

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/255708575>

Genesis of analcime and nepheline-potassium feldspar-kalsilite intergrowths: a review

Article · January 2009

CITATIONS

6

READS

83

7 authors, including:



[Piero Comin-Chiaramonti](#)

Università degli Studi di Trieste

124 PUBLICATIONS 1,942 CITATIONS

[SEE PROFILE](#)



[Ettore Ruberti](#)

ENEA

62 PUBLICATIONS 786 CITATIONS

[SEE PROFILE](#)



[Angelo De Min](#)

Università degli Studi di Trieste

85 PUBLICATIONS 1,410 CITATIONS

[SEE PROFILE](#)



[John Gittins](#)

University of Toronto

66 PUBLICATIONS 1,028 CITATIONS

[SEE PROFILE](#)

All content following this page was uploaded by [Piero Comin-Chiaramonti](#) on 05 January 2016.

The user has requested enhancement of the downloaded file. All in-text references [underlined in blue](#) are added to the original document and are linked to publications on ResearchGate, letting you access and read them immediately.

GENESIS OF ANALCIME AND NEPHELINE-POTASSIUM FELDSPAR-KALSILITE INTERGROWTHS: A REVIEW

PIETRO COMIN-CHIARAMONTI^{1,*} · A. CUNDARI² · E. RUBERTI³ · A. DE MIN¹
J. GITTINS⁴ · C. B. GOMES³ · L. GWALANI^{5,6}

1. Dipartimento di Scienze della Terra, Università di Trieste, Via Weiss 8, I 34127 Trieste, Italy

2. Geotrak International Pty Ltd., P. O. Box 4120, Melbourne University, Victoria AUS 3052, Australia

3. Instituto de Geociências, University of Sao Paulo, Cidade Universitária, Rua do Lago 562, BR 05508-900 São Paulo, Brazil

4. Department of Geology, University of Toronto, Toronto, CDN M5S 3B1, Ontario, Canada

5. C/o D. I. Groves, CET, SEGS, The University of Western Australia, Crawley, Perth AUS WA6009, Australia

6. Present address: C/o Ken Rogers, Level-22, Mineral Securities Limited, Allendale Square, 77 St Georges Terrace, Perth AUS WA6000, Australia

ABSTRACT

The controversial origin of potassic rock suites (lava flows and dykes) containing analcime and pseudoleucite, which may occur as giant trapezohedra {211}, has remained for several decades a hot topic in petrological research. This controversy still persists and as a contribution to the genesis of these minerals, we here examine a few interesting occurrences of analcime and pseudoleucite exhibiting complex intergrowths of alkali-feldspar-analcime-leucite or nepheline-alkali-feldspars in potassic rocks of Iran (North-Eastern Azerbaijan volcanics), Brazil (Poços de Caldas and Banhadão) and Paraguay. Our study supports the view that the phenomenon of ion exchange involving Na⁺ and H₂O, and K⁺ diffusion in presence of Na-rich water results in the conversion of leucite to analcime. Under hydrous conditions alteration or interaction takes place between pre-existing Na-rich phases, such as, nepheline, feldspar and glass. Also, at lower temperatures below the solidus, and at high CO₂ activity, sodium-rich leucite breaks down to a complex intergrowths of orthoclase and nepheline resulting in the development of pseudoleucite, which may retain the original trapezohedral form of leucite. We describe several typologies corresponding to the processes leading to the formation of analcime and complex intergrowths in pseudoleucites occurring in rare potassic suites found in widely separated localities. The study of various topologies corroborates the conclusions drawn from experimental petrology, which indicates that the replacement of leucite by analcime is a solid-state reaction involving cation exchange by volume diffusion.

KEYWORDS: xxxxxx, xxxxxx, xxxxxx, xxxxxx

FOREWORD

THE paper is dedicated to Fabrizio Innocenti, Professor of Petrology at the Pisa University. Fabrizio, passed away at 29 January 2009, for more of 40 years was friend of Piero Comin-Chiaramonti and worked together on the petrogenesis and geodynamics of the volcanic rocks from Iranian country.

INTRODUCTION

SiO₂-undersaturated alkaline magmatic rocks of potassic to ultrapotassic affinity, particularly leucite normative rock-types (e.g., Group I, II and III of Foley 1992), often show euhedral (trapezohedral) megacrysts of analcime or pseudoleucite (*sensu* Gittins 1980) usually associated with nepheline. The former two minerals tend to cluster along the analcime-leucite tie line of Petrogeny's Residua System (Fudali 1963, Comin-Chiaramonti and Gomes 1996). It is well known that nepheline may alter to analcime during subsolidus interactions with deuteric and/or hydrothermal fluids (Deer *et alii* 1992, 2004; Wilkinson and Hensel 1994) and that leucite readily changes to compositions approaching analcime

through similar processes (Cundari 1979, Comin-Chiaramonti *et alii* 1979, Cundari and Comin-Chiaramonti 1996, Prelević *et alii* 2004, Moradian 2008). Particularly, Karlsson and Clayton (1991), while discussing the problem of origin of analcime phenocrysts, suggested that this mineral either resulted from subsolidus oxygen isotopic exchange or it was formed from preexisting leucite (cf. also Putnis *et alii* 2007).

Although there are many papers dealing with the problem of pseudoleucite genesis (e.g., Knight 1906; Bowen and Ellestad 1937; Larsen and Buie 1938; Fudali 1963; Seki and Kennedy 1964; Hamilton and McKenzie 1965; Davidson 1970; Taylor and MacKenzie 1975; Gittins *et alii* 1980, and the enclosed references), we here examine some interesting occurrences of analcime and pseudoleucites where phenocryst-like analcime exhibits complex intergrowths of alkali-feldspar-analcime-leucite/plagioclase or nepheline-alkali-feldspar intergrowths, which may have been derived from an original leucite-bearing igneous rock through subsolidus processes.

Preliminary description of rare analcime and pseudoleucite occurrences from the Upper Cretaceous

* Corresponding Author: P. Comin-Chiaramonti: comin@univ.trieste.it

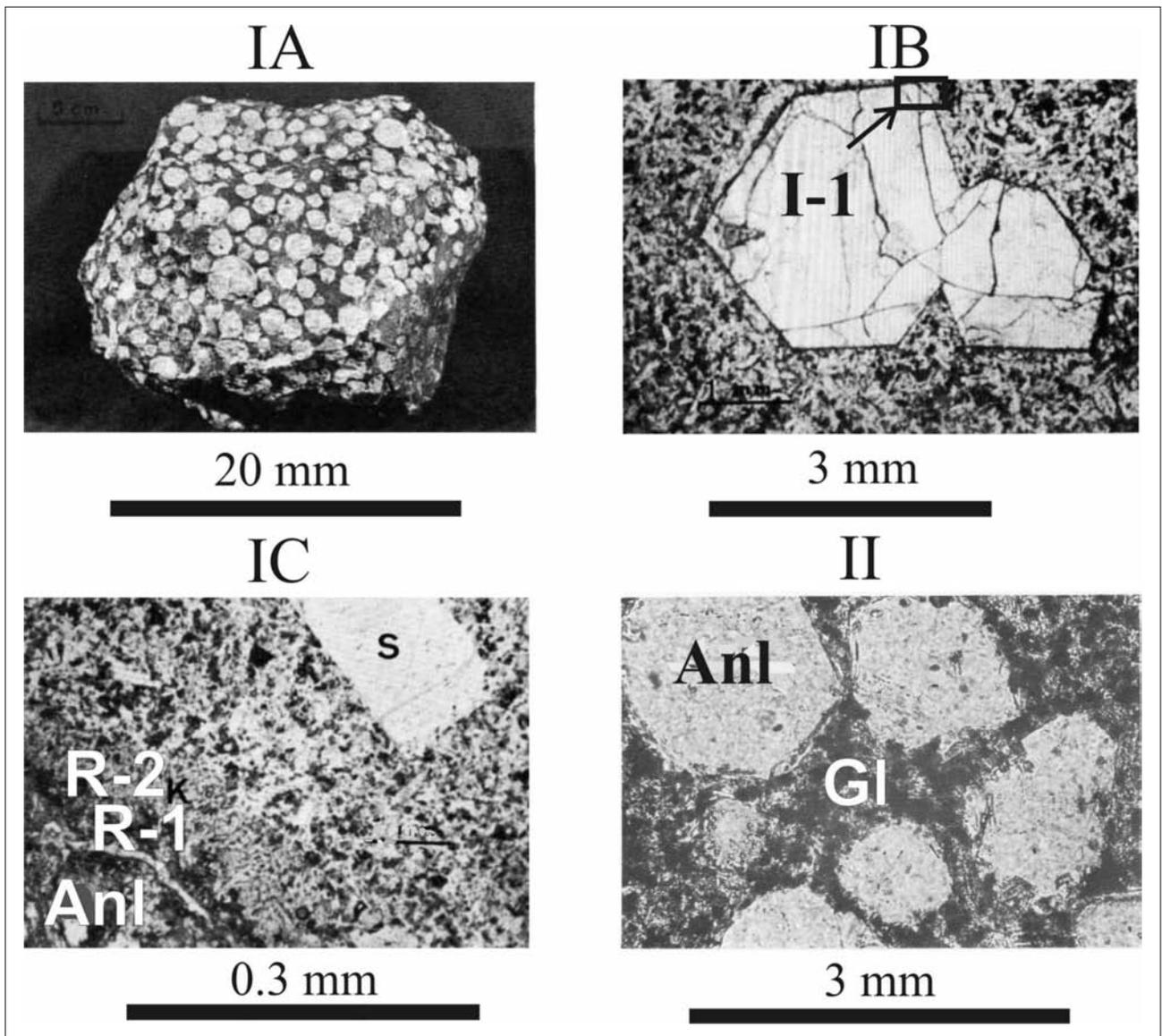


FIG. 1. Typology I. (cf. Table 1): A, macrocrysts of analcime in analcinite; B: phenocryst-like analcime in lava flow. Crossed Nicols; the square represents the Fig. I-C: analcime (Anl) with K-rich rims (Table 1); S, sanidine. Typology II. (Table 1): Phenocryst-like analcime in a glassy groundmass (GI).

to Miocene volcanism of Iranian Azerbaijan (Alberti and Comin-Chiaramonti 1979, Comin-Chiaramonti 1979, Comin-Chiaramonti *et alii* 1979) and from the Lower and Upper Cretaceous magmatic complexes in Southern Brazil and Eastern Paraguay, have been described in earlier work (Hussak 1890; Valença and Edgar 1974; Comin-Chiaramonti and Gomes 1996, 2005; Sgarbi *et alii* 2000; Ulbrich *et alii* 2005; Ruberti *et alii* 2010, and included references). From a few other localities individual trapezohedral phenocrysts of pseudoleucite attaining very large dimension, up to 15 cm long, have been reported from Montana, USA (Larsen and Buie 1938) and the Panwad-Kawant sector of the Chhota Udaipur alkaline subprovince in the Deccan Traps of West-Central India (Sukeheswala and Sethna 1967, Gwalani *et alii* 1993).

Representative whole rock chemical analyses are included in the Appendix.

ANALCIME AND COMPLEX INTERGROWTHS IN POTASSIC SUITES

The origin of potassic rock suites containing analcime is a controversial subject. Multiple stages of igneous activity and low-grade metamorphism (not considered herein) have been responsible for the formation of analcime-bearing potassic rocks occurring as lava flows as well as dykes. Analcime and the complex intergrowths in the alkaline rock suites of Iran, Brazil and Eastern Paraguay may occur in various typologies summarized in Appendix and briefly described below.

1. Conspicuous phenocryst-like icositetrahedra, which are occasionally enveloped by potassium-rich anisotropic rims (FIG. 1, Pls. I-A-B-C).

2. Euhedral to subhedral or subrounded analcime phenocrysts occurring in a cryptocrystalline to glassy groundmass (FIG. 1, Pl. II).

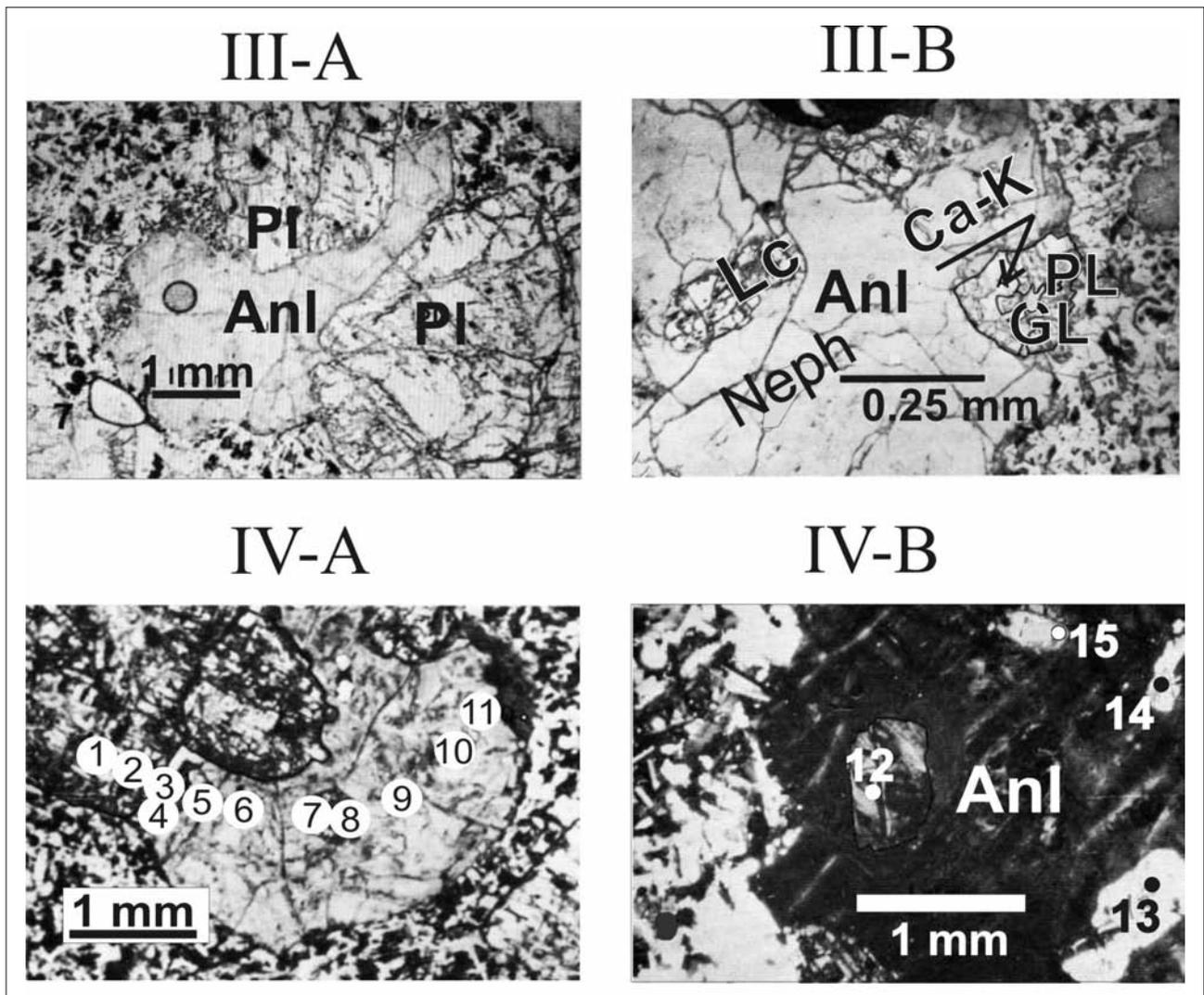


FIG. 2. Typology III. (cf. Table 2): A, B macrocrystals of analcime (Anl) in phonolitic lava HK-1, Iran, including leucite (Lc) and nepheline (Neph); Note Ca-K feldspar (Ca-K) and glass at the contact with plagioclase (Pl) and Anl (B). Parallel polars. Typology IV. Phenocryst-like analcime in a microcrystalline groundmass; Crossed polars. The numbers correspond to the analyses in Table 3. Note the ghost of plagioclase (12) enclosed in Anl in Fig. IV-B.

3. Wedge-shaped analcime interfaced predominantly with large plagioclase crystals, which may be associated with metasomatic Ca-K feldspar (FIG. 2: Pls. III-A and III-B).

4. Subhedral to subrounded analcime interfaced with plagioclase laths and comparatively fine-grained groundmass. In Figure 2 (Pls. IV-A and IV-B), plagioclase is enclosed in analcime and is partially to completely resorbed.

5. Complex intergrowths comprising analcime, alkali-feldspar, leucite, plagioclase, glass and kalsilite.

6. Pseudoleucite occurring as large polygonal crystals or as phenocryst and crystals with irregular outline commonly exhibit coarse-grained intergrowths, which are mainly composed of alkali-feldspar-nepheline / kalsilite intergrowths.

Pseudoleucite, described as an association of nepheline and alkali feldspar, suggests ion-exchange where potassium-rich magma, initially crystallized potassic leucite

that later changed into a more sodic chemistry with falling temperature (Gittins 1980, and enclosed references). Subsequent cooling caused exsolution of nepheline and alkali feldspar where the leucite structure is destroyed, but retaining the leucite crystal morphology.

Notably, leucite (pseudoleucite) and analcime tend to cluster along the analcime-leucite tie-line of the Petrogeny's Residual System and fall in the primary leucite field, coexisting with analcime rich compositions (Comin-Chiaromonti *et alii* 1992).

PROCESSES OF ANALCIME FORMATION

During late or post-magmatic stages analcime may be formed by one of the following processes:

a) *Ion exchange in leucite.* If sufficient Na-rich water solutions are present (e.g., K^+/Na^+ as low as 0.3), the conversion of leucite to analcime may occur up to surface temperature in two different ways through diffusion in-

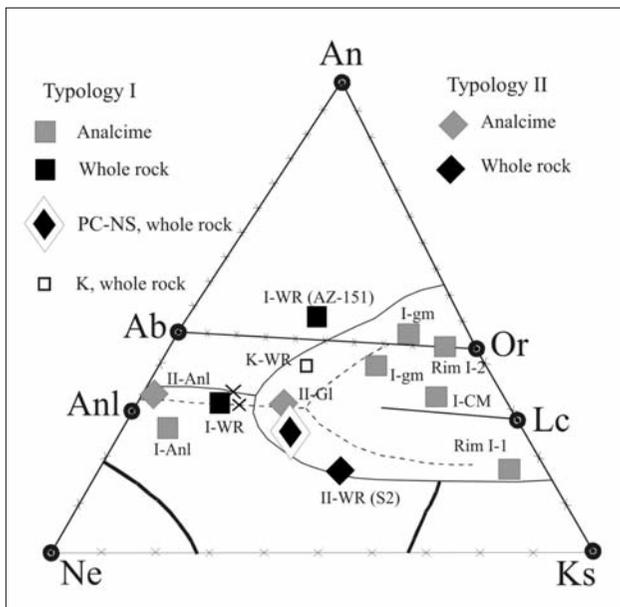


FIG. 3. Typology I-II. Part of the phonolite pentahedron with the ternary feldspar plane rotated into $KAlSiO_4-NaAlSiO_4-SiO_2$ plane. Phase relationships between nepheline, alkali feldspar and leucite are represented at 1 bar, solid line, and at 1 Kb, dashed line, water-vapor pressure; x, ternary minimum (cf. Schairer, 1957; Fudali, 1963; Carmichael *et alii*, 1974). WR, whole rocks, CM, chilled margin (see Appendix); gm, groundmass (cf. Fig. 1 and Table 1). PC-NS: nepheline syenite, whole rock nephelinite from Poços de Caldas (in Appendix).

volving Na^+ and H_2O , and K^+ along the original leucite-groundmass interfaces (Gupta and Fife 1975). The experimental data presented by Taylor and MacKenzie (1975) also supports the view that sodium in plagioclase may be replaced by potassium by ion exchange forming a metastable series of K-Ca feldspar (cf. Viswanathan 1970, Comin-Chiaramonti 1979).

b) *Alteration or interaction between pre-existing Na-rich phases.* The Na-rich phases, such as nepheline, feldspars and glass at subsolidus temperatures may react in the presence of water-rich fluids to form analcime (Henderson and Gibb 1977 and Wilkinson and Hensel 1994).

While normative nepheline appears in variable amounts in all rock samples containing pseudoleucite, only a few samples contain normative leucite varying between 0.9 to 36.3 wt% (cf. Appendix; Table 1). It is, therefore, interesting to study the phases from which analcime may have developed in these rocks. A possible explanation may be based on the assumption of a complete transformation of an earlier highly potassic phase (e.g., leucite) to analcime through metasomatic processes.

TYOLOGY I AND II (DEVELOPMENT OF ANALCIME COMPOSITIONS FROM LEUCITE)

In our samples of phonolites traces of original mineral leucite were found in the potassic rims developed around analcime (Typology I) containing K_2O up to about 21 wt% (TABLE 1; cf. Figure 1, Pls. I A-C). The

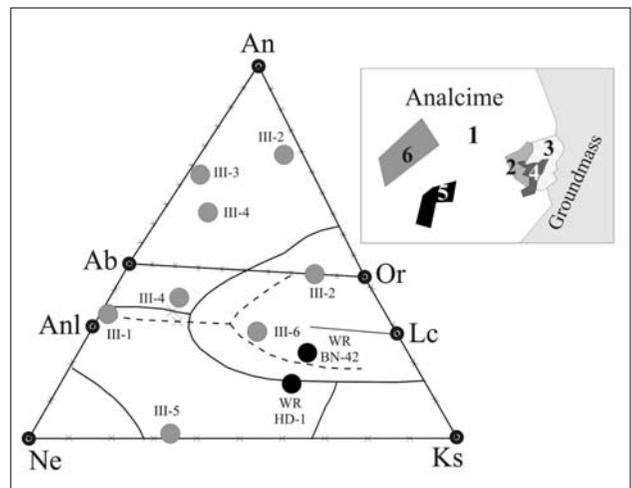


FIG. 4. Typology III. Sketch map in Fig. 2, Plate III-B (inset) and chemical analyses of the phases present in HK-D1 (Iran) and PO (Brazil) samples plotted in the PRS and Or-Ab-An diagrams (cf. Fig. 3). Numbers as in Table 2. Whole rock compositions, HD-1 and BN-42, as in Appendix.

analcime phenocrysts are present in the granular groundmass. This occurrence of analcime in the phonolite is quite different from Typology II (FIG. 1, Pl. II), where the mineral occurs as phenocrysts in a glassy groundmass. The whole-rock data plot along the line of the leucite stability at 0.1 kb H_2O in the Petrogeny's Residua System (PRS). The data for both analcime and groundmass appear on the same Anl-Lc tie line (FIG. 3).

TYOLOGY III

(WITH CA-K FELDSPAR SOLID SOLUTION SERIES)

The representative examples of Typology III are observed within both the samples of a phonolite dyke (sample number HK-D1 from Azerbaijan province of Iran, and of a kamafugite flow occurring in the Presidente Olegario (PO, Alto Paranaíba) in Brazil (cf. Sgarbi *et alii* 2000, Comin-Chiaramonti and Gomes 2005). Whole rock analyses of these rocks are shown in the Appendix, whilst Table 2 gives their microprobe mineral analyses of "K-Ca-feldspar", analcime, plagioclase, glass, nepheline and leucite, and their textural and chemical relationships are shown in Figure 2 (Pls. III-A-B) and Figure 4. Although accurate optical and X-ray structural determinations were not possible, however the component marked as Ca-K in Figure 2 (Plate III-B) represents an anisotropic mineral having a composition close to $Or_{35}Ab_7An_{58}$, consistent with the results of back scatter images (not shown). The K- and Ca-feldspars do not form stable mixed crystals, and their solid solution series usually do not occur in nature. However, Viswanathan (1970), produced a K-Ca feldspar solid solution series with feldspar containing 60 to 20% An, both of 'ordered' and 'disordered' state, by ionic exchange methods. It seems therefore possible that the analyzed anisotropic material of Typology III belongs to the K-Ca feldspar solid solution series and that the formation of these metastable phases is favoured by metasomatic re-

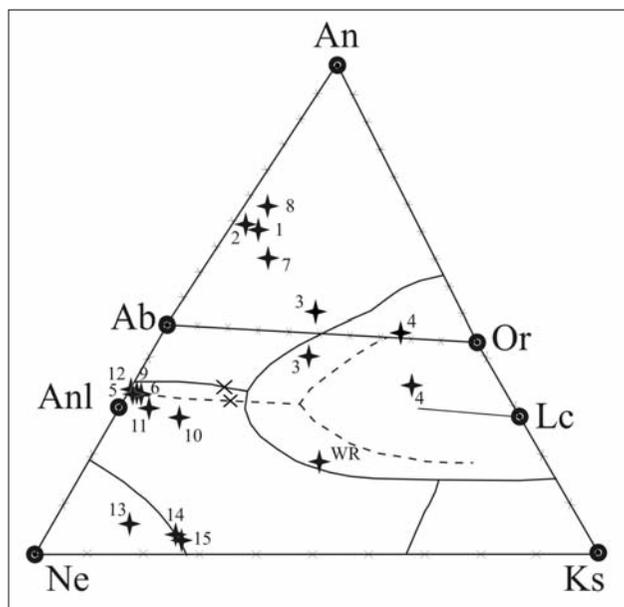


FIG. 5. Typology IV. Compositional relationships for the analcime and coexisting phases (cf. Fig. 3): numbers as in Table 3. WR, whole rock; cf. Analyses AZ-172 (phonolite) of the Appendix. Numbers 1-11 as in Plate IV-A of Fig. 2; numbers 12-15 as in Plate IV-B of Fig. 2.

actions involving nepheline, alkali-feldspar, analcime and plagioclase.

TYPOLOGY IV (PLAGIOCLASE CONTRIBUTION IN THE FORMATION OF ANALCIME)

The Typology IV is characterized by a large plagioclase contribution to the analcimization process (FIG. 2, Pls. IV-A-B and FIG. 5), up to the complete resorption of plagioclase inclusions (FIG. 2, Pl. IV-B, point 12) indicated by ghost structures. Compositional variation across the phenocrysts of analcime-plagioclase and groundmass interfaces were determined in detail by microprobe analyses (FIG. 5 and TABLE 3). Interstitial glass (point 4 on Figure 5) occurring along the margin of the analcime phenocryst shows a composition approaching Q = 34%, Ne = 15% and Ks = 51%.

On the other hand, the upper part of the rim (point 10 in Figure 5) has a composition corresponding to anal-

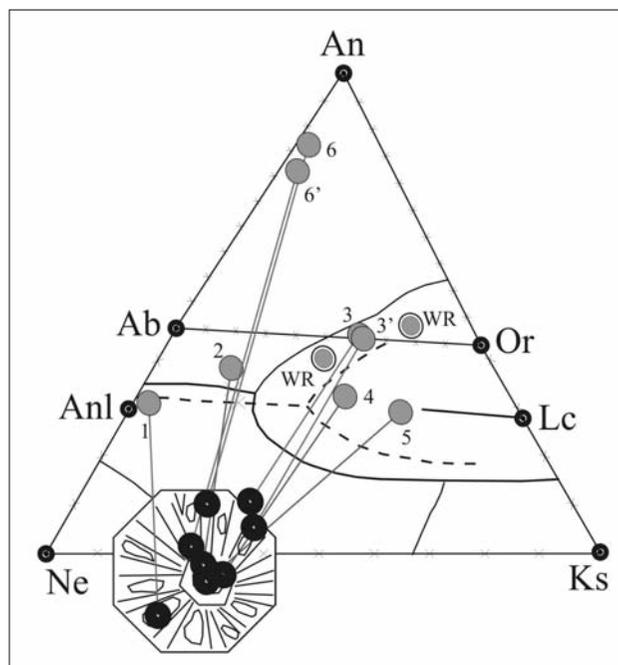
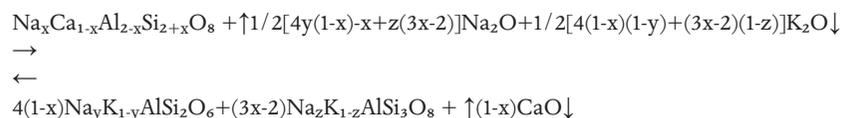


FIG. 6. Typology V. Compositional relationships for the analcime and coexisting phases (cf. Fig. 3): numbers as in Table 4. WR, whole rock composition of AZ-117 (trachyphonolite) given in the Appendix.

cime 83% and leucite 17%, which may represent incomplete analcimization. Therefore, the resorption of plagioclase (point 12 on Figure 5) and potassium concentration at the analcime borders may be significant as a general trait.

TYPOLOGY V (ROLE OF EXSOLVED LEUCITE IN ANALCIME FORMATION)

These types very well correspond to the typology representing 'greatly- and lightly exsolved leucite' as indicated by the experimental results of Wilkinson (1968, 1977). If we accept that the illustrated intergrowths among the involved phases (FIG. 6, TABLE 4) originated by ion exchange processes producing metastable sodium-rich leucites, at subsolidus temperature, a possible reaction may be explained as shown below:



where the arrows indicate the reversible exchange of alkalis and calcium between crystal and glass phases, in the presence of water to form analcime.

TYPOLOGY VI (FORMATION OF ALKALI FELDSPAR-NEPHELINE INTERGROWTHS)

A few dykes of tinguaite containing pseudoleucite phenocrysts have been reported from the Deccan Trap

lava flows of the Chhota Udaipur alkaline subprovince (Panwad-Kawant sector) in Gujarat, India (Sukheswala and Sethna 1967, Gwalani *et alii* 1993). Phenocrysts of pseudoleucite are also present within the orthoclase-nepheline syenites associated with Banhadão complex, Brazil (Ruberti *et alii* 2010).

The pseudoleucites from both localities are distinctive for their occurrence and size, measuring 1 to 10 centimetre across. They may exhibit characteristic leucite

TABLE 1. Representative microprobe analyses of Typology I and II. Anl, R-1, R-2 (sample AZ 151) and Anl, Gl (sample S2) as in Figure 1. Host rocks: samples AZ151 and S2 of the Appendix.

Typology I (AZ-151)	Analcime I Anl	Rim R-1	Rim R-2	Typology II (S2)	Analcime Anl	Glass Gl
SiO ₂	51.39	47.61	61.35		55.0	57.1
Al ₂ O ₃	23.48	24.96	19.81		22.9	22.9
Fe ₂ O ₃	1.55	0.40	0.28		0.7	1.6
MgO	0.21	-	0.04		-	0.9
CaO	0.20	0.21	0.15		0.9	1.7
Na ₂ O	12.78	1.46	1.02		12.1	7.5
K ₂ O	1.92	20.86	14.59		0.6	6.8
H ₂ O+	8.20	-	-		-	-
Sum	99.73	95.50	97.24		92.2	98.5
Q	26.7	18.4	42.8		33.0	30.7
Ne	66.0	7.1	5.0		64.6	42.0
Ks	7.3	74.5	52.2		2.4	27.3

TABLE 2. Representative microprobe analyses of Typology III. Compositions of the host rocks HK-D1 and BN-42 are given in the Appendix.

Typology III (HK-D1, BN-42)	Analcime 1	Ca-K Felds 2	Plagioclase 3	Glass 4	Nepheline 5	Leucite 6
SiO ₂	57.43	55.30	56.65	53.22	41.06	56.68
Al ₂ O ₃	21.65	25.49	26.02	23.92	34.83	24.04
CaO	0.14	11.51	9.40	5.48	0.03	0.01
Na ₂ O	13.21	0.79	6.16	6.35	14.51	6.87
K ₂ O	0.30	5.79	0.87	3.22	10.08	11.76
Sum	92.73	98.88	99.10	92.19	100.51	99.36
Q	33.6	48.5		38.6	0.0	28.6
Ne	65.3	8.1		44.8	66.3	31.6
Ks	1.1	43.4		16.6	33.7	39.8
An		58.3	44.9	27.2		
Ab		6.8	50.2	53.8		
Or		34.9	4.9	19.0		

TABLE 3. Representative microprobe analyses across analcime of type IV (sample AZ-172 of the Appendix). The numbers correspond to those shown in Figure 2, Plates IV-A and IV-B. Pl, plagioclase; AF, alkali feldspar; GL, glass; Anl, analcime; Ne, nepheline.

Typology IV	Pl IV-1	Pl IV-2	AF IV-3	GL IV-4	Anl IV-5	Anl IV-6	GL IV-7	Pl IV-8	Anl IV-9	GL IV-10	Anl IV-11	Anl IV-12	Ne IV-13	Ne IV-14	Ne IV-15
SiO ₂	56.80	54.89	65.00	59.38	54.53	54.50	55.89	54.17	54.45	57.82	55.13	55.18	46.19	44.66	43.97
Al ₂ O ₃	25.36	26.82	19.54	17.10	21.83	21.99	23.44	26.88	22.00	21.66	22.12	23.45	31.87	33.37	33.36
Fe ₂ O ₃	0.59	0.51	0.34	4.07	0.20	0.16	2.20	0.77	0.18	0.15	0.51	-	1.06	0.41	0.51
MgO	0.06	0.05	0.08	3.43	-	-	0.83	0.08	-	0.03	0.06	-	0.01	-	-
CaO	8.06	8.83	1.62	0.23	0.11	0.16	5.66	10.03	0.12	0.08	0.14	1.64	0.05	0.10	0.06
Na ₂ O	6.32	7.42	6.24	2.42	13.13	13.22	6.50	5.39	13.18	12.59	12.99	11.82	17.10	15.80	15.75
K ₂ O	1.77	0.78	8.13	10.79	0.16	0.20	2.93	1.35	0.20	3.65	1.25	0.91	3.98	7.03	7.08
Sum	98.96	99.30	101.0	97.42	89.96	90.23	97.45	98.67	90.13	95.98	92.20	93.00	100.3	101.4	100.7
Q			40.6	33.7	31.9	31.4			31.4	28.8	30.2	32.5	6.3	4.0	3.5
Ne			30.4	15.5	67.5	67.9			67.9	58.7	65.1	63.9	80.0	72.0	72.8
Ks			29.0	50.8	0.6	0.7			0.7	12.5	4.7	3.6	13.7	23.6	23.7
Or	10.0	4.1	44.1	74.7			17.2	7.8							
Ab	51.5	56.5	48.5	24.0			54.8	44.1							
An	38.5	39.4	7.4	1.3			28.0	48.1							

TABLE 4. Representative microprobe analyses of the phases present in the Type v analcime (from sample AZ-117 given in the Appendix). The numbers correspond to those reported in Figure 6. Pl, plagioclase; AF, alkali feldspar; GL, glass; Anl, analcime; Ne, nepheline.

Typology v	Anl 1	Anl 2	AF 3	AF 3'	Sodic Lc 4	Sodic Lc 5	Pl 6	Pl 6'
SiO ₂	54.8	56.67	65.52	64.95	52.7	53.3	59.59	59.42
Al ₂ O ₃	22.0	20.54	19.18	18.92	21.1	21.1	25.39	25.17
Fe ₂ O ₃	0.9	0.17	0.23	0.15	0.2	0.4	0.39	0.47
MgO	-	-	0.02	0.02	-	-	0.05	0.10
CaO	0.2	0.43	0.21	0.11	0.7	0.5	4.80	6.32
Na ₂ O	12.9	9.25	4.21	4.41	5.5	4.0	8.61	7.21
K ₂ O	0.7	4.20	10.28	10.56	9.9	13.3	0.62	0.77
Sum	91.5	91.26	99.65	99.12	90.1	93.3	99.47	99.32
Q	32.0	38.2	44.7	43.3	32.1	29.9		
Ne	65.4	46.3	19.8	20.6	29.3	20.4		
Ks	2.6	15.5	35.5	36.1	38.6	49.7		
Or			62.4	62.2			3.6	4.7
Ab			36.6	37.2			72.6	63.0
An			1.0	0.6			23.8	32.3

TABLE 5. Representative analyses of the phases present in the nepheline-alkali feldspar intergrowths (cf. whole rock BN-42 in Appendix). Alkali feldspar is a disordered orthoclase and contains up to 0.50 wt% of BaO.

	Kalsilite core	Kalsilite rim	Nepheline core	Nepheline core	Alkali Feldspar	Whole Intergrowths
SiO ₂	37.44	36.60	41.65	41.83	63.87	55.84
Al ₂ O ₃	31.47	32.76	33.77	34.09	18.19	24.12
Fe ₂ O ₃	0.81	0.80	1.14	0.92	0.29	0.39
CaO	-	-	0.03	-	-	-
Na ₂ O	0.09	0.08	15.36	15.56	0.12	5.78
K ₂ O	29.40	29.20	8.10	7.84	16.76	13.64
Sum	99.20	99.43	100.05	100.25	99.23	99.77
Q	0.0	0.0	0.0	0.0	42.2	27.2
Ne	0.4	0.4	72.1	72.8	0.6	24.0
Ks	99.6	99.6	27.9	26.9	57.2	45.8

TABLE 6. Representative compositions of Fig. 8, expressed in terms of Quartz (Q), Nepheline (Ne) and Kalsilite (Ks). WR, whole rock; Lc, Leucite; Ex, exsolutions; Or, orthoclase; Anl, analcime.

	A (PS-530)			B (PS-245)			C (3153)	
	WR	Lc	Ex	WR	Ne	Or	WR	Anl
Q	24.7	27.8	32.4	17.0	2.1	43.4	34.7	26.3
Ne	10.1	5.9	26.6	38.1	68.0	8.7	21.5	62.2
Ks	65.2	66.3	41.0	44.9	29.9	47.9	43.8	11.5

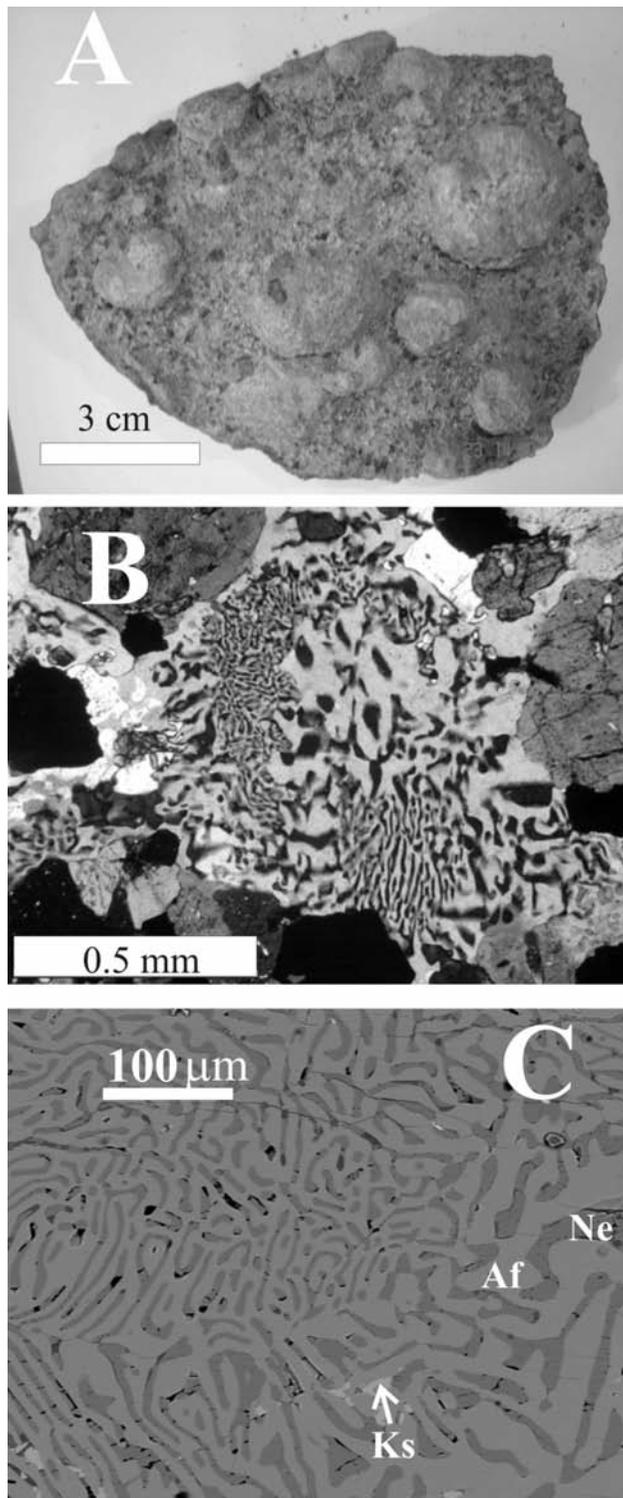


FIG. 7. Pseudoleucite from Banhadão (Southern Brazil; Ruberti *et alii*, 2010). A: Pseudoleucite “warts” in nepheline-syenites; B: Intergrowths Alkali feldspar-nepheline (crossed polars). C: Backscattered electronic image of pseudoleucite. AF (light grey), alkali feldspar; Ne, nepheline (dark grey); Ks, kalsilite (very light grey).

crystal habit (polygonal or eight sided trapezohedral) or appear as rounded to subrounded intergrowths (up to 40 vol.%; FIG. 7) of alkali feldspar-nepheline with kalsilite segregations within the Brazilian samples. Kalsilite may occur as a late-crystallized phase, proba-

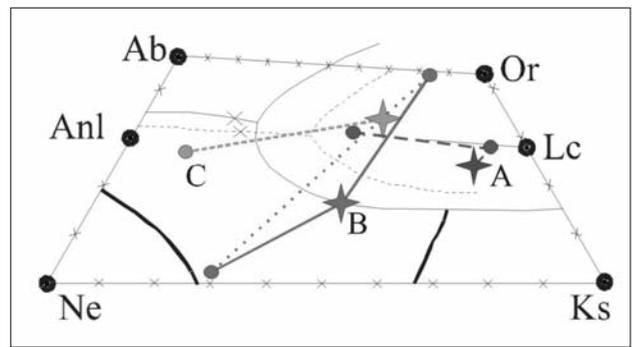


FIG. 8. Plot of part of the Phonolite pentahedron for selected whole rock compositions (stars) from Eastern Paraguay (Asunción-Villarica rift; Comin-Chiaramonti and Gomes, 1996, 2005) and compositions from trapezohedral phases (Tab. 6). A: PS-530 sample, corresponding to slightly exsolved leucite of Taylor and Mac Kenzie, 1975); B (PS-245) and C (3153), roughly corresponding to exsolved leucite (Taylor and Mac Kenzie, 1975) and to analcime of Comin-Chiaramonti *et al*: (1979), respectively. To be note that A represents a close intrusive body, B is an alkaline-carbonatitic complex (relatively high CO₂ content) and C shows high H₂O activity Comin-Chiaramonti and Gomes, 1996).

bly formed as a subsolidus product of exsolution-segregation from a K-rich nepheline or a Na-rich leucite (cf. Ferry and Blencoe 1978).

Other distinctive characteristics are the presence of abundant primary carbonates of carbonatitic affinity, and the scarcity of hydrated phases, mica occurring only as an accessory phase. Similar intergrowths are common in the alkaline complexes of Brazil having carbonatitic affinity (e.g. Alto Paranaíba kamafugites; cf. Sgarbi *et alii*, 2000) and in the alkaline-carbonatitic dykes from Eastern Paraguay (Comin-Chiaramonti and Gomes 1996). These vermicular, fingerprint-like intergrowths of nepheline-alkali feldspar are similar to those described by Gittins *et alii* (1980), the chemistry of the phases overlapping in the phonolite pentahedron (FIG. 9).

Nepheline-syenites and tinguaite are also reported from the Poços de Caldas alkaline-complex (Ulbrich *et alii* 2005). We note in this case that:

a) The Poços de Caldas massif is represented by multiple magma batches, mainly comprising nepheline-syenites and tinguaite.

b) The nepheline syenites (LOI = 3.3 ± 1.4 wt%, $K_2O/Na_2O = 1.0$, $H_2O/CO_2 = 3.77 \pm 0.30$, wt ratios) are characterized by the presence of euhedral analcime (similar to the Typologies I and II) and scarce primary carbonate occurrence.

c) On the other hand, the tinguaite (LOI = 1.7 ± 0.8 wt%, $K_2O/Na_2O = 1.1$, $H_2O/CO_2 = 0.4 \pm 0.1$, wt ratios) show the typical alkali-feldspar-nepheline intergrowths (similar to those of the Banhadão complex) and primary carbonates (cf. Costanzo *et alii* 2008).

In particular, in the alkaline and alkaline-carbonatitic complexes from Eastern Paraguay, all the described typologies are present and also those described by Taylor and MacKenzie (1975), even those referred to the «slightly-exsolved leucite» (FIG. 8). The latter represents

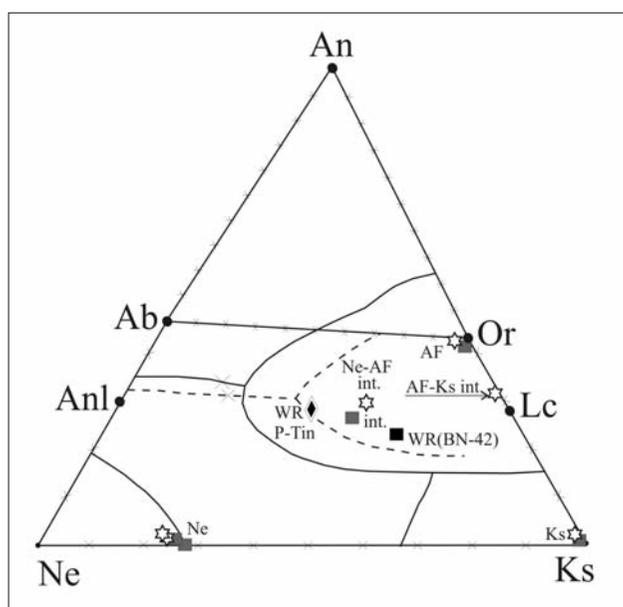


FIG. 9. Intergrowths nepheline-alkali feldspar (Banhadão complex) of Table 5 plotted in the phonolite pentahedron. Stars: from Table 1 of Gittins *et alii*, 1980. P-Tin, Poços de Caldas (cf. Appendix). WR, whole rock; Ks, kalsilite; Ne, nepheline; AF, alkali feldspar; int., intergrowths.

a very rare typology (one occurrence over 527 analyzed rocks from Eastern Paraguay) occurring in a very close system (Comin-Chiaramonti and Gomes 1996).

CONCLUDING REMARKS

The analcime typologies here considered are from natural systems, and are substantially supported also by the experimental data of Taylor and MacKenzie (1975).

The latter authors demonstrated that the assemblage analcime-melt (\pm nepheline, albite and orthoclase) may exist in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-NaAlSi}_3\text{O}_4\text{-KAlSi}_3\text{O}_4\text{-H}_2\text{O}$ within a very narrow pressure-temperature range, i.e. > 2 kb and 600-640 °C, respectively.

Gupta and Fife (1975) have demonstrated the rapid rate of conversion of leucite to analcime, the activation energy of the reaction being small (≈ 8 kcal mol⁻¹). Hence the reaction is rather insensitive to temperature and is also favoured by low pressure. Provided sufficient Na⁺-bearing water is present (e.g. $\text{K}^+/\text{Na}^+ < 0.3$), the conversion will proceed at surface temperatures.

Moreover, Hovis *et alii* (2002) stated that the limited solid solution between natural analcime and leucite must be attributed to energetically favoured heterogeneous equilibria involving minerals such as feldspars and feldspathoids, and not because of immiscibility between the end members. It appears that the introduction of sodium into leucites by ion exchange processes produces metastable sodium-rich phases, allowing a great compositional range for pseudoleucites. This indicates that metastable leucite-analcime solid solutions may be produced even between leucite crystals and hydrous glass. According to Wilkinson (1977), the most

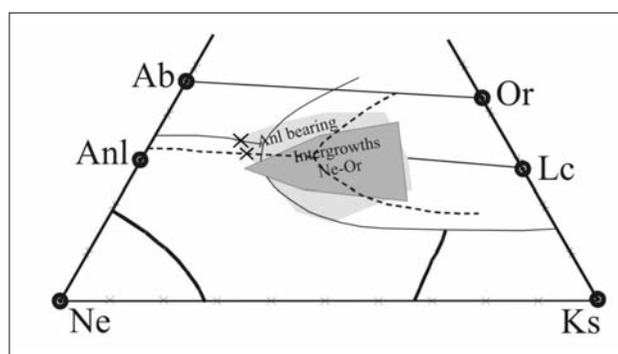


FIG. 10. Equilibrium diagram of the ternary system Nepheline-Kalsilite-Quartz (cf. 1). Grey field: Anl bearing rocks containing analcime; dark grey field, Intergrowths Ne-Or bearing rocks containing pseudoleucite. Data sources: this work, Larsen and Buie (1938), Taylor and MacKenzie (1975), Valença and Edgar (1979), Gwalani *et alii* (1993), Comin-Chiaramonti and Gomes (1996; 2005).

convincing evidence of the widespread analcimization of leucite has been provided by Cundari and Graziani (1964).

The intergrowths could have formed from a pre-existing, homogeneous, solid phase, with change in bulk composition, either by subsolidus replacement of a stable phase, by sub-solidus breakdown of an unstable phase, or by reaction with a fluid phase (Davidson 1970). Notably, rocks containing analcime and orthoclase-nepheline intergrowths show overlapping fields (Fig. 10).

Probably the difference between analcime-bearing rocks and rocks where nepheline-alkali feldspar (kalsilite) appear as intergrowths, are linked to kind of fluids becoming active at subsolidus temperatures. The H₂O-rich fluid plays a role in the formation of analcime, while CO₂ rich fluids are responsible for the development of intergrowths in the mineral, and this we have supported by petrographic evidences.

However, not all nepheline-alkali feldspar intergrowths may be considered as pseudoleucite, especially those represented by flame or plume-like intergrowths that appear as quench textures (cf. Gittins *et alii* 1980).

ACKNOWLEDGEMENTS

The paper resulted from the an academic-scientific protocol between the University of Trieste (Italy) and the University of São Paulo (USP, Brazil, grants: CNPq-303428/2005-8 and FAPESP-07/57461-9).

REFERENCES

- Alberti A. and Comin-Chiaramonti P. (1979). Su alcuni aggregate simili alle pseudoleuciti. «Bollettino della Società Adriatica di Scienze», 63, 17-25.
- Bowen L. and Ellestad R. B. (1937). Leucite and Pseudoleucite. «Am. Mineral.» 22, 409-415.
- Carmichael I. S. E., Turner F. J. and Verhoogen J. (1974). Igneous Petrology, New York, McGraw-Hill Book Co., 241-248.
- Comin-Chiaramonti P. (1979). On the K-Ca solid solution series. «N. Jahrb. Miner. Mh.», H11, 495-497.

- Comin-Chiaramonti P., Cundari A., Gomes C.B., Piccirillo E.M., Censi P., De Min A., Bellieni G., Velázquez V.F. and Orué, D. (1992). Potassic dyke swarm in the Sapucaí graben, Eastern Paraguay: petrographical, mineralogical and geochemical outlines. «Lithos», 28, 283-301.
- Comin-Chiaramonti P., Meriani S., Mosca R. and Sinigoi S. (1979). On the occurrence of analcime in the northeastern Azerbaijan volcanics (northwestern Iran). «Lithos», 12, 187-198.
- Comin-Chiaramonti P. and Gomes C. B. (eds) (1996). Alkaline magmatism in Central-Eastern Paraguay. Relationships with coeval magmatism in Brazil. São Paulo (Brazil), «Edusp/Fapesp», 464 pp.
- Comin-Chiaramonti P. and Gomes C. B. (eds) (2005). Mesozoic to Cenozoic alkaline magmatism in the Brazilian platform, São Paulo (Brazil), «Edusp/Fapesp», 752 pp.
- Costanzo A., Moore K. and Feely M. (2008). Identification of multiple carbonatite events in the magma history of the Poços de Caldas massif using the trapped fluid phases. MPI07, Alkaline and carbonatite magmatism and related ore deposits. 33rd International Geological Congress, Oslo, <http://www.cprm.gov.br/33IGC/1338751.html>
- Cundari A. (1979). Petrogenesis of leucite-bearing lavas in the Roman Volcanic Region, Italy. The Sabatini lavas. «Contrib. Mineral. Petr.», 70, 9-21.
- Cundari A. and Comin-Chiaramonti P. (1996). Mineral chemistry of alkaline rocks from the Asunción-Sapucaí graben (central-eastern Paraguay). In: P. Comin-Chiaramonti and C. B. Gomes (eds.), Alkaline magmatism in central-eastern Paraguay. Relationships with coeval magmatism in Brazil, São Paulo (Brazil), «Edusp/Fapesp», 181-194.
- Cundari A. and Graziani G. (1964). Prodotti di alterazione della leucite nelle vulcaniti vicane. «Per. Mineral.», 33, 35-43.
- Davidson A. (1970). Nepheline-K-feldspar intergrowth from Kamik Lake, Northwestern territories. «Can. Mineral.», 10, 191-205.
- Deer W. A., Howie, R. A. and Zussman, J. (1992). An introduction to the rock-forming minerals, ???, Longman, 696 pp.
- Deer W. A., Howie R. A., Wise W. S. and Zussman J. (2004). Rock-Forming Minerals. 4B. Framework Silicates: Silica Minerals, Feldspathoids and the Zeolites, 2nd edn., ???, The Geological Society, 982 pp.
- De La Roche H., Leterrier J., Grandclaude P. and Marchal M. (1980). A classification of volcanic and plutonic rocks using R1-R2 diagram and major element analyses. Its relationships with current nomenclature. «Chem. Geol.», 29, 183-210.
- Ferry J. M. and Blencoe J. G. (1978). Subsolidus phase relations in the nepheline-kalsilite system at 0.5, 2.0, and 5.0 kbar. «Am. Mineral.», 63, 1225-1240.
- Foley S. F. (1992). Petrological characterization of the source components of potassic magmas: geochemical and experimental constraints. «Lithos», 28, 187-204.
- Fudali R. F. (1963). Experimental studies bearing on the origin of pseudoleucite and associated problems of alkalic rocks systems. «GSA Bull.», 74, 1101-1126.
- Gittins J., Fawcett J. J., Brooks C. K. and Rucklidge J. C. (1980). Intergrowths of nepheline-potassium feldspar and kalsilite-potassium feldspar: A re-examination of the 'pseudo-leucite problem'. «Contrib. Mineral. Petr.», 73, 119-126.
- Gupta A. K. and Fife W.S. (1975). Leucite survival: the alteration to analcime. «Can. Mineral.», 13, 361-363.
- Gwalani L. G., Rock N. M. S., Chang W. J. Fernandez S., Allègre C. J. and Prinzhofer A. (1993). Alkaline rocks and carbonatites of Amba Dogar an adjacent areas, Deccan Igneous Province, Gujarat, India. Geology, petrography and petrochemistry. «Mineral. Petrol.», 47, 218-253
- Hamilton D. L. and McKenzie W. S. (1965). Nepheline solid solutions in the system NaAlSiO₄-KAlSiO₄-SiO₂. «J. Petrol.», 1, 1-56.
- Henderson C. M. B. and Gibb F. G. F. (1977). Formation of analcime in the Dippin sill, Isle of Arran. «Mineral. Mag.», 41, 534-537.
- Hovis G. L., Roux J. and Rodrigues E. (2002). Thermodynamic and structural behaviour of analcime-leucite analogue systems. «Am. Mineral.», 87, 523-532.
- Hussak E. (1890). Ueber leucit-pseudokrystalle in Phonolith (Tinguait) der Serra de Tinguá, Estado Rio de Janeiro, Brazil. «Neues Jb.», 1, 166-169.
- Karlsson H. R. and Clayton R. N. (1991). Analcime phenocrysts in igneous rocks: primary or secondary? «Am. Mineral.», 76, 189-191.
- Knight C. W. (1906). A new occurrence of pseudoleucite. «Am. J. Sci.», 21, 286-295.
- Larsen E. S. and Buie B. F. (1938). Potash analcime and pseudoleucite from the Highwood Mountains of Montana. «Am. Mineral.», 23, 837-849.
- Le Maitre R. W. (1989). A classification of igneous rocks and glossary of terms, Oxford, Blackwell Science, 194 pp.
- Moradian A. (2008). A contribution to the genesis of analcime after leucite in potassic volcanic rocks of the Nadik area, Kerman, Iran. «Journal of Sciences, Islamic Republic of Iran», 19, 31-48.
- Prelević D., Foley D. S. F., Cvetković V. and Romer R. L. (2004). The analcime problem and its impact on the geochemistry of ultrapotassic rocks from Serbia. «Mineral. Mag.», 68, 633-648.
- Putnis C. V., Geisler T., Schmid-Beurmann P., Stephan T. and Giampalo C. (2007). An experimental study of the replacement of leucite by analcime. «Am. Mineral.», 92, 19-26.
- Ruberti E., Enrich G. R., Azzone R. G., Comin-Chiaramonti P., De Min A. and Gomes C. B. (2010). Petrology and geochemistry of the Bahadão alkaline complex (Paraná State, Brazil). «Mineral. Petrol.», submitted.
- Sgarbi P. B. A., Gaspar J. C. and Valença, J. G. (2000). Brazilian kamafugites. «Revista Brasileira de Geociências», 30, 417-420.
- Schairer J. F. (1957). Melting relations of the common rock-forming silicates. «Am. Ceram. Soc. J.», 40, 215-235.
- Seki Y. and Kennedy G. C. (1964). An experimental study on the pseudoleucite problem. «Am. Mineral.», 49, 1267-1280.
- Sukheswala R. N. and Sethna S. F. (1967). Giant pseudoleucites of Ghori, Chhota Udaipur, India. «Am. Mineral.», 52, 1904-1910.
- Taylor D. and MacKenzie W. S. (1975). A contribution to the pseudoleucite problem. «Contrib. Mineral. Petrol.», 49, 321-333.
- Ulbrich H. H., Vlach S. R. F., Demaiffe D. and Ulbrich M. N. C. (2005). Structure and origin of the Poços de Caldas alkaline massif, SE Brazil. In: P. Comin-Chiaramonti and C. B. Gomes (eds.), Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform, São Paulo (Brazil), «Edusp/Fapesp», 367-418.
- Valença J. G. and Edgar A. D. (1979). Pseudoleucites from Rio de Janeiro State, Brazil. «Am. Mineral.», 64, 733-735.
- Viswanathan K. (1970). The existence of a K-Ca feldspar solid solution series. «Naturwissenschaften», 57, 451.
- Wilkinson J. F. G. (1968). Analcimes from some potassic igneous rocks and aspects of analcime rich igneous assemblages. «Contrib. Mineral. Petrol.», 18, 252-269.
- Wilkinson J. F. G. (1977). Analcime phenocrysts in a vitrophiric analcime – primary or secondary? «Contrib. Mineral. Petrol.», 64, 1-10.
- Wilkinson J. F. G. and Hensel H. D. (1994). Nephelines and analcimes in some alkaline igneous rocks. «Contrib. Mineral. Petrol.», 118, 79-91.