Coexisting glasses occurring as inclusions in leucite from lamproites: examples of silicate liquid immiscibility in ultrapotassic magmas

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Abstract

Inclusions occurring in leucites from the Oscar and Zirkel Mesa leucite lamproites consist of high (>10 wt.%) and low (<4 wt.%) K_2O discrete glass phases which are interpreted to have resulted from silicate liquid immiscibility. Both glasses are quartz-normative and rich in Ti, Fe, Mg, Ca and Ba and poor in Al. The high-K glass is strongly peralkaline. Neither of the glasses have compositions representative of any known lamproites. These inclusions represent the first described examples of silicate–silicate immiscibility shown by glass in alkaline rocks.

KEYWORDS: leucite, inclusions, glasses, lamproite, silicate liquids, immiscibility.

Introduction

THE existence of *bona fide* liquid immiscibility between silicate melts has been demonstrated in a variety of lunar and terrestrial basaltic rocks (Roedder and Weiblen, 1970; De, 1974; Roedder, 1979). In the case of alkaline rocks the evidence is less compelling and the presence of crystalline silicate ocelli set in a matrix of contrasting composition has usually been interpreted as resulting from immiscibility (Ferguson and Currie, 1971; Philpotts, 1972, 1976). Importantly, none of the postulated examples of silicate immiscibility in alkaline rock compositions have been based upon the observation of coexisting silicate glasses. Nevertheless, extrapolating from these data, immiscibility is commonly called upon to explain the coexistence of alkaline rocks of dramatically differing compositions. A possible alternative hypothesis is that silicate ocelli could be created by surface tension effects between partially-crystallized parental liquids and their compositionally distinct differentiates. In such cases the formation of the ocelli is unrelated to immiscibility. This paper describes coexisting silicate glasses that appear to be unambiguous examples of silicate–silicate immiscibility occurring on a microscopic scale.

It has long been recognized that leucite crystals characteristically contain small inclusions of glass which are commonly arranged in a quasi-radial or 'clock face' pattern. The inclusions are usually considered to represent trapped samples of the silicate melt from which the leucites formed. Typically the inclusions are very small (<1 μm) and not amenable to analysis by electron microprobe methods because of the excitation of the enclosing leucite.

In this work, examples of glass inclusions in leucite are described from lamproites occurring at the Oscar Plug, West Kimberley, Australia (Prider, 1982; Jaques *et al.*, 1986) and Zirkel Mesa, Leucite Hills, Wyoming (Cross, 1897). In both examples the inclusions are large enough for satisfactory analysis by SEM/EDS methods but not by electron microprobe.

Inclusions in leucite from the Oscar Plug

The Oscar Plug consists of hyalo-olivine lamproite. Leucite occurs as partially-resorbed microphenocrysts set in a brown glassy matrix, in association with ilmenite, phlogopite, apatite and diopside. Many of the leucite crystals are characterized by curvilinear invaginations of groundmass glass. Back scattered electron imagery and qualitative EDS analysis indicate that the margins of these zones are enriched in K. This may be due to the dissolution of the adjacent leucite. A typical example is shown in Fig. 1.

Within the body of the leucite crystal are small (up to 20 μm) inclusions with spherical cross-sections. In transmitted light they can be seen to
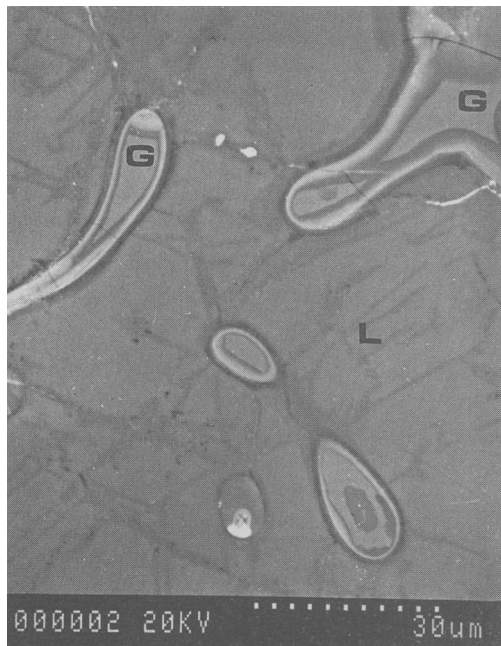
FIG. 1. Resorbed leucite crystal (L) with curvilinear invaginations of groundmass glass (G). Note the regions of relatively high average atomic number in the glass adjacent to the leucite. These regions are relatively rich in potassium. Back-scattered electron image. Oscar hyalo-olivine leucite lamproite.

atomic number. The inclusions are not enriched in K at the contact with their leucite host. This observation indicates that reaction of the original inclusion liquids with the host leucites, analogous to that observed for the groundmass liquid, did not occur.

Crystalline phases within the inclusions are rare and comprise small (<1 μm) skeletal apatite and chalcopyrite crystals set within the glasses of low average atomic number. Examination of the inclusions by conventional and back scattered SEM imagery did not result in the recognition of any compositional or textural domains which might be interpreted as very fine grained assemblages of minerals.

The inclusions are considered to be glass because of their spherical shape, isotropic character, overall compositional uniformity, presence of a sharp meniscus between the two phases and lack of crystallinity as demonstrated by SEM observations. These features demonstrate that the inclusions cannot represent mixtures of fine grained minerals formed by the alteration of glass (see below). If such alteration processes had occurred, they would be expected to have also affected the host leucite. However, the leucite appears fresh and unaltered. No channels or

consist of two phases separated by a sharp boundary that is interpreted to be a meniscus. They are easily distinguished from the brown groundmass glass by their pale yellow to pale green colors. The refractive index of the pale green glass is greater than that of the pale yellow glass. The inclusions are isotropic between crossed polars.

Back scattered electron imagery illustrates the nature and structure of the inclusions better than conventional optical methods. Fig. 2 shows clearly that the inclusions consist of two discrete portions, with a sharp boundary (meniscus) separating areas of high and low average atomic number. In many examples a small (<5 μm) spherical cavity is present in the glass of low average atomic number. This is interpreted to represent the remnants of a vapour bubble. The proportions of the two glass phases vary widely, presumably reflecting the orientation of the section. In the majority of inclusions examined, each glass phase appears to be of uniform composition. Rarely, the glasses of low average atomic number are heterogeneous and contain irregular patches enriched in elements of high
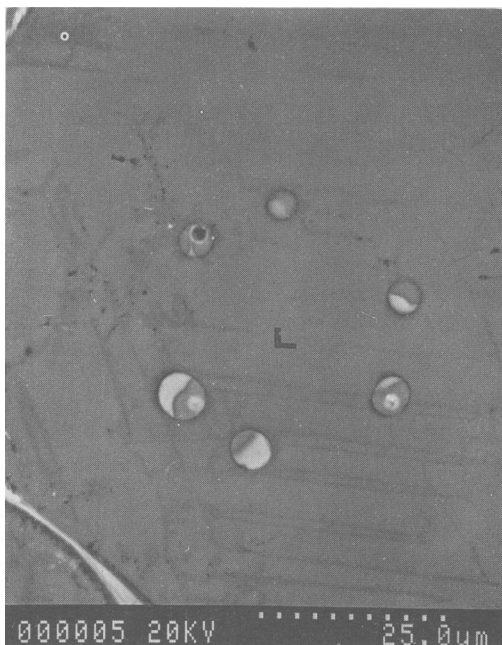

FIG. 2. Inclusions of compositionally distinct immiscible glasses in leucite (L). Back-scattered electron image. Oscar hyalo-olivine leucite lamproite.

Table 1. Representative compositions of inclusions of glass in leucite from the Oscar lamproite.

	1	2	3	4	5	6	7	8	9
SiO_2	50.9	48.9	51.6	48.4	51.5	53.6	45.9	59.4	58.1
TiO_2	8.3	9.1	7.9	9.5	8.1	9.4	11.9	8.2	8.6
Al_2O_3	0.7	1.1	1.3	1.3	1.1	1.6	3.8	2.2	2.1
FeO^*	7.7	5.6	7.5	6.2	7.5	4.0	2.9	7.4	7.1
MgO	9.4	7.3	8.6	4.4	8.5	3.2	3.3	3.8	3.5
CaO	3.5	2.9	3.9	3.2	3.9	3.4	4.0	0.7	0.6
Na_2O	2.0	0.0	1.4	0.8	1.5	0.0	0.0	0.0	0.0
K_2O	11.4	1.9	11.3	0.8	10.5	2.4	3.6	1.6	3.6
BaO	3.3	3.3	3.5	4.2	3.0	3.9	14.0	1.9	1.9
	97.2	80.1	97.0	78.8	95.6	81.5	89.4	83.3	88.6
P.I.	20.7	1.9	11.0	1.7	14.2	1.6	1.0	0.8	1.9

Anhydrous CIPW norm

	1	2	3	4	5	6	7	8	9
Q	23.4	39.9	23.4	44.6	25.3	50.2	30.8	55.9	52.3
Or	4.1	7.8	7.6	6.3	5.9	11.3	27.5	11.4	13.7
Plag	–	–	–	3.0	–	–	–	1.5	–
Ns	4.2	–	2.9	1.4	3.2	–	–	–	–
Ks	18.3	1.9	17.7	–	17.0	2.0	0.2	–	3.3
Di	14.5	14.1	16.2	16.6	16.3	16.9	20.5	2.1	2.8
Hy	18.8	17.2	16.2	7.8	15.7	2.4	1.4	10.5	9.1
Ilm	16.8	15.4	16.1	17.6	16.6	10.9	8.1	18.7	17.9
Ru	–	3.7	–	3.5	–	6.4	11.5	–	0.8

*Total Fe expresses as FeO; P.I. = peralkalinity index; n.a = not analysed
Compositions 1-2, 3-4, 5-6 represent co-existing high- and low-K glasses respectively; 7 Ba-rich glass co-existing with 2; 8-9 groundmass glasses. Analyses 1-7 by quantitative SEM/EDS; 8-9 wavelength dispersive electron microprobe.

cracks that might have conveyed the agents of alteration to the inclusions were observed.

Inclusions in leucite from Zirkel Mesa

Glass inclusions in leucite are common in leucite phlogopite lamproites from Zirkel Mesa. In these rocks microphenocrystal leucites are associated with phlogopite phenocrysts, apatite, diopside, potassium titanian richterite and priderite.

The inclusions reach a maximum diameter of 5 μm and are difficult to characterize in transmitted light. Back-scattered electron imagery reveals that many are two-phase inclusions, similar in structure and character to those occurring in the Oscar leucites. Unlike the latter, many of the leucites contain single-phase inclusions that belong exclusively to the low or high average atomic number type. Vapour bubbles and crystals of baryte and chalcopyrite are rarely present. Coexisting glasses of differing composition are homogeneous and separated by a sharp meniscus.

Composition of the glass inclusions

Inclusions were analysed quantitatively at Lakehead University using a Hitachi 570 scanning electron microscope equipped with an energy dispersive detector. The instrument was operated at 20 kV with a beam current of 0.38 nA. X-ray spectra were processed using full ZAF correction methods (Tracor Northern MicroQ software package). Groundmass glass was analysed using a defocussed beam (15 kV, 10 nA) with a Cameca WDS electron microprobe by standard methods at Purdue University.

Analysis of glasses by electron beam methods is difficult in that alkali loss is commonly encountered. The small size of the inclusions analysed here precluded defocussing of the electron beam and K and Na loss during analysis is a distinct possibility. However, the high and consistent values found for alkalis and total oxides suggests that such problems are not significant in this case. Leucite hosts analysed under the same operating conditions did not show any K-loss.

Representative compositions of glass inclusions in leucite from the Oscar intrusion are given in Table 1. Care was taken in the analysis of the glasses to ensure that excitation of the host leucite did not occur. Such cases could easily be recognized by the high Al content of the resulting composition. Consistent analytical totals were found for each variety of glass. These data confirm the conclusion that the inclusions are glass. The analysis of mixtures of fine grained alteration or devitrification products would not be expected to give such consistent results.

Glasses with high average atomic number are rich in K relative to those with low average atomic

number. Both types of glasses are characterized
by high Ti, Fe, Mg and Ba contents. Low
analytical totals presumably reflect the presence
of volatiles. These comprise only 2–5 wt.% of the
high K glass but are present in significantly
greater amounts (18–21 wt.%) in the low K
glasses.

High-K glasses are strongly peralkaline and
relatively Si-rich. Anhydrous CIPW norms are
dominated by Q, Ks, Hy, Ilm and Di (Table 1).
Low-K glasses, recalculated on an anhydrous
basis for comparative purposes, are even richer in
Si but in contrast are barely peralkaline despite
their low Al contents. Anhydrous CIPW norms
are dominated by Q, Di, and Ilm (Table 1).

The compositions of coexisting glasses are

shown in Fig. 3 High-K glasses form a cluster of
relatively restricted composition whilst low-K
glasses are seen to be of more variable compo-
sition with respect to their Ti, K and Si contents.
Table 1 and Fig. 3 show clearly that the glass
inclusions in leucite do not represent inclusions of
the material which crystallized as the groundmass
glass. The latter is notably poor in Ba and Ca and
rich in Si relative to the former. Table 1 shows
that domains of high average atomic number in
the low-K glass have very unusual compositions in
that they are highly enriched in Ti and Ba.

Glass inclusions in the Zirkel Mesa leucites
proved to be very difficult to analyse due to their
relatively small size. Representative compo-
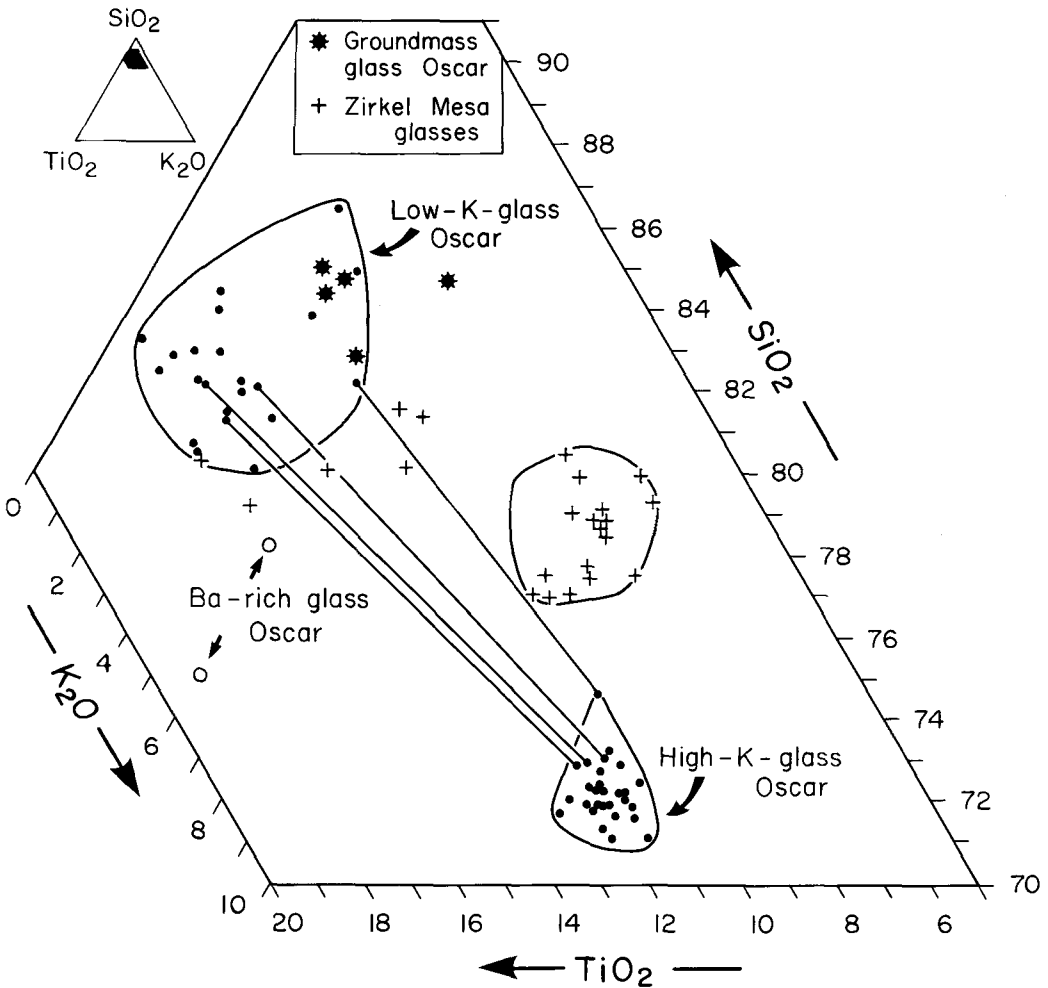sitions that are considered to be free of leucite

FIG. 3. Compositions of coexisting immiscible glasses in leucites from the Oscar and Zirkel Mesa lamproites plotted
in the ternary system SiO_2–K_2O–TiO_2 (wt.%). Tie-lines connect the compositions of representative coexisting
glasses in the Oscar leucites.

Table 2. Representative compositions of inclusions of glass in leucite from the Zirkel Mesa lamproite.

	1	2	3	4	5
SiO_2	43.6	41.6	45.5	58.2	56.5
TiO_2	8.8	8.3	7.7	6.7	7.4
Al_2O_3	3.7	2.8	4.7	2.5	1.9
FeO*	8.7	8.1	7.5	6.2	6.1
MgO	0.7	1.4	1.3	6.9	7.0
CaO	5.2	5.6	4.8	1.0	0.5
Na_2O	0.0	0.0	0.6	3.7	4.5
K_2O	1.8	2.6	3.3	8.9	9.2
BaO	2.0	1.1	1.2	4.5	5.6
	74.5	71.5	76.6	98.6	98.7
P.I.	0.5	1.0	1.0	6.1	9.2

Anhydrous CIPW norm

	1	2	3	4	5
Q	51.9	50.5	42.5	31.9	31.9
Or	15.9	24.4	28.4	14.5	11.1
Plag	7.2	-	7.4	-	-
Ns	-	-	-	7.7	9.5
Ks	-	-	-	11.5	13.1
Di	-	-	-	4.1	2.1
Hy	-	-	-	16.7	17.8
Ilm	25.0	25.1	21.3	13.5	14.0
Ru	-	-	-	-	0.5

* Total Fe expressed as FeO; P.I. = peralkalinity index.
Compositions 1-3 are low-K glasses; 4-5 are high-K glasses. All data are by quantitative SEM/EDS analysis.

contamination are given in Table 2. These data show that the inclusions also consist of coexisting high- and low-K glasses. Their compositions are broadly similar to those of the Oscar glasses (Fig. 3). The low-K glasses differ in being characterized by lower Mg and higher Ca, Al and K contents. Anhydrous CIPW norms are dominated by Q, Or and Ilm (Table 2). High-K glasses are similar to those in the Oscar leucites but have higher Si, Na and lower Ca contents. Anhydrous CIPW norms are dominated by Q, Or, Ks, Hy and Ilm (Table 2).

Discussion

Leucites from two localities exhibit the same feature of containing inclusions of two coexisting silica-rich glasses. Petrographic interpretation suggests that these represent immiscible silicate liquids. The most notable feature of both of their compositions is the enrichment in Ti, Mg and Ba and the low Al content. These features may well have been inherited from their parental liquid. It is not possible to determine the exact composition of this liquid lacking knowledge of the proportions of the derivative liquids. However, it must have been Si, Ti, Ba, Mg, K and volatile-rich and Al-poor.

The glass compositions are not equivalent to those of the average compositions of phlogopite

lamproites in either the West Kimberly or Leucite Hills lamproite provinces as they are relatively poor in Al. The average Al_2O_3 contents of West Kimberley and Leucite Hills phlogopite lamproites recalculated on an anhydrous basis are 8.13 and 10.22 wt.% respectively (Mitchell and Bergman, 1991), as compared to 0.76 and 1.36 wt.% Al_2O_3 in the anhydrous high- and low-K glasses respectively.

The significance of the glass compositions with respect to the petrogenetic evolution of these provinces is unclear beyond demonstrating that it is possible to form residual Ti, Ba silica-rich liquids which may or may not be peralkaline. On the basis of these data it is certainly unwise to conclude that liquid immiscibility plays any significant role in magmatic evolution of these provinces. The origin of the Al-depletion may be related to local undersaturation in Al consequent upon leucite crystallization and the liquids thus may not really be representative of the bulk of magma existing at the time of leucite crystallization.

The significance of this study is that it demonstrates, albeit on a microscale, the existence of true liquid immiscibility in alkaline magmas. The data cannot be directly or usefully compared with other postulated examples of liquid immiscibility or with the experimental studies of Roedder (1951) because of the extremely different compositions involved.

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