Rb-Sr Ages Of Precambrian Mafic Dikes, Bighorn Mountains, Wyoming

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ABSTRACT

Rb-Sr isochron data from whole-rock samples of dolerite and metadolerite indicate emplacement of dikes 2,826 ± 58 m.y. ago, during formation of the Bighorn gneiss and granitic complexes. Whole-rock samples of other dolerite dikes and mineral separates mark another intrusive event at 2,200 ± 35 m.y. B.P., well after the regional metamorphism. Two episodes of mafic dike emplacement are consistent with field relations but are not in agreement with recent K-Ar age determinations. Key words: geochronology, Precambrian, mafic dikes.

INTRODUCTION

Precambrian basaltic rocks in the Bighorn Mountains are represented almost exclusively by mafic dikes. Studies have been made on many of these dikes by Condie and others (1969), Manzer and others (1971), Armbrustmacher (1972), Ross and Heimlich (1972), Heimlich and Manzer (1973), Heimlich and others (1973, 1974), and Manzer and Heimlich (1974).

Reconnaissance geochronologic studies involving the K-Ar method have been reported by various workers (Heimlich and Banks, 1968; Condie and others, 1969; G. K. Manzer, Jr., 1972, written commun.), and the 10 ages given fall in the range 1,390 to 2,520 m.y. The present Rb-Sr age study more clearly defines the time(s) of intrusion of the mafic dikes. Impetus for this approach was given by the work of Van Schmus (1965), Fairbairn and others (1971), Gates and Hurley (1973), and Baadsgaard and Mueller (1973).

GEOLOGIC SETTING

Mafic dikes in the Bighorn Mountains have intruded rocks in two broad terranes. The northern half of the area consists of a granitic terrane dominated by metasomatic rocks largely of quartz monzonitic and quartz dioritic composition (Fig. 1). These rocks are medium grained to pegmatitic and are well foliated in some areas. The terrane to the south consists of foliated quartzofeldspathic gneissic rocks with interlayered amphibolite. The gneiss is medium grained and locally migmatitic. Rocks of both terranes are in the low-amphibolite facies. Reconnaissance mapping (Heimlich, 1969) of the granitic and gneissic rocks suggests that the structure, defined by the attitude of foliation, is continuous throughout the area and independent of lithologic contacts, which are everywhere gradational. The mafic dikes transect the foliation in both terranes. The dikes range in thickness from 2 cm to 150 m. Some have been traced for as much as 20 km. Dips are characterized steep (70° to 90°), and strike directions are commonly north-easterly, north-westerly, and east-westerly. Contacts are invariably sharp and marked by dense basalt.

Dolerite and metadolerite dikes occur within both the granitic and gneissic terranes (Ross and Heimlich, 1972; Heimlich and others, 1973, 1974; Manzer and Heimlich, 1974). The dolerite dikes have ophitic and subophitic textures and lack evidence of regional metamorphism such as that described by Hanson and Malhotra (1971) in mafic dikes in Minnesota. There are several extremely porphyritic "leopard rock" dolerite dikes with plagioclase phenocrysts typically 5 to 8 cm across (Heimlich and Manzer, 1973). The metadolerite dikes generally consist of two intergradational facies. The marginal facies consists of granoblastic aggregates of clear andesine and hornblende. The interior facies is characterized by relict ophitic and subophitic clouded andesine-labradorite and granular augite, the latter peripherally replaced by hornblende. Petrographic contrasts between the dolerite and metadolerite dikes have been summarized by Heimlich and others (1973). Chemical data (Heimlich and others, 1973) indicate that both types are of tholeiitic basalt affinity.

The dikes sampled in this study are described in Table 1. Dolerite and metadolerite dikes were included from throughout the Precambrian terrane, although emphasis was placed on the three areas in which the dikes were mapped in detail (Fig. 1). For precise locations, see Ross and Heimlich (1972; Bald Mountain area), Heimlich and Manzer (1973), Manzer and Heimlich (1974; 1972; Heimlich and others, 1973, 1974; Manzer and Heimlich, 1974).
TABLE 1. INFORMATION REGARDING DIKE SAMPLES

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<th>Sample</th>
<th>Nature</th>
<th>Position</th>
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<th>Designation†</th>
<th>Classification</th>
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<td>Contact</td>
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<td>N</td>
<td>Metadolerite</td>
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</tbody>
</table>

* Fine-grained sample within 1 m of contact.
† Refers to dike label in Heimlich and others (1973, 1974), Heimlich and Manzer (1973), Manzer and Heimlich (1974), and Ross and Heimlich (1972).
‡ Burgess Junction–Tongue River area.
§ Canyon Creek–Doyle Creek area.

Burgess Junction–Tongue River area), Manzer and others (1971; Canyon Creek–Doyle Creek area), and Heimlich and others (1973; Canyon Creek–Doyle Creek area).

ANALYTICAL METHODS AND RESULTS

Rb and Sr concentrations (Table 2) in powdered whole-rock samples and mineral separates were determined on aliquots of sample solutions by the isotope dilution technique, using spikes enriched in Rb$^{87}$ and Sr$^{88}$, respectively. Strontium-isotopic compositions were measured on unspiked aliquots by means of a 30.5-cm-radius mass spectrometer with a double-filament source and a strip-chart recorder equipped with expanded-scale readout.

We assign an experimental uncertainty of ±2 percent to the Rb$^{87}$/Sr$^{86}$ ratios and ±0.06 percent to the normalized Sr$^{87}$/Sr$^{86}$ ratios, on the basis of duplicate sample analyses here (Table 2) and in other studies. Replicate analyses of the Eimer and Amend SrCO$_3$ standard have given a mean Sr$^{87}$/Sr$^{86}$ ratio of 0.70795 ± 0.00013. Rb-Sr isochron ages and initial Sr$^{87}$/Sr$^{86}$ ratios were calculated according to the regression method of York (1969), with no allowance for possible correlation of errors. A value of 1.39 x 10$^{-11}$ yr$^{-1}$ was used for the decay constant of Rb$^{87}$. Errors for ages and initial ratios are given as one standard deviation.

DISCUSSION

The whole-rock data are plotted on a strontium evolution diagram (Fig. 2). With the exception of two anomalous samples, these points define two isochrons that indicate two ages of dike emplacement. Twelve samples from dikes throughout the Bighorn range (Fig. 1) yield an isochron age of 2,826 ± 38 m.y., with an initial ratio of 0.7019 ± 0.0003. Seven of the eight dikes classified as metadolerite (Table 1) fall on this isochron. Sample 3401, which could belong to either of the two isochrons, was assigned to the older isochron because it is a metadolerite. Five whole-rock samples from other dikes in the Bighorn range (Fig. 1) define a second isochron age of 2,240 ± 100 m.y. and an initial ratio of 0.7022 ± 0.0007. Metadolerite sample 3312, which lies on this isochron (Fig. 2) is probably anomalous, and therefore we have not included it in the calculation of either of the isochron ages.

The two clearly anomalous points (Fig. 2; 3294 and 70-20) can be explained only as the result of open-system behavior with respect to Rb and (or) Sr. There is nothing unusual about the dikes represented or their concentration levels of Rb and Sr (Table 2). Gates and Hurley (1973) found that the absolute abundances of Rb and Sr in mafic dikes and the degree of scatter about the isochron are apparently affected by the composition of the intruded rock. Such a relationship was not found in the Bighorn mafic dikes. Although the composition of the host rock is quite diverse, there is no correlation with Rb and Sr abundances, and the scatter about the isochrons of all but the two anomalous points is generally within analytical uncertainty. All the dolerite dikes analyzed in this study show some degree of deuteric alteration. Anomalous sample 70-20 shows intense deuteric alteration and, unlike all but three of the other whole-rock samples, it is from the interior of a dike rather than from a chilled margin.
The anomalous points on the strontium evolution diagrams suggest the possibility of contamination of those samples that lie on the isochrons. The initial Sr\(^{87}\)/Sr\(^{86}\) ratios for both isochrons represent reasonable isotopic ratios for mantle-derived magmas of these ages. However, slightly lower values might have been expected, so the isochronous points may reflect relative Sr\(^{87}\) contamination. Contamination would have to affect each sample proportionately in order to have maintained an isochron relationship. This is considered unlikely (see Baadsgaard and Mueller, 1973; the Rb and Sr contents of the samples are quite variable, and the intruded rocks are of diverse composition.

Gates and Hurley (1973) have suggested that Rb-Sr analyses of minerals from mafic dikes can detect thermal overprinting of the dikes and also subsequent contamination by radiogenic Sr\(^{87}\) from the host environment. Their results show that in most cases Rb-Sr mineral isochron ages from individual samples are concordant with the Rb-Sr whole-rock age for the dike swarm as a whole. They concluded that the Rb-Sr whole-rock isochron method can yield consistent age determinations on mafic dikes of ancient age.

Minerals were analyzed from two Bighorn mafic dikes, one from each of the two whole-rock isochrons. Whole-rock sample 926, from Sheep Mountain, lies on the 2,826-m.y. isochron. This sample, a leprous rock, plagioclase phenocrysts as well as groundmass separated from this sample are more nearly coincident with the 2,826-m.y. isochron. Whole-rock sample 70-60, which lies on the 2,240-m.y. isochron, is from the chilled margin of a dolerite dike in the Burgess Junction-Tongue River area (Fig. 1). Minerals were separated from two other samples from the interior of the dike at the same locality, as well as from a sample of the interior of the dike at another locality, along strike (Table 1; Fig. 1). Because the dike is a leprous rock, plagioclase phenocrysts as well as groundmass plagioclase and augite were obtained. The analytical data for the six mineral separates (Table 2) are plotted in Figure 4, along with data from the five whole-rock analyses previously used to define the 2,240-m.y. isochron. All these data yield an isochron age of 2,200 ± 35 m.y., which we consider to be a better estimate of the second age of mafic dike emplacement. The greater scatter of points about this isochron may be due to deuteric alteration, which is commonly greater in the interiors of the dikes than at their margins.

Osterwald (1955, 1959), on the basis of field and petrographic evidence in the Burgess Junction-Tongue River area, was the first to suggest two ages of mafic dikes in the Bighorn Mountains. Heimlich and others (1973) recognized two generations of mafic dikes in the Canyon Creek-Doyle Creek area (Fig. 1). Older dolerite dikes apparently were recrystallized to meta-dolerite during the regional metamorphism that formed the gneiss and amphibolite terrane, whereas younger dolerite, deuterically altered but not recrystallized, was emplaced after the regional metamorphism. Armbrustmacher (1972) established two episodes of intrusion in the Clear Creek area, northeast of the Canyon Creek-Doyle Creek area. He suggested that the older meta-dolerite dikes may have been intruded during the waning stages of regional metamorphism, but...
not before then, because they cut across the host-rock foliation and are not deformed.

Condie and others (1969) suggested three periods of mafic dike intrusion in the Bighorn Mountains (at 2,500, 1,900 to 2,200, and 1,400 to 1,800 m.y., B.P.). The K-Ar ages of eight Bighorn dikes ranged from 1,390 to 2,520 m.y. Samples from two of these dikes, in the Bald Mountain area (Fig. 1), were analyzed in our study (Table 2; samples 940 and 952). Whereas these two samples lie on the 2,826-m.y. Rb-Sr isochron (Fig. 2), the K-Ar ages determined by Condie and others are 1,880 and 2,020 m.y. G. K. Manzer, Jr. (1972, written commun.) reported a K-Ar age of 1,905 m.y. for a dolerite dike in the Burgess Junction–Tongue River area. A sample from this dike analyzed in our study (Table 2; sample 70-60) lies on the 2,200-m.y. isochron (Fig. 4).

Gates and Hurley (1973) evaluated the relative merits of K-Ar and Rb-Sr age determinations on Precambrian mafic dikes in eastern Canada. Their data showed that Rb-Sr whole-rock and mineral isochron ages are concordant within the limits of analytical uncertainty and are greater than K-Ar ages for the same material. They concluded that the K-Ar method is generally unreliable where applied to mafic dike rocks. The limitations of the K-Ar method as applied to mafic dikes have been discussed by Leech (1966), Spall (1971), Gates and Hurley (1973), and Baadsgaard and Mueller (1973); the latter applied both the Rb-Sr and K-Ar methods in the Beartooth Mountains. The Rb-Sr isochron ages presented here indicate that only two periods of mafic dike intrusion have occurred in the Bighorn Mountains and that the K-Ar ages reported by Condie and others (1969) are too low, by variable amounts, because of argon loss.

The two ages of dike emplacement are consistent with the chronology of other events established in the Bighorns. A working hypothesis for the origin of the gneiss and granitic complexes, as described by Heimlich and Banks (1968), includes folding and recrystallization of a largely sedimentary rock sequence during an interval of regional deformation. This produced a gneiss complex which, in the northern part of the area, was converted to granitic rocks by metamorphism during the same interval of time. Heimlich and Banks (1968) reported U-Pb analyses of zircon and monazite from quartz monzonite that indicate an age of 2,890 ± 25 m.y. (concordia intercept) for the granitic rocks. They pointed out that the U-Pb systems in these minerals either originated or were completely reset at that time. Studies of zircon morphology were inconclusive as to the possible detrital origin of this mineral. However, subsequent studies (Malcuit and Heimlich, 1972; Shortwell and Heimlich, 1973) suggested that the zircons are detrital in nature. Heimlich and Armstrong (1972) presented K-Ar dates for biotite separated from samples collected throughout the gneiss and granitic terrane. Fresh biotite from granitic rocks averaged 2,750 ± 50 m.y., whereas biotite from gneiss, regardless of degree of alteration, averaged 2,500 ± 70 m.y. Chloritized biotite from the northern granitic rocks averaged 2,530 ± 80 m.y., an age indistinguishable from the gneissic rock biotites. It was concluded that the fresh biotite from granitic rocks was simply more argon retentive than the others and that the major Precambrian metamorphic event that affected the Bighorns ended approximately 2,750 m.y. ago.

The first episode of mafic dike emplacement, at 2,826 ± 58 m.y. B.P., can be interpreted as having occurred after the formation of the gneiss and granitic complexes but before the termination of the regional metamorphic event, consistent with the conclusions of Armbrustmacher (1972) and Heimlich and others (1973), on the basis of field evidence. Seven of the eight metabedolerite dikes fall on the 2,826-m.y. isochron (Fig. 1). Heimlich and others suggested that the recrystallization shown by these dikes occurred during the later stages of the regional metamorphic event. The whole-rock Rb-Sr systems of most of the metabedolerites are apparently unaffected by the recrystallization process and mark the time of dike intrusion.

Five dikes classified as dolerites, all of which are located in the northern part of the Bighorn range (Table 1, Fig. 1), also lie on the 2,826-m.y. isochron (Fig. 2). The absence of metamorphic effects in these dikes is difficult to explain, as metabedolerites occur in the same area. Manzer and Heimlich (1974) reported chemical and petrographic data for northern Bighorn metabedolerites which provided evidence for metasomatism during the metamorphic recrystallization. One of these metabedolerites was analyzed in our study (Fig. 1, 70-16); unusually high Rb and Sr contents provide further evidence of metasomatism (Table 2). Because this sample lies on the 2,826-m.y. isochron (Fig. 2), the metasomatism and recrystallization must have taken place nearly coincident with intrusion. It is possible that mafic dike intrusion occurred several times in the northern
Bighorns during the interval defined by the uncertainty in the 2,826-m.y. isochron age. Those dolerites that lie on this isochron could have been intruded late in the interval, when the metamorphism was of insufficient intensity to bring about recrystallization.

The second episode of mafic dike emplacement, at 2,200 ± 35 m.y., occurred well after the termination of the regional metamorphism and probably represents the last igneous event in the Bighorn Mountains. The dolerite dikes are deuterically altered but not recrystallized. In the Canyon Creek–Doyle Creek area (Fig. 1), Heimlich and others (1973) distinguished the two ages of dike emplacement on the basis of presence or absence of metamorphic recrystallization effects. They also noted a difference in dike trends for the two groups. Samples of five dikes from this area have been analyzed (Table 2). The three metadolerite samples lie on the 2,826-m.y. isochron (Fig. 2), whereas the two dolerite samples are on the 2,200-m.y. isochron (Fig. 4). Only dolerite dikes are found in the Bald Mountain area (Fig. 1), as described by Ross and Heimlich (1972), who suggested a single episode of emplacement post-dating the regional metamorphic event. Among samples of five dikes analyzed from this area (Table 2), only one falls on the 2,200-m.y. isochron (Fig. 4). This dike does have a different trend from the other four (Ross and Heimlich, 1972, Fig. 2), which lie on the 2,826-m.y. isochron (Fig. 2). It is clear that mafic dikes representing both intrusive episodes can be found throughout the Bighorn range (Fig. 1). The chronology of Precambrian events in the Bighorn Mountains is summarized in Table 3.

The geochronology of Precambrian rocks throughout the Wyoming-Montana area has been reviewed by Reed and Zartman (1973) and by Condie (1975). Ages in the range 2,500 to 2,900 m.y. are recorded in all mountain ranges and mark a period of deformation, plutonism, and regional metamorphism that coincides with the Kenoran orogeny in the Superior province of Canada (Condie, 1975). The first episode of mafic dike intrusion in the Bighorn Mountains occurred during this interval of time. Additional evidence of mafic dike emplacement elsewhere in the Wyoming province during this period of regional metamorphism consists of dolerite dikes intruded in the Beartooth Mountains 2,550 m.y. ago, according to the Rb-Sr whole-rock isochron ages obtained by Baadsgaard and Mueller (1973). Peterman and others (1971) reported mafic dike emplacement in the Granite Mountains prior to or during the major metamorphism 2,925 ± 80 m.y. ago, on the basis of Rb-Sr whole-rock isochron ages on paragneisses and orthogneisses. Divis (1973) suggested that one of three distinct generations of mafic dikes in the Sierra Madre Range occurred >2,500 m.y. ago.

Mafic dikes were emplaced throughout the Wyoming province at various times after the major regional metamorphic event. In addition to the 2,200-m.y. event in the Bighorn Mountains, dolerite dikes were intruded ~1,300 m.y. and ~740 m.y. ago in the Beartooth range. These events were dated by the Rb-Sr isochron and K-Ar methods (Baadsgaard and Mueller, 1973). K-Ar whole-rock ages suggest that dolerite dikes were intruded in the southern Wind River and western Owl Creek Ranges about 2,000 m.y. ago (Condie and others, 1969; Condie, 1975). K-Ar and Rb-Sr ages of minerals indicate that mafic dikes were emplaced approximately 1,500 m.y. ago in the Granite Mountains (Peterman and others, 1971). Divis (1973) has inferred ages of >1,700 m.y. and <1,700 m.y. for two of the three generations of mafic dikes in the Sierra Madre Mountains. Reed and Zartman (1973) reported a whole-rock K-Ar age of 775 m.y. from the chilled margin of a diabase dike in the Teton Range. However, on the basis of K-Ar ages on biotite in the wall rocks, they suggested that the dike was actually emplaced during or prior to a thermal event 1,300 to 1,500 m.y. ago. Because of the large uncertainties involved in many of the age determinations mentioned above, any attempt to correlate episodes of dike emplacement between mountain ranges seems unwarranted at this time.

Mueller and Rogers (1973) divided the mafic dikes of the Beartooth Mountains into four separate groups on the basis of chemical criteria, principally TiO2 content. Rb-Sr and K-Ar age determinations indicated that each group has a single, consistent age of formation. Age-elemental abundance patterns suggested successively deeper sources for successively younger dike magmas. When the initial Sr87/Sr86 ratios of the magmas were plotted against their ages, the dikes were found to lie along a growth line corresponding to a source with an essentially constant Rb-Sr ratio of about 0.04. It was suggested that the failure of the data to lie along a line of decreasing Rb/Sr ratio may indicate separate source regions for the various dike magmas. The younger magmas would have come from relatively deeper sources.

In Figure 5 we have plotted the initial Sr87/Sr86 ratios obtained for the two Bighorn intrusive events, along with the data of Mueller and Rogers (1973). For the 2,200-m.y.-ago event we have used the initial ratio indicated by the isochron based on whole-rock and mineral-separate data (Fig. 4). The initial Sr87/Sr86 ratios for the Bighorn and Beartooth mafic dikes, as well as the range of values for the Yellowstone basalts (Doe and others, 1970), are all coincident with the growth line representing a source region with a constant Rb/Sr ratio of 0.04. This relationship suggests a uniformity in the composition of the source region of mafic magmas under this condition.

### TABLE 3. SUMMARY AGES OF PRECAMBRIAN DIKES, BIGHORN MOUNTAINS

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<th>Method</th>
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<tr>
<td>U-Pb</td>
<td>2,890</td>
<td>Heimlich and Banks (1968)</td>
</tr>
<tr>
<td>Rb-Sr</td>
<td>2,826</td>
<td>This study</td>
</tr>
<tr>
<td>K-Ar</td>
<td>2,750</td>
<td>Heimlich and Armstrong (1972)</td>
</tr>
<tr>
<td>K-Ar</td>
<td>2,500</td>
<td>Heimlich and Armstrong (1972)</td>
</tr>
<tr>
<td>Rb-Sr</td>
<td>2,200</td>
<td>This study</td>
</tr>
</tbody>
</table>
entire geographic area, with the younger magmas having been generated at successively greater depths. Mueller and Rogers (1973) interpreted this increase in depth of source as being due to a world-wide decrease in the geothermal gradient with the passage of time. Alternative explanations for the relationships of Figure 5 can be found in the "recycled mantle" and "replenished mantle" hypotheses proposed by Jahn and others (1974). Under these models all the Beartooth-Bighorn mafic magmas could have been derived from the same source-region depth, where the Rb/Sr ratio was maintained at an essentially constant value by some recycling and (or) replenishment process.

CONCLUSIONS

Twelve whole-rock samples obtained from dikes throughout the Bighorn Mountains yield a Rb-Sr age of 2,826 ± 58 m.y., whereas five whole-rock samples and mineral separates from other dikes in the same area define an age of 2,200 ± 35 m.y. Metadolerite and dolerite dikes are found on the 2,826-m.y. isochron, whereas only unmetamorphosed dikes are found on the 2,200-m.y. isochron. Two episodes of dike emplacement are consistent with the field interpretations of earlier workers.

The first mafic dike intrusion occurred after the formation of the Bighorn gneiss and granitic complexes but before the termination of the regional metamorphism that affected the Wyoming-Montana region 2,500 to 2,900 m.y. ago. The recrystallization shown by the metamoderlite probably occurred during the later stages of the regional metamorphism. The second episode of mafic dike emplacement followed the regional metamorphism and probably represents the last igneous event in the Bighorn Mountains.

The results of this study indicate that consistent ages can be obtained on mafic dikes of ancient age by the Rb-Sr whole-rock isochron method.

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