

Kaersutites, suboceanic low-velocity zone, and the origin of mid-oceanic ridge basalts

ABSTRACT

The isotopic composition of Sr and the abundances of K, Rb, Sr, and Ba in seven kaersutite samples found in association with peridotite xenoliths from three different regions are reported here. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios show a narrow range of 0.7027 to 0.7030 unrelated to the host basalts but comparable to that exhibited by mid-oceanic ridge basalts. From textural and geochemical considerations, we infer that the kaersutites were introduced as hydrous magmas into the lithosphere and that they occur as accidental inclusions in alkalic basalts. We suggest that the hydrous, trace-element-rich phase in the mantle needed to explain certain trace-element characteristics as well as the water content of mid-oceanic ridge basalt is kaersutitic amphibole. We propose a model in which the low-velocity zone is considered to be the region where a small volume of hydrous melt of kaersutitic composition is produced because of the instability of amphibole in a spinel lherzolite suboceanic lithosphere. The K/Rb, Ba/Sr, and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of this melt are comparable to those of the mid-oceanic ridge basalts, but the trace-element abundances are high as found in the kaersutite samples analyzed here. We propose that during asthenospheric upwelling at the mid-oceanic ridge, liquids produced by large degrees of partial melting of the anhydrous lherzolite will mix with the kaersutitic melts of the low-velocity zone. The trace-element characteristics and the Sr-isotope composition of the mid-oceanic ridge basalts reflect this mixing process.

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INTRODUCTION

The ocean basins are characterized by two contrasting magma types—the low-K mid-oceanic ridge tholeiitic basalts and the alkalic basalts of the oceanic islands. These two basalts are delineated on the basis of major-element as well as minor-element chemistry (Engel and others, 1965; Gast, 1968). Gast (1968) showed that the minor-element geochemistry alone can be a powerful discriminant in describing these two basalts. For example, the mid-oceanic ridge basalts have very high K/Rb ratios and very low K and Rb contents compared to the alkalic basalts. The alkalic basalts, on the other hand, are enriched in light rare-earth elements (REE) relative to heavy REE. Rb- and Sr-isotope compositions of these two magma types are also different (see, for example, Sun and Hanson, 1975; Hofmann and Hart, 1975). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the mid-oceanic ridge basalts cluster in the narrow range 0.7025 to 0.7030, whereas the same ratio varies widely (usually greater than 0.7030) in the alkalic basalts of the ocean islands. These

differences are usually interpreted in terms of mantle heterogeneity (see, for example, Hofmann and Hart, 1975) in the source regions of basalts. Any model of basalt genesis must take into account the constraints listed above on trace elements and isotopic ratios imposed on the two types of basalts. Because of the difficulties of modelling trace elements into laboratory petrological investigations, however, these constraints are only now being approached by experimental petrologists.

The spinel lherzolites, most commonly found as xenoliths in alkalic basalts and as massifs in alpine-type peridotites, are widely accepted to be a major constituent of the suboceanic lithosphere (Ringwood, 1975). In the course of our investigation (Basu and Murthy, in prep.) of the trace-element abundances of the spinel lherzolite xenoliths from San Quintin in Baja California (Basu, 1975a), we discovered that the abundances of K, Rb, Sr, and Ba are so low in the silicate phases that partial melting of these materials cannot account for the lithophile trace elements of even tholeiitic basalts. The extreme depletion of

the trace elements contrasts remarkably with the relatively undepleted nature of the xenoliths as revealed by the major-element chemistry and by the very high modal abundances of diopsides. It is clear that a component rich in trace elements is missing from these lherzolites and is needed for the generation of basalts by partial melting processes in the mantle. This paper concerns the identification and the role of this component in the origin of mid-oceanic ridge basalts.

Studies by Moore (1970) and by Moore and Schilling (1973) have shown that mid-oceanic ridge basalts contain in general as much as 0.4% H_2O by weight. If these basalts are produced by 25% melting of the source material in the upper mantle (Gast, 1968), then 0.1% H_2O by weight is the upper limit of the water content in the upper mantle (Bottinga and Allegre, 1976). Experimentally determined stability curves for amphibole (Lambert and Wyllie, 1968) and phlogopite (Yoder and Kushiro, 1969; Modreski and Boettcher, 1972) are well within upper-mantle conditions. Therefore, 0.1% H_2O by weight may be contained in

these two phases, since these are the most commonly observed hydrous phases in mantle-derived rocks. Oxburgh (1964) and Griffin and Murthy (1969) have suggested amphiboles as the hydrous phase in the source regions of basalts in the upper mantle. Hart and Aldrich (1967) showed that amphiboles have much higher preference for K than Rb, resulting in high K/Rb ratios in the amphiboles.

These considerations suggest the possible role of amphibole in the source regions of mid-oceanic ridge basalt in the upper mantle. We therefore direct our attention to amphiboles in the upper mantle. This study focuses on the K, Rb, Sr, and Ba contents and on the isotopic composition of Sr in kaersutite amphiboles, often found as inclusions in alkalic basalts associated with the more abundant peridotite xenoliths.

MODE OF OCCURRENCE OF KAERSUTITE IN XENOLITH SUITES IN ALKALIC BASALTS

The aluminous amphibole kaersutite commonly has four modes of occurrence in xenoliths in alkalic basalts (Best, 1974): as veins and as interstitial grains in spinel lherzolite xenoliths, as poikilitic grains in cumulate peridotite xenoliths, and as single megacrysts. Of the seven samples analyzed in this study (Table 1), five are single megacrysts (three from Dish Hill, California; one from San Carlos, Arizona; and one from Kakanui, New Zealand), one is part of a transecting vein in a peridotite xenolith in Dish Hill, California (Wilshire and Trask, 1971), and the last one is part of a hornblende eclogite xenolith in the Kakanui breccia pipe, New Zealand (Mason, 1968a).

Textural relations of the kaersutites in Dish Hill, California (Wilshire and Trask, 1971), indicate that these minerals were

added to the peridotite as veins after the peridotite had consolidated and undergone plastic deformation. The kaersutite megacrysts, according to Wilshire and Trask, are disaggregated parts of the vein in the peridotite. Studies of textural and structural relations of the kaersutite veins in peridotite xenoliths in alkalic basalts from other localities (Best, 1974) also support the view that the kaersutites are introduced as hydrous liquids into the overlying mantle from below. Frey and Green (1974) have also suggested, on the basis of trace-element data, a model in which a hydrous liquid originating at the low-velocity zone penetrates overlying peridotite in the upper mantle.

ANALYTICAL DATA AND DISCUSSION

The elemental abundances of K, Rb, Sr, and Ba and the isotopic composition of Sr of seven kaersutite samples from three different regions (Dish Hill, California; San Carlos, Arizona; and Kakanui, New Zealand) are given in Table 1. The data also include one alkalic basalt, the host rock for the four kaersutites in Dish Hill, California. The analyses were carried out on a 30-cm-radius single-focusing mass spectrometer, with on-line data reduction and magnetic field switching capabilities using a minicomputer-based system. Operational procedures are given in Murthy and others (1971). Data on the major-element chemistry of the samples are provided in the literature; for San Carlos and Kakanui samples, see Mason (1968a, 1968b), and for Dish Hill samples see Wilshire and others (1971). Mason and Allen (1973) also provided data on trace elements, including the rare earths, on the Kakanui kaersutite megacryst.

The trace-element data in Table 1 are

comparable to other published analyses (Kesson and Price, 1972). The K/Rb ratio varies between 1140 and 2800, with an average of 1660 for the seven samples. Rb is low, between 4 and 16 ppm, whereas Sr ranges from 463 to 770 ppm. The resulting Rb/Sr ratio is low for all the kaersutites. The Ba/Sr ratio is also low, varying between 0.28 and 0.48, except for the eclogitic kaersutite, which is 0.79. The REE data (Mason and Allen, 1973) of the Kakanui megacryst show a moderate enrichment in the light REE, consistent with measurements (Kesson and Price, 1972) on other kaersutites.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the kaersutites show a remarkably constant composition despite the widely separated geographic distribution of the samples. Six of the seven analyses show a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio between 0.7027 and 0.7029; the Kakanui eclogitic kaersutite shows a slightly higher value, 0.7030. The low $^{87}\text{Sr}/^{86}\text{Sr}$, high K/Rb, and low Ba/Sr ratios of the kaersutites are also characteristics of the mid-oceanic ridge tholeiitic basalts. From the data presented in Table 1 we infer the following petrogenetic history of the kaersutites.

1. The kaersutites are *not* related to their host alkalic basalts. This conclusion is demonstrably correct, at least for the Dish Hill samples, where the host basanite has a distinctly different and much higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratio than the kaersutites. This relationship may also hold for the Kakanui and the San Carlos samples, where we have no Sr-isotope data for the host basalts; the fact that the great majority of the alkalic basalts have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios greater than 0.7030 allows us to draw this conclusion.

2. For the Dish Hill samples, the vein kaersutite (Ba 1-72) has the same $^{87}\text{Sr}/^{86}\text{Sr}$ ratio as the megacrysts. This observation suggests that the megacrysts are indeed broken fragments from the veins of the peridotites, supporting the observation of Wilshire and Trask (1971).

3. The Kakanui eclogitic kaersutite has the highest $^{87}\text{Sr}/^{86}\text{Sr}$ and Ba/Sr ratios of all the kaersutites. The bulk-rock chemistry of this kaersutite-bearing eclogitic xenolith is equivalent to an olivine basanite composition. Experimental data of Merrill and Wyllie (1975) was consistent with a proposal that this kaersutite eclogite formed by the crystallization of a hydrous alkali basalt magma in deep-seated pockets within a lherzolitic mantle. The trace-element and Sr-isotope data of the kaersutite are compatible with such an origin for the kaersutite eclogite.

4. It is also consistent, from points 1

TABLE 1. ABUNDANCES OF K, Rb, Sr, Ba, AND Sr ISOTOPE COMPOSITION OF KAERSUTITE AND HOST BASALT

Sample	K (%)	Rb (ppm)	Sr (ppm)	Ba (ppm)	K/Rb	Ba/Sr	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}^*$
<i>Dish Hill</i>								
H-9	1.500	9.23	511.8	228.1	1624	0.45	0.05216	0.70288
H-13	2.201	11.23	487.9	137.1	1798	0.28	0.06664	0.70273
H-19	2.102	13.04	769.4	366.5	1612	0.48	0.04898	0.70266
Ba 1-72 (vein kaersutite)	1.279	9.56	601.6	243.1	1337	0.40	0.04597	0.70269
Ba 1-101 (host alkalic basalt)	2.131	51.56	978.6	..	413	..	0.15232	0.70379
<i>San Carlos</i>								
Megacryst	1.263	4.48	711.4	243.4	2817	0.34	0.01821	0.70271
<i>Kakanui</i>								
Megacryst	1.856	16.26	463.3	165.4	1142	0.36	0.10146	0.70290
Eclogitic kaersutite (K-14)	1.031	7.88	487.7	387.3	1307	0.79	0.04673	0.70304

Note: Elemental abundances $\pm 2\%$.

*Errors for isotope composition are (2 σ) mean and are ± 0.00005 for all samples except H-9, which has an error of ± 0.00006 .

and 2 above, that hydrous liquids similar in composition to the kaersutites intruded and consolidated as veins in the lithospheric peridotites under ambient upper-mantle conditions, and *before* the accidental incorporation of the peridotites in alkalic basalt magma generated from a different source region in the upper mantle. The hydrous liquid may be compositionally equivalent to an olivine nephelinite, having low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of ≈ 0.7027 , high K/Rb ratios of >1000 , and low Ba/Sr ratios of ≈ 0.3 . We propose in the following section that this liquid is derived from the seismic low-velocity zone and is, in fact, identical or close in composition to the liquid of the partially molten low-velocity zone.

MODEL FOR SUBOCEANIC LOW-VELOCITY ZONE AND ORIGIN OF MID-OCEANIC RIDGE BASALT

It is now widely believed that the oceanic lithosphere is created at the mid-oceanic ridge, spreads laterally away from the ridge, and, as it spreads, becomes thicker with age. Thus the depth to the low-velocity zone increases away from the ridge axis. The top of the low-velocity zone, usually equated with the top of the asthenosphere, has been interpreted to mark the beginning of melting of the mantle peridotite either in the presence of a small amount of a free-vapor phase (Kushiro and others, 1968) or through melting of a vapor-absent hornblende-bearing assemblage (Lambert and Wyllie, 1968). At the mid-oceanic ridge crest the suboceanic asthenosphere is exposed, erupting vast quantities of mid-oceanic ridge basalt.

We propose here a model (Fig. 1) in which kaersutitic amphibole is stable in a spinel lherzolite assemblage under suboceanic lithosphere conditions. Instability of this amphibole will cause a small degree of partial melting at the low-velocity zone, as suggested by Lambert and Wyllie (1968). The composition of this melt is silica undersaturated and close to olivine nephelinite in composition, as indicated by experimental melting studies of mantle peridotites in the presence of $\text{H}_2\text{O}-\text{CO}_2$ vapors (Mysen and Boettcher, 1975). Injection of this liquid upward into the lithospheric lherzolite will cause the commonly observed veins of kaersutite in peridotite as found in xenoliths. With the exception of the occasional incursions of this liquid into the overlying solid mantle, this liquid will remain dispersed throughout the low-velocity zone. The amount of this melt is considered to be small, on the order of

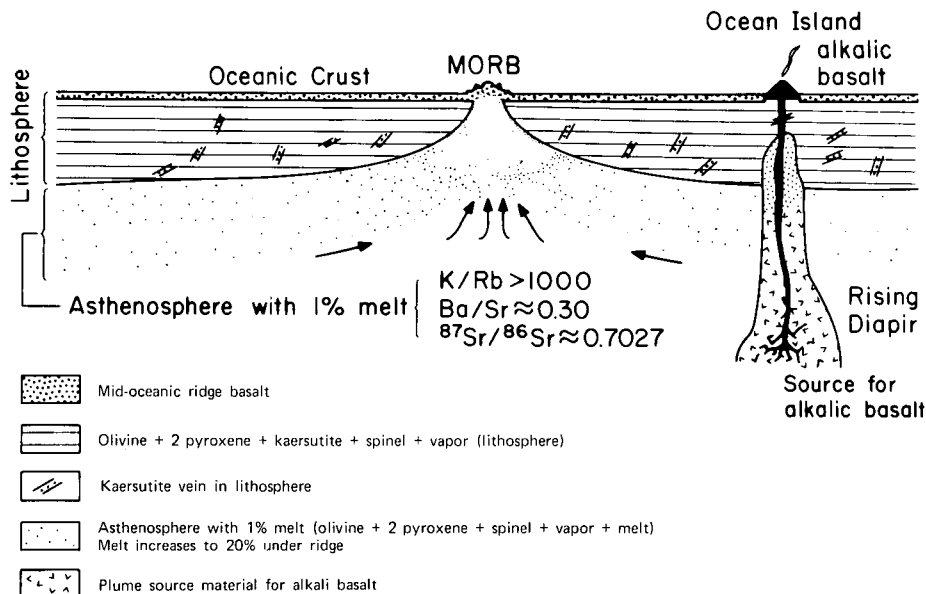


Figure 1. Diagrammatic representation of petrologic model of suboceanic lithosphere and asthenosphere with kaersutite as stable hydrous phase in lithosphere. MORB = mid-oceanic ridge basalt.

1% (see, for example, Solomon, 1976). It is well known from various experimental studies (such as Wyllie, 1971) that in the melting of a hydrous peridotite containing hornblende, the amount of liquid produced remains small over quite a large pressure-temperature variation above the solidus; the melt fraction will be larger ($>10\%$) only near the dry solidus of peridotite. Conditions for the large degree of melting are restricted to regions of asthenospheric upwelling beneath the mid-oceanic ridge (Langseth and others, 1966). During this upwelling, the pre-existing silica-undersaturated melt (kaersutitic composition) will be mixed with liquids produced by further melting of already-depleted spinel lherzolite, resulting in liquids of low-K mid-oceanic ridge basalt composition. The basalt produced in this way will have essentially the same $^{87}\text{Sr}/^{86}\text{Sr}$, K/Rb, and Ba/Sr ratios as our measured kaersutites, but the absolute abundances of these elements will be greatly reduced in the mid-oceanic ridge basalt because of the dilution factor and because the anhydrous phases of the spinel lherzolites have extremely low abundances of these elements (Basu and Murthy, in prep.).

The remarkable uniformity of mid-oceanic ridge basalt composition in both major- and minor-element chemistry, as well as in the restricted range of Sr-isotope composition, from throughout the world's ocean basins is noteworthy. We believe that two factors are responsible for the uniform composition of mid-oceanic ridge basalt. The melt in the low-velocity zone

will be well mixed because of convection. Melts produced by large degrees of partial melting of the anhydrous spinel lherzolite will also tend to have uniform compositions; the difference between a 25% melt and a 30% melt in terms of their compositions is trivial. Thus, mixtures of partial melts of anhydrous spinel lherzolite and the kaersutitic melts of the low-velocity zone will also have a restricted range in composition, provided that mixing ratios do not vary widely.

From the Rb/Sr and Sr-isotope data in Table 1, we suggest that the kaersutite samples studied here have on average not existed as closed systems for more than about 300 m.y. Otherwise their Sr-isotope composition would have grown beyond the range exhibited by mid-oceanic ridge basalt. If the identification of these amphiboles with the liquid in the low-velocity zone as proposed here is correct, the residence time of this liquid in the low-velocity zone should also be of the same magnitude.

The silica-undersaturated melt in the low-velocity zone in our model does not bear any relationship to the alkalic basalts of the oceanic islands (Fig. 1). The sources for the latter are presumably elsewhere in the mantle or may be related to mantle plumes (Schilling, 1973; Basu, 1975b). Of course, mantle plumes rising through the top of the low-velocity zone will mix with the silica-undersaturated melt of kaersutitic composition in our model. The consequences of this mixing, however, are not explored here.

There is now a consensus that both H_2O

and CO_2 exist in the mantle. Recent experimental studies show that CO_2 is almost as effective as H_2O in lowering the solidus of peridotite (Wyllie and Huang, 1975; Eggler, 1976) and leads to melting at depths below 100 km, the approximate depth to the sub-oceanic low-velocity zone. The melt composition is controlled by the $\text{H}_2\text{O}/\text{CO}_2$ ratio in the vapor phase (Mysen and Boettcher, 1975; Eggler, 1975; Brey and Green, 1975). For low contents of H_2O and CO_2 and for a wide range of $\text{H}_2\text{O}/\text{CO}_2$ ratios, the melt resembles olivine-nephelinite in composition, and in our model, it is equated with the kaersutitic melt in the low-velocity zone. There appears to be nothing in the published experimental data cited above to contradict our suggestion that the melt in the low-velocity zone is kaersutitic in composition. We conclude that basaltic liquids generated at the mid-oceanic ridge are mixtures of melts of anhydrous lherzolite and the kaersutitic melt in the low-velocity zone.

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