Abstract—The abundances of rubidium and strontium have been determined in potassium feldspar separates and some whole rock samples from two Precambrian batholiths, the San Isabel batholith of the Wet Mountains, Colorado, U.S.A., and the Buchanan massif (Lone Grove pluton) of central Texas, U.S.A. Absolute abundances of the two elements in the feldspars vary widely, but the Rb/Sr ratio is relatively constant within mapped zones or facies. Selective precipitation of potassium over rubidium into early-crystallizing potassium feldspar leaves late-stage magmatic fluids enriched in rubidium and thus causes the absolute rubidium contents and the Rb/Sr ratios of feldspars and whole rocks to be highly dependent on the activity of volatiles. Escape of volatile-rich, end-stage fluids is apparently responsible for decrease in Rb/Sr ratios toward later-crystallizing rocks. The preservation of widely different Rb/Sr ratios in minerals in different facies of a co-magmatic rock assemblage provides, through later partial melting, one method of generating non-zero initial apparent isochrons in whole-rock strontium isotope studies of igneous suites.

INTRODUCTION

Rubidium and strontium are clearly among the trace elements most important for interpretation of geologic processes. For example, the rubidium content of mafic rocks, and particularly the K/Rb ratio, is used as an index of the continental or oceanic character of the environment of eruption; strontium is used as an index of magmatic differentiation processes, with the strontium depletion trend possibly signifying feldspar extraction (Baker, 1969) and thus differentiation at shallow depths; and strontium isotopes not only provide rock ages, but the initial isotope...
ratios in igneous rocks have been used to indicate source regions of melts. An interesting recent observation concerns the increase in initial strontium isotope ratios toward more acidic rocks in apparently comagmatic suites (e.g., see summaries by Gast, 1967, and Peterman and Hedge, 1971), a variation which may yield spuriously high ages in whole-rock Rb-Sr dating.

In view of the importance of rubidium and strontium, an investigation has been made of the distribution of the two elements in a single mineral phase, potassium feldspar, in two granites for which considerable petrologic information is available. The two bodies studied are the San Isabel batholith of the Wet Mountains, Colorado, and the Buchanan massif (Lone Grove pluton) of central Texas.

Previous studies of rubidium and/or strontium contents of potassium feldspar have been made by a number of persons. The general geochemistry of alkalies was reviewed by Heier and Adams (1963). More recent specific studies include those of Brooks (1968) and Rhodes (1969).

ROCKS INVESTIGATED

The San Isabel batholith is a Precambrian mesozonal intrusion into medium-rank metamorphic rocks in the Wet Mountains of Colorado. The intrusion is dated at about 1,430 m.y. old by lead/alpha methods (Stern, 1960). The batholith is texturally zoned as shown in Fig.1, with the crystallization age decreasing toward the northwest and the sequence of crystallization of the major facies being medium grained → porphyritic medium grained → coarse grained. The average model composition of each facies is shown in Table 1, which demonstrates that textural variations are much greater than compositional ones. Structures in the batholith indicate that the melt was injected upward near the northwestern corner, flowed laterally toward the southeast, and crystallized from the southeast to the northwest during or after injection. The general increase in grain size of the potassium feldspar toward the northwest is correlated with increasing volatile content in the residual melt. The triclinicity of the potassium feldspars is generally high but shows a random variation in the batholith and indicates partial inversion from the monoclinic to the triclinic form. Studied samples of the San Isabel batholith were separated into facies on the basis of their location within map areas regardless of minor textural variations that a few individual samples exhibit. For more detailed information about the batholith see Murray (1970).

The Buchanan massif (Lone Grove pluton) was originally mapped by Keppel (1940) as one of a series of roughly circular, discordant, plutons representing the last major igneous event in the Llano uplift of central Texas. Zartman (1964) has dated the intrusion as 1,000 – 1,050 m.y old. The body has a diameter of about 5 miles, is meso- to epizonal, and shows a concentric zoning marked particularly by
change in sizes of potassium feldspar grains (Fig. 2).

The zoning of the Buchanan massif is described somewhat differently by different investigators. The zones established by Keppel (1940) were essentially accepted by Cook and Rogers (1968), and their mineralogical and textural characteristics are shown in Table 1. Zartman (1964) described a more continuous variation in potassium feldspar grain sizes than is implied by mapping zonal boundaries, and he subdivided the body into inner fine- and medium-grained facies and an outer, coarse-grained
Table 1. Texture and mineralogy of facies of investigated plutons

<table>
<thead>
<tr>
<th>Facies Description</th>
<th>Quartz</th>
<th>Potassium Feldspar</th>
<th>Plagioclase</th>
<th>Biotite and Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Isabel batholith</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse grained</td>
<td>20.8</td>
<td>30.7</td>
<td>30.0</td>
<td>18.5</td>
</tr>
<tr>
<td>Porphyritic medium grained (phenocrysts of potassium feldspar)</td>
<td>21.9</td>
<td>33.1</td>
<td>28.8</td>
<td>16.2</td>
</tr>
<tr>
<td>Medium grained</td>
<td>21.8</td>
<td>31.0</td>
<td>28.8</td>
<td>18.4</td>
</tr>
<tr>
<td>Quartzose (rocks with dominant quartz content)</td>
<td>29.0</td>
<td>36.9</td>
<td>21.9</td>
<td>12.1</td>
</tr>
<tr>
<td>Fine grained (generally reaction zones near wall rocks)</td>
<td></td>
<td></td>
<td></td>
<td>Highly variable</td>
</tr>
<tr>
<td>Pegmatite (dikes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buchanan massif</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse grained (outer) (potassium feldspars, orange-red; margin of pluton)</td>
<td>35.6</td>
<td>39.5</td>
<td>18.6</td>
<td>6.3</td>
</tr>
<tr>
<td>Coarse grained (inner) (potassium feldspars, pink)</td>
<td>24.1</td>
<td>30.0</td>
<td>32.2</td>
<td>13.7</td>
</tr>
<tr>
<td>Porphyritic coarse grained (phenocrysts of pink potassium feldspar in medium coarse-grained matrix)</td>
<td>27.4</td>
<td>29.7</td>
<td>35.7</td>
<td>7.2</td>
</tr>
<tr>
<td>Medium grained (center of pluton)</td>
<td>31.6</td>
<td>28.1</td>
<td>35.2</td>
<td>4.8</td>
</tr>
<tr>
<td>Fine grained (core displaced to one side of medium-grained zone)</td>
<td>33.4</td>
<td>29.1</td>
<td>34.6</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Facies in which he contoured the increasing potassium feldspar grain sizes inward from the outer margin. All workers agree that the body is finer grained toward the center, leading Cook and Rogers (1968) to propose increase in water content of the melt toward the cooler margins and consequent crystallization of the massif from the center outward. Ragsland et al. (1968), in studies on the neighboring Enchanted Rock batholith, explained similar zonation by progressive separate injection of younger zones outward from the center of the body.

**METHODS**

Potassium feldspar was separated by flotation in tetrabromoethane-acetone mixtures after grinding in a roll mill. Analyzed separates were examined microscopically and were 95 or more percent pure alkali feldspar. Powder pellets for X-ray fluorescence analysis were made from pulverized samples admixed with 20% (by weight) boric acid to provide better binding of the powder.

Analyses were also made of pulverized whole-rock samples using pressed pellets of undiluted powder. In addition, 17 samples from the San Isabel batholith were subdivided into coarse (greater than 1/2 mm) and fine (less than 1/32 mm) fractions and analyzed separately as a possible test of mobilization of rubidium and strontium
Distribution of rubidium and strontium

Fig. 2 Reconnaissance geologic map of the Buchanan massif (Lone Grove pluton), central Texas, U.S.A. Modified from Keppel (1940) and Zartman (1964).

into fine-grained weathering products (compare study of weathering effects by Brooks, 1968).

Weathering effects were not detected, but the analysis of fine and coarse fractions did indicate that preparation of whole-rock samples for rubidium and strontium analysis has a significant effect on the analytical data obtained. Potassium feldspar
appears to concentrate in the coarse fraction of crushed separates, thus causing coarse fractions to be enriched in rubidium and strontium. For example, the average concentrations in coarse separates of the San Isabel batholith are 120 ppm rubidium and 310 ppm strontium compared to 82 ppm rubidium and 273 ppm strontium in the fine fractions. In general, all handling, and consequent loss of dust, causes apparent enrichment of rubidium and strontium in the rock. The exceptions to the preceding observation are in those rocks in which incipient alteration or relatively low abundance of the potassium feldspar permits significant development of feldspar dust, thus causing grinding to reduce the apparent rubidium and strontium concentrations. The problems of grinding and handling may explain some of the discrepancies in rubidium and strontium analyses from different laboratories reported by Flanagan (1969).

The whole-rock rubidium and strontium data reported in Table 2 are from unsized samples. The effects of weathering are thus undetermined. Although the rocks show the typical disintegration of coarse-grained granites, no significant relationship has been found between rubidium and strontium contents and the apparent “freshness” of the samples. The writers believe that the reported whole-rock rubidium and strontium values are relatively close to those of the unweathered samples. The consistency of the Rb/Sr ratios in feldspar separates from different facies indicates comparatively little random alteration of the feldspars.

X-ray fluorescence analyses were made using molybdenum radiation and measuring rubidium and strontium Ka peaks and three bracketing backgrounds. Values of

| Table 2. Rubidium and strontium contents of potassium feldspars and whole rocks |
|---------------------------------|----------------|---------|------|------|----------------|----------------|
| San Isabel batholith            |               |         |      |      | whole rock     | whole rock     |
| Coarse grained                  | Rb  | Sr  | Rb/Sr* | no. | Rb  | Sr  | Rb/Sr* | no. |
| Coarse grained                  | 206 | 638 | 0.34   | 68  | 105 | 338 | 0.32   | 7   |
| Porphyritic medium grained      | 256 | 615 | 0.45   | 10  | 155 | 284 | 0.67   | 2   |
| Medium grained                  | 246 | 465 | 0.53   | 54  | 152 | 242 | 0.80   | 5   |
| Quartz                          | 418 | 237 | 2.74   | 10  | 227 | 331 | 0.61   | 5   |
| Fine grained                    | 243 | 247 | 1.3    | 9   | 76  | 317 | 0.24   | 1   |
| Pegmatite                       | 371 | 183 | 2.1    | 2   |     |     |        |     |
| Buchanan massif                 | Rb  | Sr  | Rb/Sr* | no. | Rb  | Sr  | Rb/Sr* | no. |
| Coarse grained (outer)          | 388 | 125 | 4.0    | 13  | 155 | 102 | 1.9    | 3   |
| Coarse grained (inner)          | 304 | 188 | 1.7    | 5   | 112 | 134 | 1.3    | 3   |
| Porphyritic coarse grained      | 620 | 84  | 9.1    | 9   | 211 | 50  | 4.7    | 3   |
| Medium grained                  | 660 | 80  | 10.4   | 9   | 271 | 49  | 6.9    | 2   |
| Fine grained (core)             | 652 | 85  | 9.2    | 7   | 340 | 49  | 7.0    | 3   |

All concentrations in parts per million of the element. “no.” is number of samples analyzed.

* Average of ratios.
standard rocks were those reported by FAIRBAIRN and HURLEY (1971). Mass absorption coefficients were calculated by Compton scattering (REYNOLDS, 1963) for whole rocks, but the low coefficients of the feldspar-boric acid mixtures were not satisfactorily obtained in this fashion. Accordingly, coefficients for the feldspar separates were obtained by calculation based on a feldspar composition of Or_{70}Ab_{30} for the perthitic materials. Maximum observed variation in thin section of Or_{60} to Or_{80} for all samples would cause a variation of ±5% in the mass absorption coefficient and thus a similar change in reported rubidium and strontium concentrations and would have no effect on Rb/Sr ratios. The values reported by ZARTMAN (1964) for potassium feldspar and total rock samples of the Buchanan massif are comparable to those obtained in the present study.

RESULTS AND CONCLUSIONS

Analytical results are presented in Table 2, which shows the rubidium and strontium contents and Rb/Sr ratios for feldspars and whole-rock samples from various facies of the San Isabel batholith and Buchanan massif. These data lead to a number of conclusions concerning the distribution of these elements in the investigated feldspars.

Frequency distributions in feldspars

The large number of analyses from the coarse- and medium-grained zones of the San Isabel batholith allow an examination of the frequency distributions of the various elements. Trace elements commonly approximate a lognormal frequency distribution, although considerable variability is found (e.g., ROĐIONOV, 1961; ROGERS and ADAMS, 1963; ROGERS, 1964; summaries by AHRENS, 1966, 1967). Histograms of rubidium and strontium concentrations and Rb/Sr ratios are shown in Fig. 3. Plots of cumulative distributions on logarithmic and arithmetic probability paper confirm the appearance of the histograms to the effect that all distributions are highly irregular and not characterized by simple frequency functions. With strontium, part of the variability undoubtedly arises because of variable incorporation of strontium into earlier- or concurrently-crystallized plagioclase. Rubidium, however, is largely contained in potassium feldspar (Table 3), and its deviation from lognormality is not easily explained.

Distribution between feldspars and whole rocks

The percentages of rubidium in the potassium feldspars of samples for which whole-rock analyses are available are shown in Table 3. Generally about 60% of the rubidium is contained in potassium feldspar in the San Isabel batholith and a somewhat higher percentage for the Buchanan massif. No relationship has been found between apparent distribution coefficients ($K_{Rb}$ and $K_{Sr}$; defined below) and modal composition for the samples analyzed.

Table 3 also shows the distribution of rubidium between potassium feldspars
and the remainder of the samples as the ratio of concentrations in feldspars and the non-potassium feldspar portion of the rock. The formula used for calculation is

\[
K_{Rb} = \frac{X_{Rb} (Kf)}{X_{Rb} (matrix)} = \frac{X_{Rb} (whole \ rock)}{X_{Rb} (Kf)} - \frac{X_{Rb} (whole \ rock) P_{Kf}}{1 - P_{Kf}}
\]

where \( X_{Rb} \) is concentration of rubidium and \( P \) is proportion (percent/100) of potassium feldspar (Kf) in the rock. For many purposes it is more useful to know the distribution coefficient in terms of the ratio of trace to major element for which the trace element substitutes (MCINTIRE, 1963). This coefficient is

\[
D_{Rb} = \left( \frac{X_{Rb}}{X_K} \right)_{Kf} / \left( \frac{X_{Rb}}{X_K} \right)_{matrix}
\]

Assuming potassium feldspar of Or70 composition (9.8% K),

\[
D = K \cdot \frac{X_K (matrix)}{X_K (Kf)}
\]

\[
= K \cdot \frac{X_K (whole \ rock) - 9.8 \cdot P_{Kf}}{9.8 \cdot (1 - P_{Kf})}
\]

Fig. 3. (a) Distribution of rubidium, strontium, the Rb/Sr ratio in potassium feldspars from the medium-grained facies of the San Isabel batholith.
Distribution of rubidium and strontium

Fig. 3. (b) Distribution of rubidium strontium, and the Rb/Sr ratio in potassium feldspars from the coarse-grained facies of the San Isabel batholith.

Table 3. Distribution of rubidium between potassium feldspars and whole rocks

<table>
<thead>
<tr>
<th></th>
<th>fraction of Rb in potassium feldspar</th>
<th>apparent $K_{Rb}$</th>
<th>apparent $D_{Rb}$</th>
<th>number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>San Isabel batholith</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coarse grained</td>
<td>0.66</td>
<td>10.7</td>
<td>.98</td>
<td>7</td>
</tr>
<tr>
<td>porphyritic medium grained</td>
<td>0.76</td>
<td>7.5</td>
<td>.48</td>
<td>2</td>
</tr>
<tr>
<td>medium grained</td>
<td>0.66</td>
<td>4.8</td>
<td>.98</td>
<td>5</td>
</tr>
<tr>
<td>quartzose</td>
<td>0.36</td>
<td>1.9</td>
<td>.33</td>
<td>5</td>
</tr>
<tr>
<td>fine grained</td>
<td>0.52</td>
<td>3.2</td>
<td>.28</td>
<td>1</td>
</tr>
<tr>
<td><strong>Buchanan massif</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coarse grained (outer)</td>
<td>0.85</td>
<td>5.7</td>
<td>1.06</td>
<td>3</td>
</tr>
<tr>
<td>coarse grained (inner)</td>
<td>0.65</td>
<td>7.6</td>
<td>.91</td>
<td>3</td>
</tr>
<tr>
<td>porphyritic coarse grained</td>
<td>0.76</td>
<td>4.5</td>
<td>.94</td>
<td>3</td>
</tr>
<tr>
<td>medium grained</td>
<td>0.80</td>
<td>6.1</td>
<td>.40</td>
<td>2</td>
</tr>
<tr>
<td>fine grained</td>
<td>0.49</td>
<td>2.4</td>
<td>.44</td>
<td>3</td>
</tr>
</tbody>
</table>

All values are averages of ratios of individual rocks. See text for meaning of apparent $K$ and apparent $D$.

* Except for fine-grained rocks, calculations for Buchanan massif are based on average % potassium feldspar in each zone because of extremely large grain size. Extremely large values of $K$ caused by nearly 100% inclusion of Rb in potassium feldspar were eliminated from averages.
The ratios shown in column 3 of Table 3 are clearly not true (Nernst-Berthelot) distribution coefficients \((D)\) between potassium feldspar and liquid. The difference is partly caused by the fact that other minerals were crystallizing before or during the formation of the potassium feldspar. The difference may also result partly from non-equilibrium crystallization of the potassium feldspar. For example, pure logarithmic crystallization (McIntire, 1963) causes apparent \(K\) and \(D\) to increase with continued crystallization if the logarithmic coefficient \((\lambda)\) is greater than 1.0 for the distribution ratio

\[
\frac{(X_{Rb}/X_K)_{\text{outer zone of Kf}}}{(X_{Rb}/X_K)_{\text{liquid}}}
\]

(see Gordon et al., 1959). The apparent \(K\) and \(D\) are the distribution ratios between all crystallized potassium feldspar and the residual melt. Thus, if rubidium is absorbed preferentially to potassium in the feldspar, then the crystal should be zoned with decreasing rubidium content outward, but the more rapid decrease in rubidium content in the melt would cause the apparent \(K\) and \(D\) to increase with increasing crystallization. Conversely, \(\lambda\) ratios less than 1.0 would cause apparent decrease in \(K\) and \(D\) with progressive crystallization.

In the case of rubidium in potassium feldspar, apparent \(D\) (and possibly true \(\lambda\)) is less than one for the San Isabel and Buchanan rocks except where the number of samples is too small for adequate calculation. Both Philpotts and Schnetzler (1970) and Noble et al. (1971) have measured potassium and rubidium concentrations in volcanic alkali feldspars and coexisting groundmasses. Both studies show that rubidium is concentrated into the melt, and calculations of the ratio

\[
\frac{(X_{Rb}/X_K)_{Kf}}{(X_{Rb}/X_K)_{\text{liquid}}}
\]

yield values of 0.3 to 0.4. Carmichael and McDonald (1961) indicate little variation in \(K/Rb\) in glass and alkali feldspar of several volcanic suites but show some enrichment in rubidium toward more differentiated liquids, as would be the case for \(\lambda\) less than 1.0. The common increase in rubidium content toward more differentiated intrusive rocks (summary by Shaw, 1968) further confirms that \(\lambda\) is less than 1.0 for most magmas.

In both the San Isabel batholith and the Buchanan massif the calculated apparent \(K\) and \(D\) for rubidium distributed between potassium feldspar and the remainder of the associated rock are probably larger than true \(K\) and \(D\) because of inclusion of previously crystallized mineral phases (largely plagioclase) in the “liquid” for the calculation. The apparent \(K\) in Table 3 could be reduced to 1.0 by assuming that 25% (for low \(K\)) to 90% (for high \(K\)) of the quartz, plagioclase, and biotite had crystallized by the time potassium feldspar was completing its crystallization. This reduction of \(K\) would also reduce \(D\).
Distribution of rubidium and strontium

Behavior of rubidium and strontium during differentiation

The crystallization trend for the San Isabel batholith is medium grained → porphyritic medium grained → coarse grained → pegmatite. For the Buchanan massif the sequence is medium grained → porphyritic coarse grained → coarse grained (inner) → coarse grained (outer). The positions of the fine-grained and quartz facies of the San Isabel batholith and the fine-grained core of the Buchanan massif are uncertain.

The variation in rubidium and strontium concentrations and Rb/Sr ratios between facies is shown in Table 2 for both potassium feldspars and whole rocks. Because of its inclusion in both potassium feldspar and plagioclase, strontium is an uncertain index of differentiation. The expected increase in rubidium content and Rb/Sr ratios toward later crystallized facies, however, is not shown in either the feldspars or the whole rocks of the San Isabel or Buchanan plutons. In fact, with the exception of the San Isabel pegmatite both the potassium feldspars and the whole rocks show consistent trends that are nearly a reverse of the normal differentiation pattern, with rubidium decreasing and strontium increasing toward later rocks.

In evaluating the reverse trends described above it is important to note that the sequence of crystallization of the various facies in each pluton is not a differentiation sequence of mineralogical change. Table 1 shows little modal variation in either pluton, which implies little variation in abundances of major elements. The distribution of rubidium and strontium, therefore, is not controlled by sequential crystallization but may be largely dependent on the water pressure variations that were responsible for the textural zonations and crystallization sequences. The Rb/Sr ratio is considerably lower in the coarser grained, presumably more hydrous, portions of the plutons (the outer zones of the Buchanan massif and the coarse-grained facies of the San Isabel batholith). Rubidium may be selectively fractionated into hydrous phases and ultimately lost from the batholith (possibly into pegmatites) during or following crystallization of the main body of magma.

Similarly, strontium may be selectively enriched in the potassium feldspars as the rate of plagioclase growth decreases in the liquid and a water-rich phase separates. As much as 10% of a granite magma can form a water-rich phase at mesozonal conditions (BARTH, 1962).

Significance of variations in Rb/Sr ratios between facies

In the San Isabel batholith, Rb/Sr ratios in feldspars are fairly uniform within facies despite major variations in the absolute concentrations of the two elements (see Fig.3). Conventional tests indicate that: 1) the difference between the medium-grained and porphyritic medium-grained facies is not significant; 2) the coarse-grained facies has Rb/Sr ratios significantly lower than those of other facies at 90% confidence; and 3) the quartzose facies and pegmatites have ratios that are very significantly higher. The differences between the coarse-grained zones and the other zones of the Buchanan massif are also significant.
The small range of Rb/Sr ratios within facies indicates that the data are not simply random. Apparently the conditions of crystallization within each facies narrowly controlled the Rb/Sr ratios in the feldspars despite large fluctuations in the elemental concentrations in the melt. The precise mechanism that could account for this control is uncertain but bears further investigation.

The differences in Rb/Sr ratios in the potassium feldspars were established by some process operating in comagmatic sequences of markedly different average rubidium and strontium contents (Table 3), and these differences have persisted for at least one billion years. It is interesting to speculate on the possibility of analogous separations occurring during events in the upper mantle, perhaps establishing large volumes of rock containing some phase whose Rb/Sr ratio was sharply different from the ratio in the same phase in adjoining volumes. Later partial melting of these regions, perhaps complete melting of the rubidium-bearing phase, should yield apparently comagmatic igneous suites of variable Rb/Sr ratios. Furthermore, the strontium in these suites would have evolved for considerable time in regions of different Rb/Sr ratio, thus causing the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the melt to be proportional to the Rb/Sr ratio. This kind of magmatic generation could explain the correlation between Rb/Sr ratios and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios found in some young volcanic suites (e.g., Cox et al., 1970; Leeman and Manton, 1971) and would also place restraints on whole rock Rb-Sr dating by yielding an initial isochron of greater than zero age.

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