Rb–Sr Isotope systematics of muscovite from Pan-African granitic pegmatites of Western and Northeastern Africa

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With 6 Figures

Received September 5, 1992; accepted May 10, 1993

Summary

Rb–Sr investigations have been carried out on early-formed muscovite from three pegmatite fields of the late Proterozoic to early Phanerozoic Pan-African Belt. The individual mineral ages obtained are highly discordant for each pegmatite field. Using Best Isochron Diagrams, isochron construction of selected muscovite samples yielded geologically realistic ages of pegmatite formation: around 670 Ma for the Bayuda Desert pegmatites of northern Sudan, around 550 Ma for the Wamba pegmatites of central Nigeria, and around 465 Ma for the Majayahan pegmatites of northeastern Somalia. Initial Sr ratios obtained from isochron calculations have unrealistic values and cannot be used for petrogenetic interpretations.

The geologically unrealistic young model ages of some of the muscovite samples are most probably attributed to open-system behaviour and post-crystallization loss of $^{87}$Sr* from the respective minerals. The amounts of $^{87}$Sr* losses have been approximated from the discrepancies between isotopically measured and theoretically calculated (from decay of Rb) $^{87}$Sr* concentrations. The loss of $^{87}$Sr* from the micas is variable in each pegmatite field. In none of the three cases can this unsystematic, post-emplacement, open-system behaviour be directly related to a particular, temporally confined, geologic event.

Zusammenfassung

Rb–Sr Isotopen-Systematik von Muskovit aus panafrikanischen Granit-Pegmatiten West- und Nordost-Africas

Rb–Sr Isotopen-Untersuchungen wurden an frühgebildetem Muskovit dreier Pegmatitfelder der spätproterozoischen bis frühphanerozoischen, panafrikanischen Mobilzone
Introduction

Several associations of granitic pegmatites of differing chemical and mineralogical composition occur in the late Proterozoic to early Phanerozoic Pan-African Belt of western and northeastern Africa. The Pan-African orogeny (900–500 Ma) led to the formation of Gondwana and was the last major crust-forming event which affected the present African Continent as a whole. Due to the multistage history and the vast regional extent of the Pan-African orogen, granitic pegmatites can be expected to have formed at different periods and in different provinces of the Pan-African Belt. Küster and Matheis (1990) have addressed the relationships between pegmatite formation, rare element enrichment, granitoid magmatism and the regional history of Pan-African crustal evolution; precise age determinations of the pegmatites are needed for the deciphering of these relationships. This paper presents Rb–Sr age determinations on Pan-African pegmatites from central Nigeria, northern Sudan and northeastern Somalia (Fig. 1). The only reliable age determinations on Pan-African pegmatites from western and northeastern Africa have so far been carried out by Matheis and Caen-Vachette (1983). These authors used Rb–Sr whole rock isochron and Rb–Sr mineral dating (feldspars and micas), and obtained ages between 562 and 534 Ma for pegmatites from southwestern and central Nigeria.

The coarse grain size of pegmatites usually makes their whole rock sampling for Rb–Sr dating a laborious if not impossible attempt. The Rb–Sr age determinations of the three pegmatite fields were thus carried out on muscovite. This mineral has also been used to assess the geochemical evolution of each of the pegmatite fields in general and their rare metal potentials in particular (Matheis and Küster, 1989; Küster et al., 1990a). The muscovite model ages obtained turned out to be unsatisfactory due to frequent occurrence of discordant ages. A closer look into the Rb–Sr isotope systematics of muscovite from the three Pan-African pegmatite occurrences was therefore felt to be necessary.

Previous studies on Rb–Sr isotope systematics in granitic pegmatite systems elsewhere, (e.g. Brookins et al., 1969; Riley, 1970; Clark, 1982; Clark and Černý, 1987) have all highlighted the open-system behaviour of $^{87}\text{Sr}$*. This study adresses again...
Rb–Sr Isotope systematics of muscovite

Fig. 1. Distribution of major Precambrian cratons (> 900 Ma) and Late Proterozoic mobile belts (900–500 Ma) in the northern part of Gondwana. Signatures: dashes—Pan-African reactivated Lower Proterozoic crustal domains; vvvv—Pan-African island arc assemblages. Location of investigated pegmatite fields is indicated by stars (Map taken from Kröner, 1991)

—the problem of post-crystallization mobility of $^{87}\text{Sr}^*$ in dating pegmatite rocks, and discusses the geological significance of muscovite model and muscovite isochron ages as well as initial Sr-isotope ratios.

The pegmatite occurrences

The pegmatite fields investigated geochronologically comprise the Bayuda Desert pegmatites of northern Sudan, the Wamba pegmatites of central Nigeria and the Majayahan pegmatites and quartz veins of northeastern Somalia (Fig. 1). All three pegmatite associations are situated in high-grade metamorphic terrains of probably Lower to Middle Proterozoic origin, which have been reworked during the Pan-African orogeny. Only in northeastern Somalia, the Majayahan pegmatites have been emplaced into low-grade metamorphic schistose country rocks which overlie the gneissic basement. Mineralogical and geological details of the three pegmatite areas are given in Table 1.

According to Černý (1991), the pegmatite associations can be classified as follows:

— the pegmatite field of the Bayuda Desert, northern Sudan, consists of pegmatites of the muscovite class;
— the pegmatite field of Wamba, central Nigeria, is composed of pegmatites of the beryl-type of the rare-element class;
— the pegmatite field of Majayahan/Dalan, northeastern Somalia, belongs to the complex-type of the rare-element class of pegmatites.

The Bayuda Desert pegmatites have been mined for industrial micas while both the Wamba pegmatites and the Majayahan pegmatites and quartz veins have been
Table 1. Geological and mineralogical characteristics of investigated pegmatite fields

<table>
<thead>
<tr>
<th>Geology</th>
<th>Mineralogy</th>
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</thead>
<tbody>
<tr>
<td><strong>BAYUDA DESERT PEGMATITES</strong></td>
<td><strong>qtz, K-fsp, musc, plag ± tourmaline, apatite, beryl, garnet, kyanite.</strong></td>
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<tr>
<td>around 40, mainly unzoned,</td>
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<tr>
<td>irregularly shaped dikes with</td>
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<td>semi-concordant contacts,</td>
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<td>thickness between 1–30 m.</td>
<td></td>
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<tr>
<td><strong>WAMBA PEGMATITES</strong></td>
<td><strong>qtz, K-fsp, musc, ± albite, biotite, tourmaline, cassiterite, columbite, beryl, garnet, apatite, lepidolite, lithiophilite-triphylite.</strong></td>
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<tr>
<td>around 80, mainly internally</td>
<td></td>
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<tr>
<td>zoned, variably dipping to flat</td>
<td></td>
</tr>
<tr>
<td>lying dikes with discordant</td>
<td></td>
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<tr>
<td>contacts, thickness between 1–</td>
<td></td>
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<tr>
<td>20 m.</td>
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<tr>
<td><strong>MAJAYAHAN PEGMATITES &amp; DALA</strong></td>
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<td><strong>N QUARTZ VEINS</strong></td>
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<tr>
<td><strong>pegmatites:</strong> around 20,</td>
<td><strong>pegmatites:</strong> <strong>qtz, K-fsp, musc, albite, ± cassiterite, spodumene, lepidolite, tantalite-columbite, tapiolite.</strong></td>
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<tr>
<td>steeply dipping, simple and</td>
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<tr>
<td>complex zoned dikes, thickness</td>
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<tr>
<td>rarely more than 1 m.</td>
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<tr>
<td><strong>qtz veins:</strong> steeply dipping</td>
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<td>veins, below 1 m thick.</td>
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worked for cassiterite. Figure 2 displays the K/Rb ratios and the Cs contents of muscovites from the three pegmatite occurrences to illustrate their differences in chemical evolution.

**Sampling and analytical methods**

Samples of early stage muscovite have been collected from several dikes of each pegmatite field. The muscovites differ in grain size, color and trace element composition (see Table 2).

Bayuda Desert muscovites are coarse grained (>10 cm), platy minerals of reddish-brown (samples BD5, BD6, BD9) to greenish (the other samples) varieties. Samples have been collected from four individual dikes of the Rahaba-Rubatab area (southern part of the pegmatite field): BD5 (Khor Rahaba dike); BD6 & BD7

![Fig. 2. Plot of K/Rb versus Cs in muscovites from the three Pan-African pegmatite fields. Data from Küster (1990) and Küster and Matheis (1990)](image-url)
Table 2. Results of Rb–Sr isotope determinations and $^{87}Sr^*$ calculations

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>$^{87}Rb/^{87}Sr$</th>
<th>$^{87}Sr*$</th>
<th>Age (Ma)</th>
<th>$^{87}Sr/^{87}Sr_0$</th>
<th>$^{87}Sr^*_{calc}$</th>
<th>$^{87}Sr^*_{meas}$</th>
<th>$^{87}Sr^*$</th>
<th>$^{87}Sr^*_{calc}$</th>
<th>$^{87}Sr^*_{meas}$</th>
<th>$^{87}Sr^*$</th>
<th>$^{87}Sr^*_{calc}$</th>
<th>$^{87}Sr^*_{meas}$</th>
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<tbody>
<tr>
<td>Bayuda Desert Muscovites</td>
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<tr>
<td>BD5</td>
<td>2.16</td>
<td>0.75</td>
<td>0.21</td>
<td>394</td>
<td>526</td>
<td>1.3</td>
<td>1.0</td>
<td>-21.1</td>
<td>3.3</td>
<td>3.5</td>
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<tr>
<td>BD6</td>
<td>2.01</td>
<td>0.48</td>
<td>0.28</td>
<td>466</td>
<td>528</td>
<td>1.2</td>
<td>1.0</td>
<td>-17.4</td>
<td>8.2</td>
<td>8.4</td>
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<tr>
<td>BD9</td>
<td>2.11</td>
<td>0.53</td>
<td>0.17</td>
<td>335</td>
<td>556</td>
<td>1.9</td>
<td>1.1</td>
<td>-1.6</td>
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<td>BD10</td>
<td>2.29</td>
<td>0.46</td>
<td>0.22</td>
<td>225</td>
<td>564</td>
<td>6.2</td>
<td>5.2</td>
<td>0.5</td>
<td>1.0</td>
<td>0.9</td>
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<tr>
<td>BD11</td>
<td>2.39</td>
<td>0.49</td>
<td>0.20</td>
<td>210</td>
<td>570</td>
<td>1.3</td>
<td>1.3</td>
<td>1.7</td>
<td>1.7</td>
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<td>BD7</td>
<td>1.83</td>
<td>0.09</td>
<td>0.05</td>
<td>270</td>
<td>715</td>
<td>6.9</td>
<td>7.1</td>
<td>2.4</td>
<td>0.8</td>
<td>0.7</td>
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<tr>
<td>BD13</td>
<td>1.78</td>
<td>0.17</td>
<td>0.14</td>
<td>220</td>
<td>705</td>
<td>4.6</td>
<td>4.7</td>
<td>1.5</td>
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<tr>
<td>BD14</td>
<td>1.96</td>
<td>0.10</td>
<td>0.05</td>
<td>250</td>
<td>690</td>
<td>4.5</td>
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<tr>
<td>BD8</td>
<td>1.80</td>
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<td>0.03</td>
<td>220</td>
<td>515</td>
<td>6.2</td>
<td>6.2</td>
<td>0.8</td>
<td>1.0</td>
<td>0.9</td>
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<td>0.02</td>
<td>220</td>
<td>515</td>
<td>6.2</td>
<td>6.2</td>
<td>0.8</td>
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<td>0.9</td>
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<tr>
<td>BD10</td>
<td>1.89</td>
<td>0.07</td>
<td>0.03</td>
<td>220</td>
<td>515</td>
<td>6.2</td>
<td>6.2</td>
<td>0.8</td>
<td>1.0</td>
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<tr>
<td>BD11</td>
<td>1.96</td>
<td>0.10</td>
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<td>250</td>
<td>690</td>
<td>4.5</td>
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<tr>
<td>BD12</td>
<td>1.96</td>
<td>0.10</td>
<td>0.05</td>
<td>250</td>
<td>690</td>
<td>4.5</td>
<td>4.5</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9</td>
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Additional trace element data are from Kister (1990) and Kister et al. (1990a) (see text for description of mica samples)

(Rahaba I dike); BD9, BD10 & BD 11 (Rahaba II dike) and BD13 & BD14 (Wadi An Ithnieh dike).

Muscovite from the Wamba area is silvery in color, the grain size of the book-like crystals varies between 2 and 10 cm. Samples have been collected from individual dikes, only W17 & W18 as well as W63 & W63bt (biotite) are from the same pegmatite. Geographic locations of their pegmatite dikes group the muscovite samples as follows: W33, W37 & W40 (SE-part of pegmatite field); W14, W17, W18 & W21 (central part of pegmatite field and main mining area); W56, W63 & W63bt (NW-part of pegmatite field).

In northeastern Somalia muscovite has been collected from pegmatites at Majayahan (samples M2, M4 & M6) and from associated quartz veins at Dalan (samples D5 & D6). Pegmatitic muscovites are light greenish, small-sized (<2 cm) minerals, while muscovites from the quartz-cassiterite veins are silvery, <1 cm sized minerals. Samples from the Majayahan pegmatites have been collected from individual dikes, while the Dalan samples are from one quartz vein only.

The Rb and Sr concentrations and the Sr isotopic compositions were measured by isotope dilution at the Laboratoire de Géochronologie, Université Clermont-
Ferrand II. The NBS standard SrCO₃ SM 987 yielded \(^{87}\text{Sr}/^{86}\text{Sr} = 0.71021\) when normalized to \(^{86}\text{Sr}/^{88}\text{Sr} = 0.1194\). A decay constant of \(\lambda^{87}\text{Rb} = 1.42 \times 10^{-11}/\text{y}\) was used for all age calculations. For the calculation of the conventional ages an initial \(^{87}\text{Sr}/^{86}\text{Sr} = 0.7120\) was assumed. Isochron calculations have been done according to Williamson (1968). Errors of 1.5% and 0.01% have been assigned to the \(^{87}\text{Rb}/^{86}\text{Sr}\) and \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios, respectively, while the error of total Rb and Sr determination is less than 2%. All errors given are 2-sigma errors. Other trace elements were determined by AAS and ICP-AES techniques (see Küster, 1990; and Küster et al., 1990 for further information).

**Geochronology**

The muscovite model ages obtained (for isotope data see Table 2) are displayed in Figs. 3a, 4a & 5a together with age data for regional Pan-African granitoid magmatism. In each pegmatite field the muscovite age data are scattered and show ages which vary by up to more than 200 Ma among each other. Nevertheless, the ages are not evenly distributed, and most of the model ages rather cluster around a time span which is characteristic for late- (Bayuda Desert) and post-kinematic (Wamba) granitoid magmatism.

The isotopic data of the individual samples are displayed in Figs. 3b, 4b & 5b, using the Best Isochron Diagram of Provost (1990). In these diagrams the scattering of data points and the disturbance of the isotopic systems are clearly exposed. It is not possible to calculate isochrons involving all samples of each respective pegmatite.
Fig. 4. Wamba pegmatite field (Nigeria) a Distribution histograms of Rb–Sr muscovite model ages, mica from SE-part of pegmatite field—dashed, mica from central part of pegmatite field—blank, mica from NW-part of pegmatite field—stippled, (age data of regional Pan-African granitoid magmatism are from Matheis and Caen-Vachette, 1983; Umeji and Caen-Vachette, 1984; Tubosun et al., 1984; Dada et al., 1989) b Best Isochron Diagram showing Rb–Sr isotope data; line shows reference isochron with initial Sr ratio of 0.75 and T = 550 Ma; see text for discussion

Fig. 5. Majayahan pegmatite field (Somalia) a Distribution histograms of Rb–Sr muscovite model ages, pegmatitic muscovite—blank, quartz vein muscovite—dashed; (age data of regional Pan-African granitoid magmatism are from Küster et al., 1990b; Lenoir et al., in prep.) b Best Isochron Diagram showing Rb–Sr isotope data; line shows reference isochron with initial Sr ratio of 0.72 and T = 465 Ma; see text for discussion
Moreover, initial Sr ratios which would be obtained from isochron calculations, even if the samples with young model ages are omitted from regression, are not precise and have unrealistic values. Resulting from the high values of the measured $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and the long extrapolation of the regression line to the $^{87}\text{Sr}/^{86}\text{Sr}$ axis (cf. Clark, 1982), the large errors do not allow determination of reliable initial Sr ratios.

Considering realistic initial values, ratios of 0.720 to 0.760 have been reported from other, less Rb-rich pegmatite associations (Brookins et al., 1969; Clark, 1982; Matheis and Caen-Vachette, 1983). If initial Sr ratios are limited between 0.700 and 0.800, as a prerequisite to draw reliable isochrons, it is clearly obvious from Figs. 3b, 4b & 5b that only a limited number of samples from each occurrence can be used for the age determinations. The following results are obtained:

For the Bayuda Desert pegmatites (Fig. 3b) the age is around 670 Ma. An isochron involving samples BD7, BD10, BD11 & BD13 has a calculated age of $668 \pm 26$ Ma (MSWD = 0.20) with an unrealistic initial Sr ratio of $0.899 \pm 1.180$. Including sample BD9, the age would be $675 \pm 16$ (MSWD = 0.29), again with an unrealistic initial Sr ratio ($0.500 \pm 0.280$).

For the Wamba pegmatites (Fig. 4b) the age is around 550 Ma. An isochron involving samples W18, W21, W40, W14 & W63bt has a calculated age of $547 \pm 15$ Ma (MSWD = 0.91) with an initial Sr ratio of $0.843 \pm 0.168$.

For the Majayahan pegmatites (Fig. 5b) the age is less well constrained. Only the samples M2 and M4 fit to a “2-point isochron” with an age of $463 \pm 24$ Ma and an initial Sr ratio of $0.720 \pm 0.600$. Including sample D6 the age would be $465 \pm 14$ Ma (MSWD = 0.04) with an unrealistic initial Sr ratio of $0.688 \pm 0.018$.

The ages obtained from the Best Isochron Diagrams can be related to specific episodes of granitic magmatism in the respective areas (see Figs. 3a, 4a & 5a). Taking into account the strong genetic relationships between granite magmatism and formation of rare-element pegmatites (Küster, 1990; see Černý, 1991 for general discussion), it is very likely that the ages outlined above represent realistic ages of respective pegmatite formation. Consequently, the isotopic ratios of the samples which do not fit to the isochrons in Figs. 3b, 4b & 5b, are disturbed and can be attributed to open-system behaviour and post-crystallization mobility of $^{87}\text{Sr}^*$. 

**Calculation of radiogenic and common strontium concentrations**

The mobility of $^{87}\text{Sr}^*$ in granitic pegmatites has been shown by Riley (1970), Clark and Černý (1987) and others. In order to reveal the amount of Sr which was apparently lost from some of the micas, the concentration of $^{87}\text{Sr}^*$ was calculated from

a. Rb concentration, using equation: $^{87}\text{Sr}^* = ^{87}\text{Rb}^{(2t-1)}$ (see Clark and Černý, 1987); and

b. from measured $^{87}\text{Sr}/^{86}\text{Sr}$ isotope data.

For calculation of $^{87}\text{Sr}^*$ from $^{87}\text{Rb}$ concentration (the latter was calculated from total Rb, according to $^{85}\text{Rb}/^{87}\text{Rb} = 2.59265$), the common decay constant ($^{2}\text{Rb} = 1.42 \times 10^{-11}/\text{y}$) and appropriate ages ($t$) of crystallization were used. Crystallization ages were assumed from the Best Isochron Diagrams: 670 Ma for
Rb–Sr Isotope systematics of muscovite

Fig. 6. Plot of Rb versus Sr for the Bayuda Desert muscovites, showing the differences between total Sr (open squares), isotopically measured common Sr (full diamonds), and theoretically calculated common Sr (full squares).

the Bayuda Desert pegmatites, 550 Ma for the Wamba muscovites and 465 Ma for the Majayahan pegmatites. For calculation of $^{87}\text{Sr}^*$ concentration from the actually measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.720 was assumed for all samples to obtain the amount of non-radiogenic $^{87}\text{Sr}$. Calculation of common Sr reveals the original concentration of total Sr at the time of muscovite crystallization. The results of $^{87}\text{Sr}^*$ and common Sr calculations are given in Table 2.

Discrepancies between the two determinations of $^{87}\text{Sr}^*$ concentrations (Table 2) are obvious. Although the differences rarely exceed 2 ppm in absolute values, percentage variation of $^{87}\text{Sr}^*$ shows large discrepancies of up to $-37\%$. If the analytical error for the determination of total Rb and Sr concentration (less than 2% at the 2-sigma level) is taken into account, nearly half of the samples have identical values of $^{87}\text{Sr}^*_{\text{calc}}$ and $^{87}\text{Sr}^*_{\text{meas}}$, but it also appears that even samples which fit to the isochrons (e.g. W40 & W14) might have been slightly affected by $^{87}\text{Sr}^*$ mobility. However, due to several uncertainties in calculation (i.e. assumption of crystallization ages and immobile behaviour of Rb and common Sr during post-crystallization history, see Clark and Černý, 1987 for discussion), the quantification of $^{87}\text{Sr}^*$ loss must remain an approximation. Nevertheless, the large negative values of percentage deviation of $^{87}\text{Sr}^*_{\text{meas}}$ from $^{87}\text{Sr}^*_{\text{calc}}$ in some of the samples (Table 2) indicate that open-system behaviour and post-crystallization loss of $^{87}\text{Sr}^*$ is real.

In highly Rb-bearing mineral phases most of their total Sr consist of $^{87}\text{Sr}^*$, especially when the minerals are geologically old. A correction of total Sr is therefore necessary to obtain the original relationship between Rb and Sr at the time of crystallization, and to avoid misinterpretation of fractionation trends (Clark and Černý, 1987). Using common Sr data of muscovite from the Bayuda Desert pegmatites (Fig. 6) a negative correlation of Sr with Rb is obtained. This trend is indicative for magmatic fractionation and is obscured when plotting total Sr data. Negative values of common Sr$_{\text{calc}}$, which were obtained in some of the samples (Table 2), give further evidence for $^{87}\text{Sr}^*$ loss.

Discussion
The effects of $^{87}\text{Sr}^*$ mobility can be summarized from Figs. 3b, 4b, 5b. Data points which are located below the isochron lines have apparently suffered $^{87}\text{Sr}^*$ loss. The two data points which are located above the isochrons (BD14 in Fig. 3b and W17 in Fig. 4b) are more difficult to interpret, they could indicate either Rb loss or $^{87}\text{Sr}^*$ gain. Since subsolidus redistribution of Rb is rather unlikely to occur due to its easy
incorporation in mica structures, the anomalous isotopic composition of these samples is more likely related to sample inhomogeneity. Rb-poor pegmatitic minerals like albite and phosphates are known for their enrichment in excess $^{87}\text{Sr}^*$ (Riley, 1970b; Clark, 1982), leached from Rb-rich mica and K-feldspar and trapped in the Rb-poor minerals during cooling of the pegmatite. Small inclusions of these minerals in the muscovites analyzed could therefore be the reason for the anomalously high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in these samples.

The Bayuda Desert muscovites have been sampled from 4 associated pegmatite dikes, containing both reddish-brown and greenish varieties. From Figs. 2 and 6 it can be suggested that both muscovite varieties and, in consequence, all dikes derived from a similar granitic magma, most likely by fractionation. It is, therefore, remarkable that only those Bayuda Desert muscovites have apparently lost $^{87}\text{Sr}^*$ which are reddish-brown in colour, while the other, greenish coloured, (±670 Ma old) muscovites remained close (Fig. 3). During the Phanerozoic the continental crust of the Bayuda Desert has been frequently intruded by various post- to anorogenic granites (Ries et al., 1985, see Fig. 3a; Barth et al., 1983). Thermal reactivation of the region due to this magmatism could be a reason for the partial reset of model ages. Nevertheless, the amount of loss of $^{87}\text{Sr}^*$ is different among the three reddish-brown muscovites (Fig. 3b) and does not support a direct link of $^{87}\text{Sr}^*$ loss with reheating due to younger magmatic activity. Slow cooling of the pegmatites is, of course, another alternative to explain the partial open-system behaviour.

In the Wamba area mica was collected from pegmatite dikes which are not strictly cogenetic but have most likely formed from different, although genetically related, batches of evolved granitic magma (Küster, 1990). This circumstance makes the isochron age determinations carried out on the Wamba muscovites somewhat equivocal. However, Matheis and Caen-Vachette (1983) obtained a similar age of 555 ± 5 Ma (3-point whole rock Rb–Sr isochron) on albitized granites and pegmatites of the Wamba area. From Fig. 4b it is evident that the muscovite samples affected by $^{87}\text{Sr}^*$ loss were not equally reset. It is all the more interesting but cannot be explained at present that the biotite sample W63bt, collected from the same dike as muscovite sample W63, remained closed (model age of 545 Ma) while the muscovite did not (model age of 435 Ma). Low-temperature fluid activity should affect biotite more strongly than muscovite due to the lower closing temperature of the former. This was confirmed by Matheis and Caen-Vachette (1983) who observed Jurassic Rb–Sr model ages on biotite from Pan-African pegmatites of southwestern Nigeria, while muscovite from the same dikes remained unaffected. Resetting of the isotope systematics of biotite has been linked by Matheis and Caen-Vachette (1983) to thermal reactivation due to Jurassic anorogenic magmatism. The 4 “young” muscovite model ages from the Wamba area do not allow a similar conclusion. They show different “ages” among each other (Fig. 4a), moreover, these “ages” are not related to the 213–141 Ma period of Mesozoic magmatic activity reported from central Nigeria (Bowden and Karche, 1984). Thus, the loss of $^{87}\text{Sr}^*$ from muscovites of the Wamba field cannot be directly attributed to younger magmatic activity. Field relationships argue for another explanation. The samples with the unrealistically young ages have been collected from pegmatite dikes which are located near brittle shear zones. These strike-slip faults are of late Pan-African age and are basically related to post-kinematic granite magmatism and pegmatite formation (Küster, 1990). It is suggested that movements along these faults (probably by reactivation
Rb–Sr Isotope systematics of muscovite

during the Phanerozoic in connection with the break-up of Gondwana and related intra-plate tectonic stresses) have caused the open-system behaviour and the loss of \(^{87}\text{Sr}\) from some of the micas, while those located at some distance from the shear zones remained closed.

The muscovites from the Majayahan field have been sampled from two different rock types: pegmatites and quartz veins. Although the quartz vein muscovites have distinctly younger model ages (Fig. 5a), this is not attributed to a temporal separation of the crystallization of both rock types. The model ages of the vein muscovites are themselves distinguished by a variation of 30 Ma. Together with the anomalously young model age of 400 Ma from one of the pegmatitic micas, this suggests post-crystallization disturbance of Rb–Sr systematics rather than difference in formation ages. Due to insufficient amount of samples unaffected by open-system behaviour, the age determination for the Majayahan pegmatites and quartz veins is not well constrained and would need further verification. Beside the opening of the Gulf of Aden during Tertiary times, there are no anorogenic magmatic activities or tectonic reactivations reported which might have seriously affected the continental crust of northern Somalia after emplacement of the pegmatites. Slow cooling of the pegmatite-quartz vein system is, therefore, a more likely explanation for the loss of \(^{87}\text{Sr}\) from Majayahan/Dalan muscovites.

In all three pegmatite fields there is a coincidence of \(^{87}\text{Sr}\) loss with distinct chemical composition of muscovite (Table 2). The minerals which suffered open-system behaviour have always the highest Mg (often accompanied by high Ti, Fe and Li concentration) and the lowest Rb contents among the muscovites of their respective pegmatite associations; sample M6 is the exception from this rule. Regarding cooling pegmatite systems on the whole, it has been shown by Riley (1970a), Clark (1982) and others, that Rb-rich minerals (mica, K-feldspar) generally tend to lose their radiogenetically produced Sr, while Rb-poor minerals (phosphates, albite) incorporate large amounts of excess \(^{87}\text{Sr}\). Looking into individual Rb-rich mineral systematics, Riley (1970a) has also found a positive correlation between Rb content and amount of \(^{87}\text{Sr}\) loss in muscovite from pegmatite generating granite, i.e. the higher the Rb content the higher the loss of \(^{87}\text{Sr}\). There is, however, no general justification for such a straightlined relationship between mineral chemistry and open-system behaviour. In all three pegmatite associations investigated in this study, \(^{87}\text{Sr}\) loss is more pronounced in (relatively) Rb-“poor”, (Mg-rich) muscovite than in Rb-rich, (Mg-poor) muscovite. However, the significance and explanation of this “selective” open-system behaviour is beyond the scope of this paper and must be left to further examination.

Conclusions

Rb–Sr model ages of individual muscovites from several pegmatite dikes are discordant and cannot be used for precise age determinations of the three Pan-African pegmatite associations investigated in this study. Using the Best Isochron Diagram, construction of muscovite isochrons yields reliable and geologically realistic ages of pegmatite formation in relation with the ages of regional granite magmatism. The Bayuda Desert pegmatites have been emplaced around 670 Ma, the Wamba pegmatites around 550 Ma, and, although less conclusive, the Majayahan pegmatites around 465 Ma.
The initial Sr ratios obtained from the muscovite isochrons are not precise and thus insufficient for petrogenetic interpretation. The high numerical values of $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with resulting large absolute errors do not allow determination of reliable initial Sr ratios. Anomalous initial Sr ratios can also be attributed to the oversimplified assumption of a common initial ratio for all samples (Clark, 1982).

The amount of $^{87}\text{Sr}^*$ loss from some of the muscovites (up to 37%) was calculated from the discrepancies between isotopically measured and theoretically calculated (from decay of incorporated Rb) $^{87}\text{Sr}^*$ concentration. Due to several uncertainties in calculation the quantification of $^{87}\text{Sr}^*$ loss is not precise and remains an approximation.

The observed losses of $^{87}\text{Sr}^*$ from the muscovites are variable in all three pegmatite fields and cannot be simply related to particular, and temporally confined geological events. None of the three pegmatite areas was subjected to a recognizable post-emplacement regional metamorphism. It is suggested that the partial open-system behaviour of $^{87}\text{Sr}^*$ is related to fluid activity which, however, did not equally reset the ages of all samples affected by $^{87}\text{Sr}^*$ loss. Fluid activity thus appears to be non-pervasive and "unsystematic" even within single pegmatite dikes. Slow cooling of the pegmatite bodies is the most probable geologic process responsible for this unsystematic fluid activity (i.e. Bayuda Desert and Majayahan). Another possible process which could have triggered fluid activity is tectonic channeling due to strike slip faulting during the Phanerozoic (i.e. Wamba). Reheating due to younger anorogenic magmatism is rather unlikely to cause the observed open-system behaviour.

Acknowledgements

I wish to thank M. Caen-Vachette for carrying out the isotope analyses in Clermont-Ferrand, VW-Foundation for financial support and G. Matheis for establishing the contacts and initiating the work. Helpful comments of R. B. Trumbull and an anonymous reviewer are highly acknowledged and improved the manuscript substantially. W. Becker is thanked for assistance in drawing the figures.

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