Contrib Mineral Petrol 75, 199–203 (1980)

Contributions to Mineralogy and Petrology

Correlation of $\delta^{18}O$ and Initial $^{87}Sr/^{86}Sr$ Ratios in Kirkpatrick Basalt on Mt. Falla, Transantarctic Mountains

Joachim Hoefs[1], Gunter Faure[2], and David H. Elliot[2]

[1] Geochemisches Institut, Goldschmidtstr. 1, 3400 Göttingen, Federal Republic of Germany

[2] Department of Geology and Mineralogy and Institute of Polar Studies, The Ohio State University Columbus, Ohio 43210, USA

Abstract. The $\delta^{18}O$ (SMOW) values of the Kirkpatrick Basalt (Jurassic) on Mt. Falla, Queen Alexandra Range, vary between $+6.3‰$ and $+8.6‰$. The apparent enrichment of these rocks in ^{18}O excludes the possibility that they were altered by interaction with aqueous solutions of meteoric origin. The $\delta^{18}O$ values of the flows correlate significantly with the initial $^{87}Sr/^{86}Sr$ ratios and all major elements. These correlations confirm the hypothesis that the basalt magma was contaminated by rocks of the continental crust through which it was extruded. Estimates of the chemical composition of the basalt magma and the contaminant, based on extrapolations of the new oxygen data, generally confirm earlier estimates based on extrapolations of initial $^{87}Sr/^{86}Sr$ ratios. The $^{87}Sr/^{86}Sr$ ratio of the uncontaminated basalt was 0.7093 which indicates that magma may have originated by melting either in old Rb-enriched lithospheric mantle under Antarctica or in the overlying crust, or both.

Introduction

Anomalously high initial $^{87}Sr/^{86}Sr$ ratios of the Kirkpatrick Basalt and Ferrar Dolerite (Jurassic) in the Transantarctic Mountains were first reported by Compston et al. (1968). Subsequent studies by Faure et al. (1972) confirmed this result and demonstrated that these rocks form a distinctive petrologic province that extends from Northern Victoria Land to the Dufek Massif of the Pensacola Mountains, a distance of 2,500 km along the strike of the Transantartic Mountains. Faure et al. (1974) proposed that the anomalous isotopic and chemical properties of basalt flows on Storm Peak, Queen Alexandra Range, could be explained by contamination of a mantle-derived tholeiite magma with varying amounts of a contaminant derived from the granitic basement rocks that underlie the Transantarctic Mountains. This petrogenetic model was found to be applicable also to basalt flows on Mt. Falla in the Queen Alexandra Range (Faure et al. 1978).

The critical evidence favoring the contamination model was summarized by Faure (in press) and includes: (1) High initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.7094 to 0.7133; (2) Systematic decrease of the initial $^{87}Sr/^{86}Sr$ ratios in successive flows up section; (3) Positive correlations between initial $^{87}Sr/^{86}Sr$ ratios and concentrations of SiO_2, FeO (total Fe), Na_2O+K_2O, and Sr; (4) Negative correlations with Al_2O_3, MgO and CaO; (5) High Rb/Sr ratios (0.46 ± 0.04) and low K/Rb ratios (231 ± 98); (6) High concentrations of SiO_2, FeO (total Fe), K_2O and Rb and low concentrations of Al_2O_3, MgO, CaO and Sr compared to average tholeiite basalts. In general, the isotopic and chemical properties of the Kirkpatrick Basalt resemble those of granitic rocks as pointed out originally by Compston et al. (1968). However, Kyle (1980) used published isotopic data and some new major element and rare earth data to conclude that the basaltic rocks of the Ferrar Group were derived from heterogeneous sources in the mantle. In presenting his arguments Kyle chose to disregard the evidence for systematic variations of initial $^{87}Sr/^{86}Sr$ ratios that exist in local lava sequences and emphasized instead the regional similarity of average initial $^{87}Sr/^{86}Sr$ ratios from widely separated localities. The new insight provided by the isotopic composition of oxygen presented in this report tends to reconcile the divergent conclusions that have been expressed by Kyle and Faure.

The importance of crustal contamination of mantle-derived magmas has been widely recognized following recent studies of the isotopic compositions of Sr and Nd in igneous rocks (Carter et al. 1978; DePaolo and Wasserburg 1979; Hawkesworth and

---

Reprint requests to: J. Hoefs

0010-7999/80/0075/0199/$01.00

Vollmer 1979). Recently Taylor (1980) summarized the effects of assimilation of crustal rocks on the $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ ratios of igneous rocks. Igneous and metamorphic rocks of the continental crust, and the sedimentary rocks derived from them, are enriched in radiogenic ^{87}Sr compared to the upper mantle (Faure and Hurley 1963). Acidic igneous and metamorphic rocks containing feldspar and quartz and sedimentary rocks composed of detrital quartz, clay minerals, carbonates and chert are rich in ^{18}O because these minerals concentrate this isotope in preference to ^{16}O. The enrichment of crustal rocks in ^{87}Sr and ^{18}O is therefore a result of two entirely different processes. The addition of crustal material to mantle-derived magmas increases both their $^{87}Sr/^{86}Sr$ and their $^{18}O/^{16}O$ ratios. Positive correlations of these ratios therefore indicate that significant contamination of Sr and O has occured. Taylor (1980) demonstrated that in most cases straight lines can be fitted to $\delta^{18}O$ values and initial $^{87}Sr/^{86}Sr$ ratios of contaminated igneous rocks and that these lines typically pass close to a point having coordinates $\delta^{18}O = +5.7 \pm 0.3‰$ and $^{87}Sr/^{86}Sr = 0.703 \pm 0.001$ which he named the "mantle representative point".

We report here new measurements of $\delta^{18}O$ values of the basalt flows on Mt. Falla for which Faure et al. (1978) measured initial $^{87}Sr/^{86}Sr$ ratios and the concentrations of the major elements. This information provides new insight into the petrogenesis of these flows.

Geology and Petrography

The Queen Alexandra Range is located along the north side of the Beardmore Glacier (Fig. 1). It consists of a basement complex of igneous and metamorphic rocks of late Precambrian to Cambrian age overlain unconformably by flat-lying sandstones and shales of the Beacon Supergroup (Permian to Triassic). The flows of Kirkpatrick Basalt occur as erosional remnants on several major peaks (McGregor and Wade 1969). The chemical composition and petrography of the Kirkpatrick Basalt were described by Elliot (1972). A study of Fleck et al. (1977) indicates an age of 175 ± 5 Ma based on the K-Ar and the $^{40}Ar/^{39}Ar$ method. This date was confirmed by Faure et al. (1978) on the basis of a Rb-Sr isochron of six flows from Mt. Falla. The flows are classified as tholeiites on the basis of their chemical compositions. They are composed of labrodorite, augite and pigeonite phenocrysts in a matrix of glass, devitrified glass, or quartzofeldspathic mesostasis (Elliot 1972). Most of the samples are not detectably altered. The present $^{87}Sr/^{86}Sr$ ratios of the flows range from 0.7122 to 0.7175 and average 0.7149. Their Sr content is 127.6 ppm on the average and that of Rb is 54.5 ppm. The corrections of the measured $^{87}Sr/^{86}Sr$ ratios for decay of ^{87}Rb average 0.43% of the $^{87}Sr/^{86}Sr$ ratio (Faure et al. 1978).

Analytical Techniques

Oxygen was extracted from the rocks by reacting the samples with BrF_5 (Clayton and Mayeda 1963). The $\delta^{18}O$-values are defined in the usual way and given relative to SMOW. The analytical reproducibility is within $\pm 0.2‰$. The $^{87}Sr/^{86}Sr$ ratios were measured on a solid-source mass spectrometer and were corrected for in-situ decay of ^{87}Rb assuming an age of 170 Ma for the flows. The Rb/Sr ratios were determined by X-ray fluorescence (Faure et al. 1978). The reproducibility of the $^{87}Sr/^{86}Sr$ ratio is ± 0.0003 or better and the error of the Rb/Sr ratios is less than 1.0%.

Discussion of Results

The $\delta^{18}O$ values of the flows from Mt. Falla are listed in Table 1 together with initial $^{87}Sr/^{86}Sr$ ratios reported by Faure et al. (1978). The $\delta^{18}O$ values of all the flows are greater than $+5.5‰$ indicating enrichment in ^{18}O compared to typical basalt. The apparent enrichment in ^{18}O excludes the possibility that the anomalous isotopic and chemical properties of the Kirkpatrick Basalt were caused by aqueous solu-

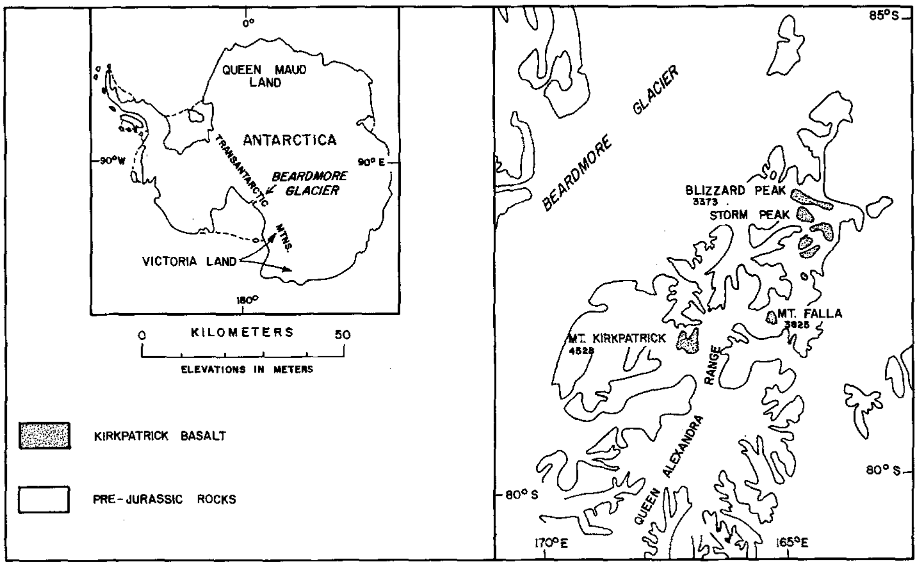

Fig. 1. Location of Kirkpatrick Basalt on Mt. Falla, Queen Alexandra Range, Transantarctic Mountains

Table 1. $\delta^{18}O$ (SMOW) and initial $^{87}Sr/^{86}Sr$ ratios of tholeiite basalt flows of the Kirkpatrick Basalt, Mt. Falla, Queen Alexandra Range, Transantarctic Mountains

Flow No.	$\delta^{18}O$‰	Initial $^{87}Sr/^{86}Sr$
14	6.3	0.7102
13	6.6	0.7100
12	6.9	0.7115
11	7.9	0.7121
10	6.7	0.7101
9	6.8	0.7111
8	7.5	0.7117
7	7.3	0.7115
6	7.3	0.7129
5	7.3	0.7131
4	7.8	0.7128
3	7.3	0.7128
2	7.5	0.7129
1	8.6	0.7128

tions of meteoric origin interacting either with the magma or with the flows. However, possible interactions at high temperature with metamorphic water enriched in ^{18}O are not excluded.

The initial $^{87}Sr/^{86}Sr$ ratios of flows 1 through 6 are constant and form an isochron from which Faure et al. (1978) determined their age. The $\delta^{18}O$ values of five of these flows are clustered around a mean of $+7.4 \pm 0.2$‰. Only flow #1 deviates from this pattern with a $\delta^{18}O$ value of $+8.6$‰. The anomalous enrichment of this flow in ^{18}O may have been caused by its contamination with weathering products that had accumulated on the surface upon which the lava flows were subsequently extruded. The variation of the chemical compositions of these flows reported by Faure et al. (1978) is attributable to the effects of fractional crystallization as stated by Faure et al. (1978) and re-emphasized by Kyle (1980). In general, the chemical composition of individual handspecimens of these basalt flows are affected by: (1) the original composition of the parent magma; (2) addition of a contaminant derived from the granitic crust; (3) fractional crystallization in the magma chamber and after extrusion; and (4) alteration after crystallization accompanying devitrification, deposition of zeolites in scoriaceous flow tops, and chemical weathering. Fractional crystallization after contamination of the magma may have adversely affected the correlation of chemical components with initial $^{87}Sr/^{86}Sr$ ratios. Nevertheless, Faure (in press) demonstrated the existence of good correlations by pooling data for Storm Peak and Mt. Falla in the Queen Alexandra Range.

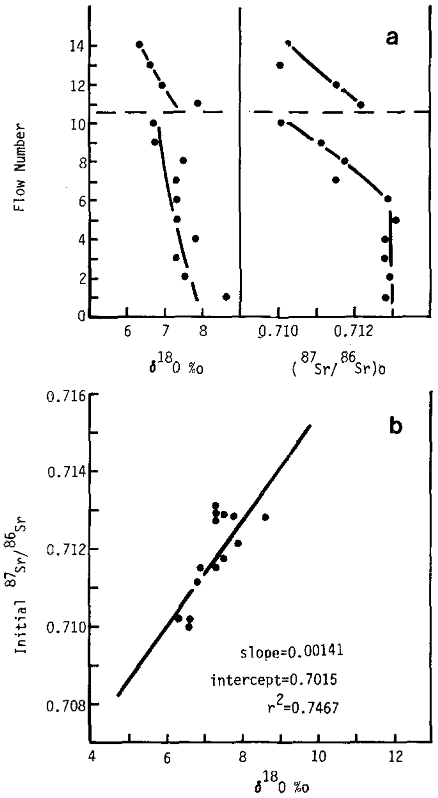

Fig. 2. **a** Schematic plot of $\delta^{18}O$ and initial $^{87}Sr/^{86}Sr$ ratios of lava flows on Mt. Falla. **b** Correlation of $\delta^{18}O$ and initial $^{87}Sr/^{86}Sr$ ratios of lava flows on Mt. Falla

The $\delta^{18}O$ and initial $^{87}Sr/^{86}Sr$ ratios were plotted diagrammatically against flow number in Fig. 2a in order to display them in stratigraphic context. Both parameters have a discontinuity between flows 10 and 11 revealed also by the major oxide components (Faure et al. 1978). The $\delta^{18}O$ values and the initial $^{87}Sr/^{86}$ ratios are positively correlated (Fig. 2b) and were regressed to a straight line:

$$\frac{^{87}Sr}{^{86}Sr} = 0.7015 + 0.00141\ \delta^{18}O\ (\mathrm{SMOW}) \tag{1}$$

with a linear correlation coefficient $r^2 = 0.7467$. Correlations with major oxide components and with Rb and Sr are summarized in Table 2.

The positive correlation of $\delta^{18}O$ and the initial $^{87}Sr/^{86}Sr$ ratios provides strong support for crustal contamination of the magma. The data fit a straight line even though the relationship between these parameters is a hyperbola when the Sr and O contents of the two end members differ. The evidence in favor of contamination of the Kirkpatrick Basalt contradicts the conclusion of Brooks and Hart (1978) that the crustal contamination hypothesis is untenable. Moreover, confirmation of crustal contamination of the Jurassic basalts of Antarctica should sound another note of caution in the use of Rb-Sr data to construct so-called "mantle isochrons" originally proposed by Brooks et al. (1976) and critically reviewed by Pankhurst (1977).

Table 2. Linear regressions of $\delta^{18}O$ with chemical and isotopic parameters, Kirkpatrick Basalt, Mt. Falla, Queen Alexandra Range

Component (y-coordinate)	Slope	Intercept	r^2	Omit
SiO_2 (%)	2.193	39.91	+0.7623	0
FeO (Total Fe%)	1.174	2.686	+0.7051	#14
MgO(%)	−1.314	13.24	−0.6899	#14
CaO^a(%)	−1.47	19.39	−	0
Na_2O+K_2O(%)	0.3339	1.170	+0.4392	#14
Al_2O_3(%)	−0.7757	19.30	−0.6609	0
Sr^b (ppm)	6.016	91.81	0.4801	0
Rb (ppm)	9.895	−17.47	0.2441	0
$(^{87}Sr/^{86}Sr)_0$	0.001412	0.70155	0.7467	0

[a] Based on data from two flows only

[b] Corrected for alteration as shown in Fig. 5B of Faure et al. (1978)

Table 3. Estimates of chemical compositions of uncontaminated magma and of the contaminant, Kirkpatrick Basalt, Mt. Falla, Queen Alexandra Range

Component	Basalt		Contaminant	
	A	B	C	D
SiO_2 (%)	52.0	51.09	66.2	68.5
FeO (total) (%)	9.1	6.9	16.8	22.4
MgO (%)	6.0	7.7	0?	0?
CaO (%)	11.28	–	1.71	–
Na_2O+K_2O (%)	3.0	2.7	5.2	6.2
Al_2O_3 (%)	15.0	16.5	10.0	5.8
Rb (ppm)	37	–	101	–
Sr^a (ppm)	125	92	164	264
$(^{87}Sr/^{86}Sr)_0$	0.7093	0.704 assumed	0.7185	0.720 assumed
$\delta^{18}O$ ($^0/_{00}$)	+5.5 assumed	+1.74	12.0 assumed	+13.1

A = Based on $\delta^{18}O = +5.5^0/_{00}$ for basalt

B = Based on $(^{87}Sr/^{86}Sr)_0 = 0.704$ for basalt (Faure et al. 1978)

C = Based on $\delta^{18}O = +12.0^0/_{00}$ for contaminant

D = Based on $(^{87}Sr/^{86}Sr)_0 = 0.720$ for contaminant (Faure et al. 1978)

[a] Corrected for alteration as shown in Fig. 5B of Faure et al. 1978)

Extrapolations of the straight lines to the typical basalt value of $\delta^{18}O = +5.5^0/_{00}$ yield estimates of the composition of the uncontaminated magma. These results are in good agreement with compositions obtained from extrapolations based on initial $^{87}Sr/^{86}Sr$ ratios (Table 3, Columns A and B) by Faure et al. (1978). The only significant exception is that Eq. (1) gives a value of 0.7093 for the initial $^{87}Sr/^{86}Sr$ ratio of the uncontaminated magma (assuming that $\delta^{18}O = +5.5^0/_{00}$) which is higher than normal for Sr derived from the mantle (Faure 1977). On the other hand, if the $^{87}Sr/^{86}Sr$ ratio is taken to be 0.7040, $\delta^{18}O$ of the magma is $+1.74^0/_{00}$, implying quite unusual depletion of the magma in ^{18}O. The data available at present do not permit an unequivocal choice among these alternatives. Igneous rocks having $\delta^{18}O$ values less than $+2^0/_{00}$ are rare at best, whereas initial $^{87}Sr/^{86}Sr$ ratios between 0.709 and 0.710 are relatively common in granitic rocks and have also been reported in volcanic rocks in continental settings and island arcs (Faure 1977). The high initial $^{87}Sr/^{86}Sr$ ratio of the basalt magma is therefore more likely to be correct than an anomalously low $\delta^{18}O$ value.

A possible explanation for the high initial $^{87}Sr/^{86}Sr$ ratio of the uncontaminated magma is that it formed by melting in the lithospheric mantle under Antarctica that was enriched in ^{87}Sr because of age, Rb enrichment, or both. Another explanation is that magma formed at the base of the continental crust composed of crystalline rocks having a somewhat higher Rb/Sr ratio than the underlying mantle. The elevated initial $^{87}Sr/^{86}Sr$ ratio of the uncontaminated basalt magma can thus be attributed either to its derivations from old lithospheric mantle, as preferred by Kyle (1980), or from the base of the crust. In either case, the enrichment of the magma in ^{18}O from $\delta^{18}O = +5.5^0/_{00}$ up to $+8.6^0/_{00}$ and its enrichment in ^{87}Sr from $^{87}Sr/^{86}Sr = 0.7093$ to 0.7131 are the result of contamination. It is possible that the magma was formed by melting both in the lithospheric mantle and the overlying crust due to decompression caused by rifting of Gondwanaland.

The chemical composition of the contaminant derived by extrapolation of Eq. (1) to $\delta^{18}O = +12.0^0/_{00}$ is compatible with estimates based on the Sr isotopic data (Table 3, columns C and D). However, the composition based on oxygen has lower FeO (16.8% vs 22.4%) and higher Al_2O_3 (10.0% vs 5.8%) concentrations. The internal consistency of $\delta^{18}O$ and the $^{87}Sr/^{86}Sr$ ratio of the contaminant is remarkably good. Equation (1) yields an $^{87}Sr/^{86}Sr$ ratio of 0.7185 for the contaminant (assuming that its $\delta^{18}O$ value was $+12.0^0/_{00}$) whereas Faure et al. (1978) assumed an $^{87}Sr/^{86}Sr$ ratio of 0.720.

The estimates of the chemical composition of the basalt magma and of the contaminant were used to determine the abundance of the contaminant in average basalt on Mt. Falla. Using the extrapolations based on oxygen (Table 3, columns A and C) for all chemical parameters yielded consistent results with a mean of 29±2% for all eight components. This value is within the range of 17.5 to 31.5% given by Faure et al. (1978) on the basis of the Sr concentrations of flows 5 and 13. The magnitude of the proportion of contaminant added to the magma is difficult to reconcile with the limited amount of superheat of a basaltic magma. Moreover, there is no evidence that a felsic magma that could have mixed with basaltic magma existed in the crust underlying the Transantarctic Mountains during the Jurassic period. Evidently, the process that caused the contamination of the basalt magma is still not understood.

Summary

The positive correlation between $\delta^{18}O$ and initial $^{87}Sr/^{86}Sr$ ratios of the flows confirms the hypothesis that the magma was contaminated with crustal material enriched in ^{18}O and radiogenic ^{87}Sr. In addition, the enrichment of the basalt in ^{18}O indicates that water of meteoric origin did not contribute to the contamination of the magma or to the subsequent alteration of the flows. Extrapolations of the linear relationships between $\delta^{18}O$ and the major chemical components yield estimates of the composition of the basalt magma ($\delta^{18}O = +5.5^0/_{00}$) and the contaminant ($\delta^{18}O = +12.0^0/_{00}$). The results are similar to those obtained by extrapolation of the initial $^{87}Sr/^{86}Sr$ ratios. The $^{87}Sr/^{86}Sr$ ratio of the magma indicated by this procedure is 0.7093 which is higher than normal for Sr of mantle origin. The basaltic magma may have formed by melting in the lithospheric mantle under Antarctica or at the base of the crust. The manner in which this magma was subsequently contaminated before extrusion is still not understood.

Acknowledgements. We are grateful to A.W. Hofmann, K.A. Foland, and P.R. Kyle for comments that helped us to improve this manuscript. The samples for this study were collected by D.H. Elliot with financial support from the National Science Foundation. This paper is Contribution No. 57 of the Laboratory for Isotope Geology and Geochemistry (Isotopia) of The Ohio State University. G. Faure was supported by the Division of Polar Programs of the National Science Foundation through Grant DPP 7721505.

References

Brooks C, Hart SR (1978) Rb-Sr mantle isochrons and variations in the chemistry of Gondwanaland's lithosphere. Nature 271:220

Brooks C, James DE, Hart SB (1976) Ancient lithosphere: Its role in young continental volcanism. Science 193:1086

Carter SR, Evensen NM, Hamilton PJ, O'Nions RL (1978) Neodymium and strontium isotope evidence for crustal contamination of continental volcanics. Science 202:743–746

Clayton RN, Mayeda TK (1963) The use of bromine pentafluoride in the extraction of oxygen from oxides and silicates for isotopic analysis. Geochim Cosmochim Acta 27:43

Compston W, McDougall I, Heier KS (1968) Geochemical comparison of the Mesozoic basaltic rocks of Antarctica, South Africa, South America and Tasmania. Geochim Cosmochim Acta 32:129–149

DePaolo DJ, Wasserburg GJ (1979) Petrogenetic mixing models and Nd-Sr isotopic patterns. Geochim Cosmochim Acta 43:615–627

Elliot DH (1972) Major oxide chemistry of the Kirkpatrick Basalt, central Transantarctic Mountains. In: RJ Adie (ed) Antarctic Geology and Geophysics Oslo Universitets forlaget, pp 413–418

Faure G Strontium isotope composition of volcanic rocks: Evidence for contamination of the Kirkpatrick Basalt, Antarctica. In: WS Fyfe (ed) Geophysical-Geochemical Evolution of the Earth (in press)

Faure G, Pace KK, Elliot DH Systematic variations of $^{87}Sr/^{86}Sr$ ratios and major element concentrations in the Kirkpatrick Basalt of Mt Falla, Queen Alexandra Range, Transantarctic Mountains. SCAR Symposium, Madison, Wisconsin, 1978. To be published in: C Craddock (ed) Antarctic Geosciences, University of Wisconsin Press

Faure G (1977) Principles of Isotope Geology. Springer Verlag, New York, 446 p

Faure G, Bowman JR, Elliot DH, Jones LM (1974) Strontium isotope composition and petrogenesis of the Kirkpatrick Basalt, Queen Alexandra Range, Antarctica. Contrib Mineral Petrol 48:153–169

Faure G, Hill RI, Jones LM, Elliot DH (1972) Isotope composition of strontium and silica content of Mesozoic basalt and dolerite from Antarctica. In: RJ Adie (ed) Antarctic Geology and Geophysics Oslo Universitets forlaget pp 617–624

Faure G, Hurley PM (1963) The isotopic composition of strontium in oceanic and continental basalts: Application to the origin of igneous rocks. J Petrol 4:31–50

Fleck RJ, Sutter JF, Elliot DH (1977) Interpretation of discordant $^{40}Ar/^{39}Ar$ age spectra of Mesozoic tholeiites from Antarctica. Geochim Cosmochim Acta 41:15–32

Hawkesworth CJ, Vollmer R (1979) Crustal contamination versus enriched mantle: $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ evidence from the Italian volcanics. Contrib Mineral Petrol 69:151–165

Kyle PR (1980) Development of heterogeneities in the subcontinental mantle: Evidence from the Ferrar Group, Antarctica. Contrib Mineral Petrol 73:89–104

McGregor VR, Wade FA (1969) Geology of the western Queen Maud Mountains. Plate XV, Sheet 16, Antarctic Map Folio Series, Folia 12, American Geographical Society, New York

Pankhurst RJ (1977) Strontium isotope evidence for mantle events in the continental lithosphere. J Geol Soc London 134:255

Taylor HP (1980) The effects of assimilation of country rocks by magmas on $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ systematics in igneous rocks. Earth Planet Sci Lett 47:243

Received September 4, 1980; Accepted October 29, 1980