**LETTER**

**Experimental partitioning of Sr and Ba in Kiglapait feldspars†‡**

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**ABSTRACT**

New electron microprobe analyses of Sr and Ba in feldspars and coexisting experimental glasses show very strong correlations of the partition coefficients with the ternary Or content of the feldspar. The correlations therefore scale inversely with temperature, as also found in the literature. The Sr content of feldspars is maximized in mesoperthites and decreases with evolution of feldspar to the ternary minimum. The relationship of $D_{\text{Sr}}$ to decreasing $X_{\text{or}}$ is initially flat at a value of 1.8 but curves sharply upward past 6.5 after the arrival of apatite at An$_{35}$. A similar concave-up curve at much higher values of $D$ is found in the literature. The value of $D$ (nine points) scales linearly with ternary Or; $R^2 = 0.99$. Experimental feldspars are consistently richer in Sr than natural ones at comparable An. They jump from 200 ppm higher to 400 ppm higher at Ap$^+$. Experimental glass compositions are correspondingly low in Sr, so the material balance is conserved. Inversion of natural feldspars to liquid compositions using the experimental partition coefficients fails because the experimental crystals contain enhanced values of Sr from the apatite and feldspar components of the melted rock compositions. The partitioning of Ba (five points; range 0.4 to 6.1) also scales with ternary Or; $R^2 > 0.99$; and there is no systematic difference between the natural and experimental concentrations of Ba in the feldspars. The inversion of $D$ to liquid compositions may be safe for Ba but must be approached with caution for Sr.

**Keywords:** Element partitioning, strontium, barium, Kiglapait, experimental, analytical, Sr and Ba in feldspar

**INTRODUCTION**

The role of strontium in feldspars is confusing and unclear when samples from various bulk compositions are considered (Smith and Brown 1988, esp. p. 362–365). One thing certain is that on the whole, the partitioning of Sr into feldspars follows a concave-upward curve in plagioclase from An$_{100}$ to about An$_{50}$ (ibid, Fig. 14.24). Drake and Weill (1975) found that partition coefficients for Sr were always greater than unity but for Ba less than unity at high temperatures, with both strongly dependent on temperature. Morse (1982) found a decrease of $D_{\text{Sr}}$, with the arrival of apatite and a preference for Sr in monoclinic sanidines compared to triclinic plagioclase. Blundy and Wood (1991) examined a wealth of literature data and showed a strong correlation between $D_{\text{Sr}}$ and $D_{\text{Ba}}$ with plagioclase composition and developed a lattice strain model to show the preference for both these elements in more sodic plagioclase. In an experimental study of hydrous metapelites, Icenhower and London (1996) found the partitioning of Sr to be independent of either the albite or the orthoclase component of the plagioclase, whereas they found a strong correlation with orthoclase for Ba and Rb. In another hydrous study using alkali feldspars, Henderson and Pierozynski (2012) showed a strong correlation for both Sr and Ba with the increasing Or content of the melt, among other compositional features.

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Morse et al. (2004); Notes:

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<th>XSp Glass</th>
<th>T° C</th>
<th>Sr Fsp ppm</th>
<th>Sr Gl ppm</th>
<th>D(Sr) Fsp/Gl</th>
<th>Or Sr ppm</th>
<th>Or Sr norm %</th>
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Notes: KI 4077 Ba data from Peterson (1999); see Supplement. EMPA data in bold type.

**TABLE 1.** Sr and Ba experimental data for Kiglapait feldspars and glass, 5 kbar graphite

**FIGURE 1.** Concentration of Sr in Kiglapait feldspars from 15 to 99.99 PCS in the intrusion (where PCS = volume percent solidified). Data from Table 1 of Morse (1982), with PCS values as a guide to stratigraphic height. The highest concentration occurs in mesoperthite, followed by a decreasing trend as the feldspars approach and reach the ternary minimum at lower concentrations of Ab.

Above 600 ppm the crystals are antiperthite to mesoperthite, and as they follow a continuing path of falling Ab and Sr but increasing Or, the crystals are ternary intergrowths.

**Stromium**

The results for Sr are shown in Table 1 and in Figures 1 to 4. Natural feldspar compositions (Fig. 1) range from ~500 ppm Sr in the Lower Zone (0–84 PCS) and early Upper Zone to 94 PCS where apatite arrives in the rock sequence. Then the Sr content rises sharply to 797 ppm where the feldspars are antiperthites to mesoperthites, then drops sharply as the feldspars become complex ternary intergrowths.

Experimental plagioclase compositions range from a minimum of 673 ppm Sr to a maximum of 1074 ppm; the glass compositions run from 103–434 ppm.

**EXPERIMENTAL METHODS**

**Trace element partitioning**

An ongoing project to retrieve element partitioning data from the experimental results of Morse et al. (2004) utilizes the high precision available with the two Cameca electron microprobes at the University of Massachusetts-Amherst. Major element chemistry in glass and feldspars was first determined on a Cameca SX-50. These results were then utilized as fixed compositions to trace measure amounts of Sr and Ba in the same material. Standards used were BaSO₄ and SrF₂. Analysis conditions for trace element analyses were 15 kV, 100 nA, and 10 µm beam in all materials, to maximize the analytical precision and minimize the diffusion effect. Peak counting time on each spectrometer and for each element was varied between 60, 200, and 400 s in all samples. Results were identical independent of the variable counting time, which ensured that diffusion has not affected the results.

Detection limits for both feldspars and glass were ~18 ppm for Sr using 200 s counting time and ~34 ppm for Ba at 100 s counting time. The low detection limit for Sr is a function of the long counting time and high beam current: for 60 s counting time the detection limit for Sr is only ~46 ppm.
As shown in Figure 2, the experimental partition coefficient for Sr in plagioclase is almost constant near 1.8 until the plagioclase composition reaches \( \text{An}_{38} \), then climbs strongly to a value of 6.5 at \( \text{An}_{40} \).

At this high value of \( D_{\text{Sr}} \), the feldspar KJ 4077 is a sanidine with ternary Or = 47.8 (Table 1 and Supplementary Table 1) and ternary \( X_{\text{K}} = 7 \); it lies at the upper \( \text{An} \) limit in Supplementary Figure 1 at \( X_{\text{K}} = 0.54 \). It coexists with liquid \( \text{Or}_{1.2}\text{Ab}_{7}\text{An}_{0.8} \) (Supplementary Table 1) that plots among the most potassic group of wet chemical analyses in Supplementary Figure 1.

The curve in Figure 2 is shown compared to the estimates of Morse (1982) from summation. The old estimates are essentially the same as the new experimental ones from high values of \( \text{An} \) down to the plagioclase composition \( \text{An}_{0.34} \), where \( \text{Ap}^+ \) occurs at 94 PCS. Thereafter the Sr abundance in the summation liquid differs strongly, as discussed below. Also shown in Figure 2 is the trend of many literature estimates by Blundy and Wood (1991) that, although it plots at values considerably higher than found here, also shows a strong concave-up trend. The scales of the two studies are not wholly comparable because of the long troctolitic history of the Kiglapait LZ, tending to stretch out the flat part of the experimental curve.

The presence of significant Ba in highly evolved feldspars

**DISCUSSION OF THE DIVERGENCE BETWEEN SUMMATION AND PARTITIONING**

If the experimental determination of Figure 2 is used to calculate the liquid composition from the observed natural feldspars (Morse 1982), the liquid shows a steep downward trend from ~280 ppm near 94 PCS to 50 ppm at the end of crystallization. In contrast, the summation liquid has 245 ppm at 99.98 PCS (Morse 1982, Table 4). The depletion trend required by the experimental result is impossible: the process of summation begins at the top of the intrusion and works its way downward. It is therefore most secure at the highest stratigraphic levels. The final liquid at the ternary minimum feldspar composition has no Mg left and nowhere else to go. Its crystallized form therefore has the liquid composition. The summation process requires that the true liquid follow closely the trend of the rocks, which declines slowly from 430 ppm at 99.75 PCS to 278 ppm at 99.98 PCS (Morse 1982, Fig. 2 therein).

The alternative choice is to consider the possibility that the experimental feldspar crystals contain more Sr than the corresponding natural ones, and that is decidedly the case, as shown in Figure 4. Moreover, the difference is about 200 ppm before \( \text{Ap}^+ \), but jumps to about 400 ppm after that. Correspondingly, the experimental glass compositions are much lower in Sr than the natural feldspar compositions (Fig. 4), so the material balance is nominally conserved. The amount of glass in the experiments (Table 1) averages 79%. The amounts of feldspar vary from 1 to 40%, but in the group with \( \text{An} < 38 \) the glass amounts are 10, 3, 10, and 1%, respectively. Accordingly, the experimental feldspars have scavenged the majority of Sr present in the natural feldspar and apatite components of the melted rocks, leaving modest amounts in the experimental glasses.

Because of this enhancement of Sr in the experimental feldspars, the partition coefficients cannot be used directly to infer the natural liquid compositions by inversion.

**BARIUM**

Wet chemical analyses of feldspars (Morse, in preparation) show high values of BaO ranging from ~1.0 to 1.4 wt% in very evolved feldspar compositions. The content of Ba is inversely related to the An content of the feldspar. Although experimentally grown K-rich feldspars were observed up to 2.2% BaO by Peterson (1999; Supplementary Table 1 here), there is no systematic difference between the experimental and natural Ba contents of the four feldspar compositions studied. Our data show partitioning results for five bulk compositions summarized in Table 1 here and illustrated in Figure 5. The charge-balanced relationship of Ba to K is given by the coupled exchange reaction BaAl (KSi)=1 and is expected because the large ionic radius of Ba\(^{2+}\) (1.35 Å) is compatible with that of K\(^{+}\) (1.38 Å). We find (Fig. 5) that the value of the partition coefficient \( D \) is linear against the Or content of the feldspar with a vanishingly small error. Although expected in principle, the degree of correlation is astounding.

The presence of significant Ba in highly evolved feldspars...
and liquids has an effect on the formal investigation of feldspar-liquid linear partitioning (e.g., Morse et al. 2004, Fig. 16). The crystal composition presents no problem, because the An content is determined solely from the Ca content. The An composition of the liquid, however, is normally calculated from the residual Al after Ab and Or are formed (e.g., Morse 2013b). If Ba is present in significant quantity, then that element must be allotted a corresponding amount of Al to make celsian, CN, BaAl$_2$Si$_2$O$_8$. When this is done, the residue given to An is less than before (so the proportion of Ab is greater) and hence the partition coefficient $X_{Ab}^{L}/X_{Ab}^{S}$ decreases from that in a low-Ba system. To correct for this effect, a conventional oxygen-norm program with a CN option was used to calculate the liquid composition for the last four samples in Table 9 of Morse et al. (2004), giving a corrected linear partitioning diagram. As expected, the intercept now falls slightly below 1.0 and the $K_f$ value rises slightly, from 0.524 to 0.541.

**Implications**

Both the positive correlations of Sr and Ba with Or occur negatively correlated with temperature, as explicitly found by Henderson and Pierozynski (2012) for alkali feldspars. They are negatively correlated with temperature, as explicitly found by Henderson and Pierozynski (2012) for alkali feldspars. These anhydrous experimental results are in accord with those found in hydrothermal experiments by Henderson and Pierozynski (2012).

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