10% HCl (Wilkinson 1965).

Pressed mounts of powdered K-feldspar mixed with about 10% of pure silicon, as internal standard, were used for X-ray diffraction in a Rigaku X-ray goniometer using Ni-filtered copper radiation, at the University of São Paulo, Brazil. X-ray scans were made over a 10 to 80° 2θ range at ½° per minute, with a chart speed of 10 mm per minute. The powder patterns were indexed following Borg and Smith (1969). Unit cell dimensions and molar volumes were refined by least square analysis, using the LCLSQ program of Burnham (1962).

K-FELDSPAR POWDER PATTERNS

The patterns are composed entirely of microcline reflections, or more commonly of a mixture of orthoclase and microcline reflections, with variable relative intensities; low albite peaks (e.g., 2θCu 131 = 31.29°, Smith 1956) also show up in



*Prancha 1 – Multiple twinning patterns in potassium-feldspars from NeS. (**A**) Incipient twinning in orthoclase showing undulatory extinction. Some small patches and irregular areas present multiple twinning. Coarse-grained lujaurite (Lu I; lujaurite-khibinite body). (**B**) Poor twinning in K-feldspar of a trachytoid NeS I (lujaurite-khibinite body). The lower part of the central feldspar lath is orthoclase; microcline with multiple twinning is observed in the upper part of the crystal. The other K-feldspars laths are untwinned. (**C**) Good twinning in a K-feldspar grain. The grain is tottally twinned with very small twinning individuals. Tabular albite is seen as larger grains wholly enclosed within feldspar, and also as more irregular small border laths with albite twinning. Fine grained lujaurite (Lu II; lujaurite-khibinite body). (**D**) Very good twinning in microcline from the Serrote eudialyte NeS*

Plate 1 – Padrão de geminação múltipla em feldspatos potássicos de NeS. (**A**) Geminação incipiente em ortoclásio com extinção ondulante; algumas "manchas" e áreas irregulares mostram geminação múltipla. Lujaurito de granulação grossa (Lu I; corpo de lujauritos-chibinitos). (**B**) Geminação pobre em feldspatos potássicos de NeS I com textura traquitóide (corpo de lujauritos-chibinitos). O grão central de feldspato mostra ortoclásio, na sua parte inferior, e microclínio com geminação múltipla na porção superior. Outros grãos tabulares e irregulares de feldspato potássico não apresentam geminação. (**C**) Geminação boa em um grão de feldspato potássico. O grão está totalmente geminado, os indivíduos de geminação são muito pequenos. A albita ocorre como grãos de maior tamanho totalmente inclusos em feldspato potássico e também como pequenas ripas com geminação de albita, bordejando os cristais de feldspato. Lujaurito de granulação fina (Lu II; corpo de lujauritos-chibinitos). (**D**) Geminação muito boa em microclínio do NeS com eudialita do Serrote

samples with microperthites, but no cryptoperthites were observed.

The whole set of K-feldspar diffraction patterns can be grouped in the seven types shown in figure 4. Types 1a and 1b are recognized by low-intensity microcline reflections, appearing at the base of intense orthoclase lines; all reflections with $2\theta > 36°$ are broad with 2θ values intermediate between orthoclase and microcline. Types 2a and 2b show sharp orthoclase and microcline peaks in the range $2\theta = 23$ to 32°; reflections with $2\theta > 32°$, usually of low intensity, are unresolved. The obliquity of the triclinic phase, $\Delta 131 = 12.5(d_{131}-d_{131})$ (Goldsmith and Laves 1954), is 0.74-0.75. Type 3 powder patterns, which are found only in the feldspars of the *Pedreira NeS*, are defined by broad and almost symmetrical peaks; only those peaks that do not depend on the structural state of the K-feldspar, such as 201, are sharp. Partially resolved microcline and orthoclase reflections occur in the 2θ ranges of the 131-131 and 130-130 lines. Types 4a and 4b are similar, and only show microcline peaks; in the 4b types, all lines in the range $2\theta = 20$ to 80° are sharp, while the peaks in the 4a pattern are less intense and only the low angle reflections (up to $2\theta \pm 32º$) are sharp. Obliquity values vary from 0.71 to 0.83 in 4a types and from 0.86 to 0.98 in 4b types.

A visual analysis of figure 4 shows an ordered sequence in the X-ray patterns (1a→1b→2a→2b→4a→4b), defined by the presence of peaks which represent progressively higher amounts of highly ordered microcline, coupled with a reduction in both intensity and sharpness of those peaks identifying the orthoclase phase. The type 3 pattern cannot be included in the sequence: relatively intense symmetry-sensitive low angle reflections, related to both orthoclase and microcline symmetries, seem to be present in the X-ray pattern, but in complete overlap and thus of difficult

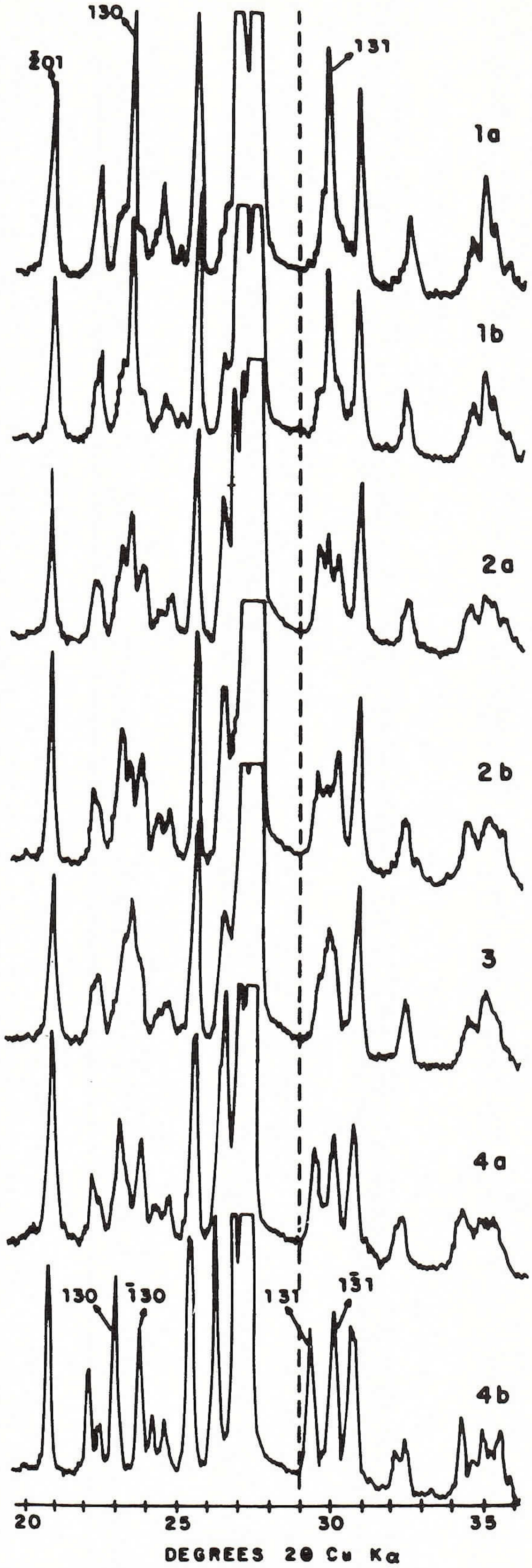


Figure 4 – X-ray diffraction patterns of K-feldspars from selected Poços de Caldas NeS showing the main features of types 1, 2, 3 and 4. Discussion in text

Figura 4 – Padrões de difração de raios X de feldspatos potássicos de NeS selecionados, do Maciço de Poços de Caldas, mostrando as principais feições dos tipos 1, 2, 3 e 4. Para discussão, ver texto

interpretation (see, for instance, the profile between 2θ 34 and 36º in Fig. 4); on the other hand, the discernible splitting observed in the 130 and 131 reflections (among others) might indicate the presence of intermediate microcline with low $t1_0$ values (between 0.5 and 0.7, cf. Stewart & Wright 1974).

Cell constants Patterns 1a, 1b, 2a, 2b and 3 (with orthoclase and microcline peaks) serve to estimate the relative proportions of the polimorphs in the samples, but are useless for cell parameter refinement, due to lack of resolution of the high angle reflections (Stewart 1975).

Patterns 4a and 4b, which are apparently composed only of microcline lines, were checked for structural homogeneity with the "three peak diagram" of Wright (1968) based on the 2θ values of the strong high angle 060 and $\bar{2}04$ reflections and also on $\bar{2}01$, which depend upon the *a* cell parameter and consequently vary according to the feldspar composition. The difference between 2θ CuKa $_{\bar{2}01}$ derived from Wright's diagram and the one obtained from the powder pattern should be less than ± 0.10º in unstrained and structurally homogeneous K-feldspars (Wright 1968, Stewart & Wright 1974). These differences are small ($\Delta 2\theta_{\bar{2}01}$ = 0.01-0.05) in all 4b type microcline patterns, and large ($\Delta 2\theta_{\bar{2}01}$ = 0.15-0.28) for 4a patterns. Consequently it can be assumed that in 4b patterns there are only microcline peaks, while 4a patterns belong to samples with microcline and small amounts of orthoclase.

The cell constants of the structurally homogeneous feldspars listed in Table 4 were obtained only from suitable 4b types. The values point to highly ordered microclines.

COMPARISON BETWEEN MICROTEXTURES, CHEMISTRY, GEOTHERMOMETRY, AND X-RAY DATA OF THE POÇOS DE CALDAS K-FELDSPARS The optical, chemical and X-ray information on K-feldspars from the NeS here discussed are summarized in table 5. The estimated geothermometric temperatures of the rocks, obtained from the Powell & Powell (1977) and Hamilton (1961) diagrams, are also given as additional information (Ulbrich 1983, 1985). Both geothermometers yield approximately the same temperatures for the medium to coarse-grained rocks, which have highly potassic feldspars and nephelines with little excess silica. On the other hand, some fine- and also medium-grained NeS present homogeneous nephelines with large excess Qz (> 5%) accompanying either strongly zoned orthoclase (as in the fine-grained *Pedreira NeS*) or highly perthitic K-feldspars with poor microcline twinning (as in the *spotted NeS*). In these cases, crystallization temperatures were estimated using only the nepheline compositions (Hamilton's diagram). Some relationships are pointed out below.

Multiple twinning and the structural state of K-feldspars The X-ray method used in this work serves as a qualitative indicator of the mixture of structural states observed in K-feldspars in powdered samples.

The relative abundances of optically untwinned and multiple-twinned K-feldspar grains are directly related to the relative intensities of orthoclase and microcline peaks, as clearly shown by data in table 5.

A division of the feldspars into Groups I and II can be made, as far as twinning quality and variety is concerned (Tab. 5). In Group I, encompassing the most frequent examples, all types of twinning, from incipient to good, can be observed. Relative predominance of one of the twinning types over the others allows a further, somewhat less distinctive, subdivision (types A to D, Tab. 5). Less frequent are samples belonging to Group II, where very good twinning is the only observed twinning type.

In Group I, the twinned areas in the feldspars (or eventually the entire grain in crystals showing good twinning) are cloudy, with myriad of tiny fluid and crystalline inclusions. The feldspars of agpaitic rocks are less cloudy than those of miaskitic-intermediate rocks. Group II K-feldspars (type 4b diffraction pattern) are texturally clean, and thus different from the K-feldspars presenting other diffraction patterns.

The K-feldspars of the *Pedreira NeS* are the only ones showing a single monoclinic phase in the fine-grained facies, and intermediate microcline (with some orthoclase; type 3 powder pattern) in the coarse grained rocks, where feldspars are very cloudy and present a peculiar "diffuse twinning".

Geothermometric temperatures, twinning and microperthites in agpaitic rocks All agpaitic NeS have multiple twinned K-feldspars. The several facies of the *lujaurite-khibinite* bodies show clearly that the twinning is better developed in the coarse-grained rocks (Group Ib, Tab. 5) than in the fine-grained types (Group Ia, Tab. 5); the last ones also have the highest estimated geothermometric temperature. Temperature values of around 580-600°C are probably true crystallization temperatures for these fine-grained agpaitic NeS (cf., Sood 1981). Less agpaitic rocks, such as the *western eudialyte NeS* poor in rare metal silicates, probably show higher solidus temperatures and consequently the values of 600-700°C, obtained for these rocks, may also represent true crystallization temperatures. The agpaitic rocks with incipiently-twinned K-feldspars (Group Ia, Tab. 5) show an intimate relationship between microperthites, twinning and tabular albite; untwinned crystals are homogeneous, while albite lamellae occur in the twinned areas of the crystals in contact with albite laths. It is remarkable that the K-feldspars of the coarse-grained *Lu I* and *khibinites* (Group Ib, Tab. 5) are non-perthitic and without tabular albite. These rocks crystallized probably from very "cool" magmas (solidus at 1 kbar at about 430°, Sood 1981).

The feldspars from other less agpaitic NeS are either microperthitic or homogeneous K-rich phases. The estimated temperatures vary from 540° to <500°C, and are lowest in rocks whose K-feldspars show very good twinning. Registered temperatures of around 500°C, or less, may pinpoint to subsolidus reequilibration between K-feldspar and nepheline.

Geothermometric temperatures, twinning and microperthites in miaskitic rocks The relationship between texture of K-feldspars, rock and mineral chemistry, and geothermometric estimates in miaskitic-intermediate rocks is more complex than in the agpaitic cases. A summary follows, depicting different examples:

The Pedreira NeS These are the typical miaskitic rocks of the district, with the lowest peralkalinity index, and a very special feldspar chemistry (Tab. 3). The temperature estimates for the fine-grained facies (± 800°C, Tab. 5), with strongly zoned, non perthitic and untwinned feldspars, are probably very close to the true crystallization temperature. Predominant among these NeS, however, are medium to coarse-grained facies. Their K-feldspars are cloudy, and the coarser-grained rocks present scarce microperthites associated with a diffuse twinning (resembling the cross-hatched pattern of granitic rocks). The estimated crystallization reequilibration temperatures are higher for the medium-grained rocks and fall rapidly with increase in grain size, suggesting in the last case thorough subsolidus re-equilibration.

Miaskitic-intermediate rocks with low geothermometric temperatures. The several facies listed in Table 5 present geothermometric temperatures between 540° and 500°C. The feldspars are highly potassic and non-perthitic and are sometimes slightly zoned; no tabular albite is observed. All K-feldspars show multiple twinning, varying from incipient to very good.

Miaskitic-intermediate rocks with high geothermometric temperature This group is represented by the *western fine-grained NeS* and some of the northern ring *spotted NeS*, with estimated temperatures of 750 - 770°C (Tab. 5). All samples have abundant tabular albite and microperthitic K-feldspars, with variable development of multiple twinning. The high excess of silica in nephelines can be interpreted as indicating absence of liquid during cooling of the nepheline-bearing mineral assemblage (Hamilton 1961).

DISCUSSION The K-feldspar microtextures here described appear to be the result of secondary processes produced by percolating solutions during a deuteric stage. Two interconnected features are addressed separately: twinning and albite crystallization.

Twinning and orthoclase-microcline inversion Some insight into the mechanisms responsible for the features observed in the Poços de Caldas K-feldspars can be obtained from the detailed TEM studies of Worden *et al.* (1990) dealing with turbidity of feldspars of the Klokken

Table 4 – Unit cell parameters and Al, Si distribution of low microclines

Tabela 4 – Parâmetros de cela unitária e distribuição de Si e Al em microclínios máximos

Sample nº	nº of lines	a	b	c	α	β	γ	t_10
476	45	8.564(3)	12.967(3)	7.214(2)	90.670(23)	115.876(16)	87.692(23)	0.96
480	46	8.574(3)	12.963(3)	7.212(2)	90.597(24)	115.873(22)	87.767(25)	0.95
462	57	8.572(2)	12.971(2)	7.214(2)	90.566(15)	115.860(18)	87.777(21)	0.94
548	65	8.564(2)	12.961(2)	7.214(1)	90.601(17)	115.863(15)	87.763(17)	0.95
669	50	8.568(2)	12.960(3)	7.215(2)	90.606(25)	115.861(20)	87.707(19)	0.97
112	46	8.585(3)	12.962(3)	7.220(2)	90.523(17)	115.982(23)	87.913(26)	0.94
512	58	8.575(3)	12.959(2)	7.219(2)	90.659(14)	115.900(18)	87.673(18)	0.99
519	39	8.572(3)	12.961(3)	7.213(2)	90.598(20)	115.861(18)	87.766(28)	0.95

All low microclines show 4b powder patterns; lattice constants refined with program by Burnham (1962); t_10 estimated using formulae of Ribbe (1984);

Table 5 – Chemical compositions, textures and multiple twinning of K-feldspars

Tabela 5 – Composições químicas, texturas e geminação múltipla de feldspatos potássicos

Miaskitic intermediate bodies (*facies*)	$2V\alpha$[1]	Chemical composition[2] (*sm; m*)[3]	Geothermometry (°C)	Powder pattern type[4]	Agpaitic bodies (*facies*)	$2V\alpha$[1]	Chemical composition[2] (*sm; m*)[3]	Geothermometry (°C)	Powder pattern type[4]
All grains untwinned									
Pedreira NeS (*fine grained facies*)		$Or_{54}Ab_{40}An_6$ (c) $Or_{75}Ab_{24}An_1$ (b)	±800 *b*						
Diffuse twinning in grains[5]									
Pedreira NeS (*medium grained*) (*coarse grained*)	54-46°	$Or_{71}Ab_{28}An_1$ $Or_{82}Ab_{17}Ab_1$	730 b - 600 *a* ±500 *b*	*330,* *234*					
Group I twinning: incipient, poor, good twinning[5]									
a) Incipient twinning predominates. Many grains untwinned, some grains good to poor twinning									
Serrote biotite NeS	28-30°	$Or_{89}Ab_{11}$ ↓ $Or_{95}Ab_5$	550-500 *a*	**1a** *311* **1b** *321* *327*	lujaurite-khibinite (*trachytoid NeS I, II*) (*medium-fine grained Lu II*)		$Or_{85}Ab_{15}$ *sm* $Or_{86}Ab_{14}$ *sm*	580-600a 580 a	**1b** 216
					western eudialyte NeS (*medium grained*)		$Or_{85}Ab_{15}$ *sm*	700-600 b	
b) Poor twinning predominates. Larger crystals incipient twinning, few small grains good to very good twinning									
western fine-grained		$Or_{77}Ab_{23}$ ↓ $Or_{95}Ab_5$ *sm*	±750 *b*		lujaurite-khibinite (*coarse-grained Lu I*)	43-46°	$Or_{87}Ab_{13}$ ↓ $Or_{91}Ab_9$	540-<500 a	**1b** 223
					(*khibinites*)	40°	$Or_{84}Ab_{16}$ ↓ $Or_{93}Ab_7$	540-500 a	**1a** 47 **1b** 169
c) Incipient twinning predominates. Many grains untwinned, some grains good to poor twinning									
Pseudoleucite NeS	23-50°	$Or_{96}Ab_4$	< 500 *a*	**4a** *482*					
western fluorite NeS	56-58°	$Or_{94}Ab_6$	± 500 *a*	**2a** *525*					
Serrote gray NeS		$Or_{90}Ab_{10}$ ↓ $Or_{94}Ab_6$	500 *a*	**2a** *178*					
spotted NeS (*fine-medium grained with large feldspars*)	50-63°	*m*	± 700 *b*	**4a** *540,* *541*					
d) Good twinning predominates. Some larger grains, poor to incipient twinning									
nothern rim gray NeS (*several* (*facies*)	40-48°	$Or_{97}Ab_{23}$ ↓ $Or_{99}Ab_1$ *sm*	500-<500 *a*	**4a** *49a,* *432, 500* **2a** *551* **2b** *413*					
Group II twinning: Very good twinning[5]									
Serrote porphyritic NeS	80°	$Or_{99}Ab_1$	<500 *a*	**4b** *611,* *669*	western eudialyte NeS (*medium-coarse grained*) *porphyritic facies*)	78-82°	$Or_{99}Ab_1$	500-<500 b	**3b** *512,* *519*
spotted NeS (*medium grained with some large K-feldspars*)	84°	*m*		4b 548	Serrote eudialyte NeS	78-80°	$Or_{99}Ab_1$	<500 a	**4b** *159* *112*
					Botelhos khibinites *pegmatoid, banded)*	76-82°		500 *b*	**4b** *476* *480, 462*

Notes: 1 - 2V meassured in untwinned grains or in optically homogeneous areas of twinned crystals; 2 - chemical composition determined in non-perthitic grains; (c), (b) - center and border of strongly zoned K-feldspars; arrows indicate compositional variations of unzonned K-feldspars, in the same or in different samples. 3 - m microperthites in all K-feldspar grains; sm, *microperthites restricted to those crystal areas in contact with tabular albite; 4 - see text for description of pattern type; in italics, corresponding sample number; 5 - see text for description of twinning;* **a** *- data based on K-feldspar and nepheline compositions (Powell & Powell 1977);* **b** *- data based only on nepheline composition (Hamilton 1961)*

(South Greenland) syenite. According to these authors, the turbid areas consist of either "fluid-filled micropores or sites of previous fluid inclusions"; the micropores develop in any part of the crystals and are "associated with abrupt coarsening of perthites". The authors also observed that microcline in the coarsened areas shows an irregular albite twin microtexture or, ocassionally, a "cross-hatched microtexture".

The K-feldspars of the Poços de Caldas rocks here included in Group I show that the twinned areas in the K-feldspars are always turbid containing tiny fluid inclusions. They may represent micropores, at least partly, and in that case the turbid areas can be more permeable to the invading fluids (Walker 1990).

The driving force to initiate the process cannot be uniquely associated with the release of the strain energy of coherent perthites (as pointed out by Worden *et al.* for the Klokken syenite); in most Poços de Caldas rocks, the K-feldspars are already K-rich and perthite coarsening is a localized feature. In any case, the reconstructive changes, once initiated in some spots of the crystals, will develop rapidly outwards. The optical observations show that multiple twinning (and turbidity) depend on crystal size; in all samples, the smaller grains are totally twinned (good twinning) while the larger ones show incipient twinning. The grains appear to maintain their original crystal outlines.

The agpaitic magmas have low solidus temperatures, but their K-feldspars begin to crystallize at higher temperatures, similar to those of non-agpaitic NeS. Experimental data show that feldspars in naujaites (agpaitic nepheline sodalite syenites) nucleate at 800°C, 1 kbar, and in lujaurites they are liquidus phases at 900°C, 1 kbar (Sood 1981). Consequently, they crystallize as monoclinic grains, as is also clearly indicated by textural features in most Poços de Caldas NeS feldspars.

The change of the monoclinic phase to "orthoclase" (possibly of the tweed variety, cf. Brown & Parsons 1989) certainly began at subsolidus temperatures, this orthoclase remaining at an arrested stage in the *Pedreira NeS*, where it seems to coexist with intermediate microcline (cf., type 3 powder pattern) and in the untwinned crystals (or untwinned areas of twinned crystals) observed in the other NeS (Tab. 5).

A rather puzzling texture is the "diffuse twinning" observed in the K-feldspars of the coarser-grained non-agpaitic *Pedreira NeS*. The K-feldspars are brownish on account of their extreme turbidity, but little twinning is observed in contraposition to what is seen in other NeS. These feldspars are richer in Ca and show unusual amounts of Sr, and this composition may establish a crystallochemical barrier for the structural inversion.

In the Group I feldspars (Tab. 5) the coexistence of the twinned and untwinned areas in the same crystal (or in the same thin section) shows that this frozen-in orthoclase structural state can be broken, leading to the development of twinned highly ordered or low microcline with various degrees of turbidity.

In the Group II K-feldspars, on the other hand, all grains are clean and show very good twinning (Tab. 5).

These observations can now be considered from a genetic point of view. Feldspar reconstitution and the passage from the monoclinic to the triclinic stages has to be envisaged as a continuous process, controlled at subsolidus temperatures by late or post-magmatic deuteric fluids. The turbidity in the twinned areas is mostly caused by tiny fluid inclusions which may represent remnants related to the micropores; these are the preferred ways of fluid percolation, unblocking the arrested orthoclase stage and triggering further reordering (Worden *et al.* 1990, Walker 1990). The late deuteric fluids in agpaitic rocks are certainly richer in F and possibly other mineralizing substances (e.g., Edgar 1977, Sood 1981); they may be more effective reconstitution agents, at the same time healing most of the micropores and conferring a less turbid aspect to the twinned areas. These substances are scarcer in the deuteric fluids that accompany non-agpaitic NeS, and larger amounts of micropores may be preserved, hence the relatively more turbid look of the K-feldspars twinned areas in these rocks.

The process reaches its culmination in the Group II K-feldspars (Tab. 5), converting them into a very Na-poor low microcline with the entire healing of the micropores. These feldspars ("tiled microclines" of Smith & McLaren 1983) can also be interpreted as a result of recrystallization of already twinned crystals involving the coarsening of subgrains and eventually of perthites and the disapearance of turbidity by precipitation of new feldspar healing the micropores (Worden *et al.* 1990).

The optical observations made in *khibinites* of the *lujaurite-khibinite* bodies show untwinned orthoclase and inciently to poorly twinned K-feldspars coexisting with small grains of microcline showing very good twinning. These features suggest that the reequilibration of the feldspars, at least in these highly agpaitic NeS, is related not only to the composition of the fluid phase but also to the amount of fluid and to the reordering timespan (Brown *et al.* 1983); changes in these variables could explain why the modifications shown by the K-feldspars of the *lujaurite-khibinite* bodies were not completed, since the corresponding rocks occupy a small volume and probably cooled rather quickly after their solidus was reached.

The entire range of data presented here strongly indicates that the multiple twinning observed in the K-feldspars develops by recrystallization of non-twinned earlier crystals; there is no evidence to support the hypothesis of direct formation of ordered microcline (e.g., microcline crystallizing directly from magmas, cf. Smith & McLaren 1983).

The microtextures of the K-feldspars in the Poços de Caldas NeS are very different from the familiar cross-hatched pattern typical of the microclines of most older granite intrusions. In both cases, the K-feldspars may present very similar chemistries, except perhaps for a somewhat higher Ca content that is frequently observed in the granites. Deuteric fluids, however, are certainly different in the two contrasted chemical systems, and may be the actual cause for the differences in the recrystallization history and hence the twinning style.

Tabular and perthitic albite The late magmatic solutions of the crystallizing NeS were certainly sodic as indicated mainly by the crystallization of late sodic minerals such as the common ocurrence of interstitial analcime and fibrous aegirine aggregates (Ulbrich, cited references). Optically visible perthites in K-feldspars are always associated with multiple twinning and in some cases also with albite laths (tabular albite). All these features are thus genetically related. The visible perthites occupy a very small part of the affected K-feldspar areas, and represent possibly exsolution and not metasomatic features. A textural exception is the *spotted NeS* (Tab. 5) in which all K-feldspars have coarser patch perthites. This is a fine-grained rock, but the texture can also be explained as the result of unmixing of an initially more Na-rich alkali feldspar, as it appears in hypersolvus rocks. Whatever the cause, perthite development in this case was accomplished with little or no feldspar-nepheline reequilibration (see Geothermometry, Tab. 5).

It is difficult to argue on the origin of tabular albite. In most cases there is no structural continuity between these laths and perthite orientation; an exception is again observed in the *spotted NeS*. Evidences for proposing metasomatic growth by means of fluid-controlled Na addition are weak. The preferred explanation is that of Na *redistribution* within the rock by deuteric fluids causing both perthite exsolution and localized replacement of K-feldspar by tabular albite.

The *late* district-wide hydrothermal alteration affected cooler rocks (see Introduction) and is characterized by sericitic alteration of nepheline and K-feldspar reconstitution, with little or no albite crystallization; in fact, this late alteration withdraws Na (among other elements, cf., Garda 1990) from the system and is thus *not* the cause of the monoclinic-triclinic K-feldspar transformation, or for the appearance of albite.

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