MANTLE METASOMATISM AS A PRECURSOR 
TO THE GENESIS OF ALKALINE MAGMAS 
— ISOTOPIC EVIDENCE*

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Dedication
To Dale, a friend and colleague who contributed greatly to our knowledge of ultramafic rocks.

ABSTRACT. Metasomatized mantle lherzolites occur as nodules in alkali basalt flows on Nunivak Island, Alaska, and at Ataq, South Yemen. Pargasites separated from the Nunivak peridotites have a range in $^{87}$Sr/$^{86}$Sr = 0.70270 to 0.70337, identical to that of the enclosing basalts ($^{87}$Sr/$^{86}$Sr = 0.70251 to 0.70322). Similarly pargasites in nodules from Ataq have a range in $^{87}$Sr/$^{86}$Sr = 0.70344 to 0.70408, indistinguishable from the associated alkali basalts ($^{87}$Sr/$^{86}$Sr = 0.70353-0.70426). It is proposed that mantle metasomatism, or the introduction of a K,REE,P-rich component, is a precursor to the genesis of alkaline magmas. Pervasive enrichment events, of which amphibole is a remnant, locally scavenge and deposit incompatible elements during upward migration in the mantle. Metasomatic or enrichment events are shown to be isotopically variable within and between the volcanic centers at Nunivak and Ataq, where metasomatism is thought to be associated with localized mantle degassing and diapirism. The addition of incompatible elements prior to the melting event eliminates the need for low degrees (<1 percent) of melting in the production of alkaline magmas. Larger degrees of melting (5-20 percent) can be accommodated after 10 percent contamination of the dry mantle by metasomatic fluids.

INTRODUCTION
Recent hypotheses for the origin of alkaline magmas (Kay, 1977; Carter and others, 1978) have invoked mantle “enrichment events” prior to, or synchronous with, the eruption of alkaline magmas. Such events enhance the trace element, particularly the LIL element, content of the source region. Petrographic studies of hydrous spinel and garnet lherzolites from sub-oceanic and sub-continental mantle provide evidence for such localized enrichment, contamination, or metasomatic events. This infiltration of alkal-rich fluids or mantle metasomatism, is defined as the introduction of K, REE, P etcetera as an intergranular component or as hydrous phases. Commonly these migratory fluids radically change the chemical and mineralogical constitution of the anhydrous mantle producing modified mantle sometimes termed alkali peridotite. Prior to metasomatism the mantle lherzolites are essentially anhydrous with a major and minor element chemistry compatible with that of “pyrolite” (Ringwood, 1975). Such “dry” peridotites, however, lack sufficient quantities of trace elements vital for the production of alkaline and tholeiitic magmas.

In an attempt to define the isotopic relationship between introduced components and alkaline magmas in the sub-oceanic and sub-continental lithosphere, amphibole lherzolites and the enclosing basalts have been analyzed for K, Rb, and Sr contents and $^{87}$Sr/$^{86}$Sr isotopic ratios. The

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same samples have also been analyzed for Sm, Nd contents, and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (Menzies and Murthy, 1979).

**ANALYTICAL DATA**

*Sample description.*—Lherzolites and alkali basalts were analyzed from Nunivak Island, Alaska and Kirsh volcano, Ataq, South Yemen (Francis, 1976; Varne, 1970; Varne and Graham, 1971). A kaersutite megacryst from Nunivak Island was also analyzed.

Nunivak Island is a Tertiary to Recent volcanic center located behind the Aleutian Arc on the Bering Sea shelf (possibly continental crust). Alkaline basalts constitute 2 percent of the volcanic rocks and contain abundant xenoliths (Hoare and others, 1968; Mark, ms). Pargasite is found in less than 1 percent of the nodules (Francis, 1976) due to its unstable nature in the presence of the basanitic magma. Fifty percent, however, contain diopside, olivine, and spinel in a porous Al-rich glass believed to be a relic of amphibole. Pargasite was separated from spinel peridotite and pyroxenitic nodules containing variable amounts of olivine, orthopyroxene, Cr diopside, and spinel.

The Kirsh volcano, South Yemen, is located within the Shuqra volcanic field 125 km northeast of Aden (Gass, Mallick, and Cox, 1965). Olivine basalt flows contain a variety of foliated peridotite nodules composed mainly of olivine with lesser amounts of orthopyroxene, clinopyroxene, and pargasitic amphibole. The pargasite occurs in intimate association with diopside and spinel somewhat similar to the Nunivak samples.

*Analytical techniques.*—The techniques used are essentially those described by Murthy and others (1971). Minerals were separated from each lherzolite (or megacryst) by hand picking under a binocular microscope. Amphiboles were chosen, where possible, for their clearness and lack of inclusions. Adhering particles or minerals were mechanically removed and the final mineral separates were acid washed in 2N HCl, washed in acetone in an ultra-sonic bath, and crushed in a boron-carbide mortar. Chips of basalt (and nodules) were washed in 2N HCl and crushed in a boron carbide mortar. The final chips used for analysis were handpicked under a binocular microscope and crushed in a boron carbide mortar.

All other sample handling procedures were carried out in an ultraclean laboratory, using quartz and teflon ware. Samples were processed under a positive pressure of dry filtered nitrogen in teflon hoods. After digestion in HF and HClO₄, the samples were refluxed in HCl to bring them into solution. Chemical separations were carried out using standard cation exchange methods.

Errors in our isotope dilution data arise principally from uncertainty in measuring amounts of the individual spikes and from isotopic fractionation during the mass spectrometry. These may show deviations of as much as 1 percent. Therefore, except where noted, conservative esti-
mates of errors of 3 percent are assigned to element abundance values and \(^{87}\text{Rb}^{86}\text{Sr}\) ratios.

Blank levels for total analytical procedures are \(K = 20\text{ ng}\), \(Rb = 0.1\text{ ng}\), and \(Sr = 1.0\text{ ng}\).

All analyses were performed on a 30.5 cm single-focusing spectrometer using the data acquisition system described by Murthy and others. (1971). In no case do we assign 2\(\sigma\) errors less than 0.00005 to a particular run, as it is considered the practical limit of precision and long-term reproducibility of our system, as determined by periodic measurements of isotopic standards over the last several years. Since August 1, 1972, 31 periodic measurements of the isotopic standard NBS SrCO\(_3\) no. 987 define a normally distributed value of \(0.71018\pm0.00005\) (2\(\sigma\)).

**Analytical data.**—K, Rb, and Sr contents and \(^{87}\text{Sr}^{86}\text{Sr}\) isotopic ratios for the hydrous minerals and enclosing basalts are given in table 1 and figures 1 and 2. The basalt data represent a summary of unpublished data. The pargasites exhibit a considerable range in K/Rb ratio (336-9058); those separated from the Nunivak rocks (K/Rb = 1203-3058) have consistently higher K/Rb ratios than those from Ataq (K/Rb = 336-475). The Sr content of the Nunivak pargasites (600-806 ppm) is similar to the range reported elsewhere for amphiboles (Basu, 1978). However, the Ataq pargasites are enriched in Sr by a factor of two (Sr = 1128-1434

### Table 1

**K, Rb, and Sr contents and \(^{87}\text{Sr}^{86}\text{Sr}\) ratios in hydrous minerals from amphibole lherzolites and host alkali magmas**

<table>
<thead>
<tr>
<th>(A) Hydrous minerals from xenoliths</th>
<th>K (ppm)</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>Rb/Sr</th>
<th>K/Rb</th>
<th>(^{87}\text{Sr}^{86}\text{Sr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nunivak, Island, Alaska 10050 (UM1) pargasite</td>
<td>5260</td>
<td>4.37</td>
<td>805.9</td>
<td>0.016</td>
<td>1203</td>
<td>0.79337 ± 8</td>
</tr>
<tr>
<td>Nunivak, Island, Alaska 13008 pargasite</td>
<td>11285</td>
<td>3.69</td>
<td>599.6</td>
<td>0.017</td>
<td>3058</td>
<td>0.70304 ± 5</td>
</tr>
<tr>
<td>Nunivak, Island, Alaska 13002 pargasite</td>
<td>12868</td>
<td>4.54</td>
<td>621.6</td>
<td>0.020</td>
<td>2821</td>
<td>0.70270 ± 9</td>
</tr>
<tr>
<td>Nunivak, Island, Alaska 10051 mica</td>
<td>55793</td>
<td>155.2</td>
<td>199.2</td>
<td>2.252</td>
<td>359</td>
<td>0.70256 ± 10</td>
</tr>
<tr>
<td>Ataq, south Yemen AT15 pargasite</td>
<td>4957</td>
<td>10.49</td>
<td>1401.3</td>
<td>0.020</td>
<td>472</td>
<td>0.70408 ± 8</td>
</tr>
<tr>
<td>Ataq, south Yemen AT20 pargasite</td>
<td>4003</td>
<td>8.41</td>
<td>1434.4</td>
<td>0.014</td>
<td>475</td>
<td>0.70374 ± 11</td>
</tr>
<tr>
<td>Ataq, south Yemen AT22 pargasite</td>
<td>3356</td>
<td>9.98</td>
<td>1128.3</td>
<td>0.026</td>
<td>336</td>
<td>0.70344 ± 6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(B) Megacryst</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nunivak, Island, Alaska 13003 kaersuite</td>
<td>15978</td>
<td>6.07</td>
<td>463.9</td>
<td>0.038</td>
<td>2632</td>
<td>0.70314 ± 11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(C) Enclosing lavas</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nunivak, Island, Alaska</td>
<td>19822</td>
<td>36.40</td>
<td>847.7</td>
<td>0.121</td>
<td>535</td>
<td>0.70251 ± 5</td>
</tr>
<tr>
<td>Nunivak, Island, Alaska</td>
<td>970</td>
<td>9.70</td>
<td>592</td>
<td>0.099</td>
<td>—</td>
<td>0.70322 ± 7</td>
</tr>
<tr>
<td>Ataq, south Yemen</td>
<td>7861</td>
<td>15.11</td>
<td>1454.8</td>
<td>0.029</td>
<td>520</td>
<td>0.70333 ± 5</td>
</tr>
<tr>
<td>Ataq, south Yemen</td>
<td>10253</td>
<td>41.05</td>
<td>171.63</td>
<td>0.682</td>
<td>249</td>
<td>0.70426 ± 12</td>
</tr>
</tbody>
</table>
Mantle metasomatism as precursor to the genesis of alkaline magmas

ppm). A kaersutite megacryst from Nunivak is more radiogenic than the majority of megacrysts analyzed previously (Basu, 1978), but the relative abundance data for K, Rb, and Sr are compatible with those previously published by Basu and Murthy (1977a) and Basu (1978).

The analyzed basalts from Nunivak are alkali basalts with a range in $^{87}$Sr/$^{86}$Sr = 0.70251 to 0.70322 (Mark, ms; Menzies, unpub. data) and high K, Rb, and Sr contents (table 1). The Ataq lavas are more radiogenic having a range in $^{87}$Sr/$^{86}$Sr = 0.70353 to 0.70426. These alkali basalts show K $>$ 7100 ppm, Rb $>$ 15.11 ppm, and Sr $>$ 1420 ppm. It is interesting to notice that the Sr contents of the alkali basalts and amphiboles are very similar. The Nunivak amphiboles average 622 ppm Sr compared with an average of 725 ppm for 27 basalts. The Ataq amphiboles are richer in strontium, averaging 1321 ppm compared with 1491 ppm for 8 basalt analyses.

**Discussion**

*Anatexis of anhydrous mantle.*—Some modern concepts of magma genesis are based primarily on the premise that anhydrous spinel and garnet peridotites, which constitute the sub-oceanic and sub-continental mantle, are fertile in all aspects of their chemistry and as such represent pristine mantle (Rugwood, 1975). Exhaustive studies show that the major and minor element content of anhydrous lherzolite nodules (see Maaaløe and Aoki, 1977 for references and summary) are consistent with such an hypothesis. However, sub-oceanic and sub-continental mantle is deficient in some lithophile elements needed for the production of basaltic and alkaline magmas (table 2) (Griffin and Murthy, 1969; Stueber

![Diagram](image)

Fig. 1. Sr isotopic composition of hydrous minerals as representatives of mantle metasomatic events, at Nunivak, Alaska, and Ataq, South Yemen, relative to host alkaline magmatism. Nunivak basalt data includes that of Mark (ms), South Arabian Coast data (Dickinson and others, 1969) is included [dark shading] on the Ataq figure.
and Ikramuddin, 1974; Dasch and Green, 1975; Burwell, 1975; Menzies and Murthy, 1978a). Despite the compatibility of lherzolite major-minor element chemistry with undepleted mantle models (Ringwood, 1975; Maaløe and Aoki, 1977), a simple calculation of K, Rb, and Sr abundances of typical lherzolite nodules (table 2) indicates the very low relative abundances of these elements (K = 5.3-26.3, Rb = 0.01-0.09, and Sr = 1.4-15.7). The K, Rb, and Sr content of anhydrous mantle was calculated using published mineral analyses (Dasch and Green, 1975; Basu and Murthy, 1977a; Menzies and Murthy, 1978a) and a modal abundance of olivine:diopside:enstatite = 75:10:15. The compositions of liquids produced during anatexis (table 3) were calculated using the equations of Shaw (1970) and the partition coefficients of Shimizu (1974) and C. J. Allegre (personal commun., 1978). For each individual anhydrous lherzolite the change in the K, Rb, and Sr content of liquids (5-30 percent; anatexis) was calculated and is shown in figures 3 and 4. The marked decrease in the K, Rb, and Sr content of the liquids with increased melting is due to the involvement of olivine ± orthopyroxene in the melting event. Such minerals have very low abundances of K, Rb, and Sr, and consequently the K, Rb, and Sr content of the liquid decreases due to a dilution effect. The inability of these lherzolites to produce natural basalts is apparent when one compares the K, Rb, and Sr content of the partial melts with that of tholeiitic and alkaline magmas (figs. 3 and 4). Anhydrous lherzolites from Baja California (Basu and Murthy, 1977b), Lanzo, Beni Bouchera (Menzies and Murthy, 1978a), and Victoria, Australia (Dasch and Green, 1975) are so devoid of trace elements that < 5 percent melting is needed to generate liquids with a

![Diagram](https://example.com/diagram.png)

Fig. 2. Isotopic composition of hydrous mantle minerals (representing enrichment events) and associated alkaline and tholeiitic magmas. Note the Sr isotopic discrepancy between the majority of kaersutite megacrysts and host alkaline magmas. Comparative basalt data is after Hofmann and Hart (1977) and kaersutite-host data is after Stuckless and Erickson (1976), Stuckless and Irving (1976), Basu and Murthy (1977a), Basu (1978), and Menzies and Murthy (unpub. data on amphiboles from Antarctica, Arizona, and Utah).
K, Rb, and Sr content similar to mid-ocean ridge basalts. Melting in excess of 10 percent as is commonly proposed for the genesis of ocean ridge tholeiites may well produce liquids similar in REE abundance to ridge tholeiites (Schilling, 1975), but these liquids are severely depleted in K, Rb, and Sr. As such they have no terrestrial equivalent. It appears from this apparent contradiction in the major and trace element contents of some lherzolites that the behavior of LIL elements is decoupled, during anatexis, from that of the major and minor elements. Consequently the production of tholeiitic and alkaline magmas may require the infiltration of LIL elements along preexisting grain boundaries or fractures prior to, or synchronous with, magmas genesis.

_Petrographic evidence for mantle metasomatism._—Griffin (1973) and Francis (1976) have described amphibole-bearing lherzolites from the Fen alkaline complex, Norway and Nunivak Island, Alaska.

Francis (1976) demonstrated that the formation of the pargasite predates the incorporation of the nodule in the basanite. Pargasite is observed to be unstable in the presence of the basanite and is replaced by olivine + diopside + spinel in an Al-rich glass. This is compatible with experimental data (Stewart, Boettcher, and Eggler, 1979) on the stability of pargasite. At temperatures similar to that of the host magma (≥1025°C) pargasite reacts and forms olivine + diopside + liquid. This adequately explains the lack of mantle amphibole in most of the Nunivak and Ataq nodules. Furthermore, Francis (1976) concluded that the mantle amphibole formed by secondary processes involving a reaction between spinel and introduced alkali-rich fluids.

This replacement hypothesis is compatible with the mantling of spinel by amphibole, the increase in the Cr content of the amphibole

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**Table 2**

K, Rb, and Sr abundances in anhydrous and hydrous mantle. This data is used for the calculations shown in figures 3 and 4 and table 3

<table>
<thead>
<tr>
<th></th>
<th>K (ppm)</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(A) Anhydrous</strong> mantle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Victoria, Australia***</td>
<td>—</td>
<td>0.99</td>
<td>5.095</td>
</tr>
<tr>
<td>Baja California††</td>
<td>26.31</td>
<td>0.40</td>
<td>1.469</td>
</tr>
<tr>
<td>Beni Bouchera††</td>
<td>5.39</td>
<td>.010</td>
<td>15.742</td>
</tr>
<tr>
<td><strong>(B) Hydrous</strong> mantle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nunivak</td>
<td>286.4-547</td>
<td>0.254-0.47</td>
<td>49.71-90.0</td>
</tr>
<tr>
<td>Ataq I</td>
<td>227.70-425</td>
<td>0.463-0.88</td>
<td>126.28-197.0</td>
</tr>
<tr>
<td>Ataq II</td>
<td>181.12-356</td>
<td>0.536-1.0</td>
<td>71.95-128</td>
</tr>
<tr>
<td>Hydrous mantle range =</td>
<td>181-547</td>
<td>0.25-1.0</td>
<td>49.7-197.0</td>
</tr>
<tr>
<td>Anhydrous mantle range =</td>
<td>5.3-26.3</td>
<td>0.01-0.09</td>
<td>1.4-15.7</td>
</tr>
</tbody>
</table>

* Anhydrous mantle calculated using a lherzolite mode of olivine: clinopyroxene: enstatite of 75:10:15.


*** Dasch and Green, 1975
† Basu and Murthy, 1975
†† Menzies and Murthy, 1978a
adjacent to included spinel grains, and the embayed character of the spinel inclusions in amphibole (Francis, 1976). Best (1974) similarly interprets paragases in lherzolites from the Grand Canyon, Ariz. to be formed by the reaction of a fluid with spinel and diopside. Wilshire and others (1980) invoke migration of Fe-rich fluids into the lherzolitic mantle to account for the observed chemical variations in kaersutite and paragase veins. Their model allows kaersutite and paragase to be produced by a single event due to a continued change in the composition of the migrating fluid resulting from wall-rock reaction. This model is presently being tested using isotopic techniques. The existence of amphibole, mica, apatite, et cetera in mantle peridotites (for example Wilshire,

**Table 5**

K, Rb, and Sr abundances in partial melts generated by anatexis of anhydrous and hydrous mantle

<table>
<thead>
<tr>
<th>Sample</th>
<th>Degree Melting</th>
<th>K</th>
<th>Rb</th>
<th>Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydrous mantle*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lanzo, Italy</td>
<td>5</td>
<td>194</td>
<td>0.73</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>65</td>
<td>0.24</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>39</td>
<td>0.15</td>
<td>7</td>
</tr>
<tr>
<td>Beni Bouchera, Morocco</td>
<td>5</td>
<td>99</td>
<td>0.25</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>33</td>
<td>0.09</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>20</td>
<td>0.05</td>
<td>61</td>
</tr>
<tr>
<td>Victoria, Australia</td>
<td>5</td>
<td>—</td>
<td>1.05</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>—</td>
<td>0.78</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>—</td>
<td>0.47</td>
<td>22</td>
</tr>
<tr>
<td>San Quintin, Baja</td>
<td>5</td>
<td>569</td>
<td>0.82</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>190</td>
<td>0.27</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>114</td>
<td>0.16</td>
<td>6</td>
</tr>
<tr>
<td>Range anhydrous mantle</td>
<td>5-25</td>
<td>20-569</td>
<td>0.05-2.3</td>
<td>6-264</td>
</tr>
<tr>
<td>Hydrous mantle**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nunivak, Alaska</td>
<td>5</td>
<td>4089-7814</td>
<td>4.2 - 7.9</td>
<td>768-1389</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1705-3259</td>
<td>1.6 - 2.9</td>
<td>304-551</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1077-2059</td>
<td>0.9 - 1.8</td>
<td>190-343</td>
</tr>
<tr>
<td>Ataq, I, S. Yemen</td>
<td>5</td>
<td>3250-6076</td>
<td>7.8 - 14.8</td>
<td>1951-3087</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1355-2534</td>
<td>7.5 - 11.8</td>
<td>773-1212</td>
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<td>25</td>
<td>856-1601</td>
<td>7.8 - 11.8</td>
<td>482-756</td>
</tr>
<tr>
<td>Ataq II, south Yemen</td>
<td>5</td>
<td>2778-5098</td>
<td>9.0 - 17.4</td>
<td>111-1986</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1138-2124</td>
<td>3.4 - 6.5</td>
<td>440-786</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>718-1341</td>
<td>1.7 - 3.3</td>
<td>275-412</td>
</tr>
<tr>
<td>Range anhydrous mantle melts</td>
<td></td>
<td>20-509</td>
<td>0.05 - 2.3</td>
<td>275-412</td>
</tr>
<tr>
<td>Range hydrous mantle melts</td>
<td></td>
<td>715-7814</td>
<td>0.9 - 17.4</td>
<td>190-3057</td>
</tr>
<tr>
<td>Alkali basalts***</td>
<td></td>
<td>6700-15390</td>
<td>5 - 35</td>
<td>660-950</td>
</tr>
<tr>
<td>Ridge tholeiites†</td>
<td></td>
<td>500-2060</td>
<td>0.7 - 3.0</td>
<td>131-400</td>
</tr>
</tbody>
</table>

* Anhydrous mantle calculated from a modal mixture of 10 percent Cpx, 25 percent Opx and 65 percent Olv. K<sub>d</sub> values after Shimizu (1974) and C. J. Allegre (1978, personal commun.). Peridotite data from Table 2.

** Hydrous mantle calculated from modal mixtures of 5 percent paragase, 5 percent Cpx, 15 percent Opx, 65 percent Olv, and 10 percent paragase; 5 percent Cpx, 10 percent Opx, and 65 percent Olv. The range in K, Rb, and Sr relative abundance data reflects this difference in modal mineralogy, for example, K (Nunivak) at 5 percent melting has a range of 4089 (5 percent paragase in source) to 7814 (10 percent paragase in source).

*** After Kay and Hubbard (1978) and Kay (1977).

† After Hofmann and Hart (1978) and Kay and Hubbard (1978).
Calk, and Schwarzmann, 1971; Wilshire and Trask, 1971; Lloyd and Bailey, 1975) suggests that pervasive metasomatic events affected the peridotites and by a series of complex reactions modified the original mineralogy. These enrichment episodes predate entrainment of the peridotite in the basalt (Wilshire and Trask, 1971) or the kimberlite (Erlank and Rickard, 1977).

**Chemical evidence for mantle metasomatism.**—The importance of exotic mineral species within mantle source regions was recently demonstrated by Beswick and Carmichael (1978). Examination of published REE and trace element analyses of several hundred mafic lavas revealed a positive correlation between $P_2O_5$ content and Ce/Yb or Sm/Nd ratios. Similarly, Frey, Green, and Roy (1978) reported a further correlation of $P_2O_5$ and Sr, Ba, Zr, Hf, Th, and U in volcanic rocks from Australia. The correlation reported by these authors strongly suggests the presence of apatite (a phase known to be introduced by mantle metasomatism) in the mantle source region, where it can provide an important source for $P_2O_5$, REE, et cetera.

Trace element and isotopic studies of anhydrous mantle peridotites further suggest the presence of exotic minerals or intergranular components enriched in labile elements (for example, Frey and Green, 1974; Dasch and Green, 1975; Menzies, 1976; Basu and Murthy, 1977b; Menzies and Murthy, 1978a).

![Diagram](image-url)

Fig. 3. K and Rb content of hypothetical melts produced by anatexis of hydrous mantle (10 percent metasomatism) from table 2. Note that the K and Rb content of liquids extracted from anhydrous mantle at 5-10 percent melting is identical to that of alkaline magmas. MORB and alkali basalt data after Kay and Hubbard (1978) and Hofmann and Hart (1978), San Quintin and Lanzo data after Basu and Murthy (1976) and Menzies and Murthy (1978a).
Mantle Xenoliths and Their Host Magmas

izes and Murthy, 1978ab). Frey and Green (1974) and Frey and Prinz (1978) defined two genetically unrelated components in spinel lherzolite nodules from Victoria, Australia and San Carlos, Ariz. The anhydrous spinel lherzolites (and harzburgites) are believed to represent melting residua that contain an exotic intergranular component with a composition similar to liquids produced by <5 percent anatexis of garnet peridotites. Compositional liquids are basanites or olivine leucitites and are rich in K, REE, P, et cetera. Menzies (1976) and Jagoutz, Lorenz, and Wänke (1977) reported a similar light REE enriched component within spinel lherzolites from the Massif Central, France. These enrichment events involve lherzolitic mantle, but frequently metasomatic episodes contaminate parts of the mantle which are totally devoid of all magmaophile elements due to previous melting events. The resultant, somewhat anomalous rocks, is a “fertile harzburgite,” and it is found to contain excessive amounts of light REE, Na, Ti, et cetera. These have been reported as nodules from alkali basalt flows (Frey and Green, 1974) and kimberlite pipes (Hervig, Smith, and Dawson, 1977).

In contrast to these many reports of the gain of an interstitial component, Jackson and Wright (1970) and Menzies and Murthy (1978a)

![Diagram](image)

Fig. 4. Rb and Sr content of hypothetical melts produced by anatexis of hydrous mantle (10 percent metasomatism) from table 2. Note that the Rb and Sr content of liquids produced by 5 to 20 percent melting of hydrous mantle is similar to that of other alkaline magmas. Comparative data after Kay and Hubbard (1978) and Hofmann and Hart (1978), and anhydrous mantle data after Dasch and Green (1975), Basu and Murthy (1976), and Menzies and Murthy (1978a).
reported the loss of LIL element enriched liquids in the sub-oceanic mantle. Jackson and Wright (1970) calculated the composition of liquids produced by melting of suitable Hawaiian peridotites and compared the hypothetical melts with Hawaiian basanites. The chosen parental rock, however, was found to contain insufficient amounts of K, P, and Ti, needed to account for the abundances of these elements in the basanites. Jackson and Wright (1970) concluded that these lithophile elements had been lost due to local depletion in the mantle near areas of basalt genesis. Similarly, Menzies and Murthy (1978a) calculated that the sub-oceanic mantle, as represented in alpine lherzolites, had lost an alkali–nephelinitic fraction during some earlier melting episode. The degree of melting in both instances must have been small (<5 percent) since the residuum is similar to "pyrolite" in major and minor element chemistry and in modal mineralogy.

Intergranular phases in mantle nodules tend to be enriched in Rb and Sr and have a considerable range in Sr isotopic composition, for example, $^{87}$Sr/$^{86}$Sr 0.704 – 0.707 (Dasch and Green, 1975; Basu and Murthy, 1977b). Lherzolite nodules from Baja California (Basu and Murthy, 1977b) lost an alkali fraction rich in LIL elements some 3 b.y. ago, and very recently, prior to their entrainment in the alkali basalt, they gained a radiogenic LIL enriched component. Similarly, peridotite nodules from Australia (Dasch and Green, 1975; Burwell, 1975) have gained a Rb- and Sr-rich component. Isotopic and trace element data (Philpotts, Schnetzler, and Thomas, 1972; Boettcher and others, 1977) are consistent with the petrographic observation that the hydrous minerals are not formed by reaction of the host basanite with the peridotite nodule. Previous isotopic studies have also shown that the hydrous minerals are isotopically unrelated to the host alkali basalt. Although this may be the case for much of the kaersutite data (fig. 2), the pargasitic amphiboles are isotopically identical to the enclosing basalts (table 1).

The widespread loss of an exotic component (basanite–nephelinite), leaving a residuum of anhydrous lherzolite, and its localized gain in metasomatized or contaminated mantle, points to the upward migration and penetration of a volatile-rich fluid or melt. These fluids scavenge incompatible elements from the lower mantle and deposit K, REE, P, Ti, Fe, Rb, Sr, Zr, Nb, Ba, Th, U, and H$_2$O along preexisting grain boundaries and fissures in the mantle. Not all parts of the mantle, however, have encountered an enrichment or depletion event, perhaps indicating the localized nature of metasomatism in association with alkaline magmatism.

Is this localized introduction of metasomatic fluids accomplished by single or multiple events? Consideration of the Sr isotopic data (table 1) for introduced hydrous minerals may help answer this question, since the isotopic composition of the amphibole, mica, et cetera is presumably identical to that of the migrating fluid. Firstly, the Nunivak hydrous minerals (table 1) appear to have originated in a mantle that has a lower Sr isotopic composition than the Ataq amphiboles (table 1). Secondly,
the range in $^{87}\text{Sr}/^{86}\text{Sr}$ at a single eruptive center may indicate that the fluids were introduced as multiple pulses from isotopically different parts of the mantle. For example, the interstitial mica found in nodules from Nunivak (table 1) may have formed, along with other metasomatic minerals, from a fluid that presumably had a different source to the pargasite in sample 10050 (table 1), since their Sr isotopic compositions are very different. Thirdly, multiple events or superposition of one enrichment event on another may account for the replacement of pargasite by kaersutite observed in nodules from California (Boettcher and others, 1979). Single pulses can, however, account for interstitial pargasite and vein kaersutite in lherzolite nodules from Dish Hill and Deadman lake, Calif. (Wilshire and others, 1980). The complexity of metasomatic events is illustrated by these contradictory relationships, the wide range in amphibole composition (kaersutite to richterite–pargasite), the variable composition of the fluids, and the occurrence of elaborate wallrock reactions (Best, 1974).

It seems clear from these arguments and the high content of K, Rb, Sr, and REE in amphibole that amphiboles are genetically related to alkaline magmatism. Basu and Murthy (1977a) proposed a model for the origin of MORB, that involved mixing of a kaersutite melt and an “anhydrous mantle” melt. Despite the fact that the Sr isotopic compositions of selected kaersutites from continental alkaline magmas are identical to those of oceanic tholeiites, if we try to match “model” liquid compositions with oceanic tholeiites, we encounter some serious difficulties. Essentially, melts produced by a mix of kaersutite: lherzolite = 10:90 have insufficient total REE when compared with an average parental tholeiite at approx 10$\times$ chondrite. Any attempt to match the REE of the hypothetical melt (that is, 25:75 mix) with a tholeiite produces a liquid with K, Rb, and Sr abundances similar to alkaline basalt and unlike an average ridge tholeiite (K = 500-2000 ppm, Rb = 0.7-3.0 ppm, Sr = 131-400 ppm). We suggest that both kaersutite and pargasite represent minerals that were part of a metasomatic precursor to the genesis of isotopically distinct alkaline magmas. Kaersutites have a considerable range in Sr isotopic composition ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7027-0.70415$) (fig. 2) that immediately permits comparison with alkali basalts. The amphiboles reported by Basu and Murthy (1977a) could, if involved in anatexis of hydrous mantle, produce alkali-rich fluids with low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and considerable amounts of K, Rb, Sr, and REE (compare, Nunivak basanites, table 1). Conversely, kaersutites with a more radiogenic Sr isotopic composition (Stuckless and Irving, 1976; Stuckless and Erickson, 1976) are perhaps remnants of a metasomatic event that occurred prior to the production of more radiogenic alkaline magmas (see fig. 2 for Sr isotopic range of alkaline magmas).

Anatexis of metasomatized mantle.—Continued volatile or fluid flux into the upper mantle, as in the case of Nunivak, may be caused by the upward migration of fluids associated with diapirism (Francis, 1978) or, as in the case of Ataq, may be caused by mantle degassing
during continental breakup. These precursory metasomatic events introduce sufficient volatiles (CO₂ and H₂O) and other fluxes (Lloyd and Bailey, 1975; Boettcher and others, 1979; Boettcher and O'Neil, 1980) to trigger mantle anatexis. Melting of hydrous Iherzolites (table 2) will produce liquids with higher contents of K, Rb, Sr, and REE compared to liquids produced by anatexis of anhydrous mantle (compare figs. 3 and 4). Anhydrous Iherzolites (Maaloe and Aoki, 1977) have an order of magnitude less K, Rb, Sr, and REE than contaminated mantle. If we consider a section of sub-oceanic (or sub-continental) mantle that has experienced 5 to 10 percent metasomatism, anatexis will generate liquids with alkali basalt affinities at 5 to 20 percent melting (figs. 3 and 4) (compare, Gast, 1968). If the degree of metasomatism, and therefore the infiltration of LIL elements, is higher in the source mantle materials, larger degrees of partial melting can be accommodated. The REE content of these liquids can be calculated, if we first determine the bulk REE content of metasomatized mantle using the data of Varne and Graham (1971) and Menzies and Murthy (1978a). The recently published partition coefficients for the REE (Mysen, 1978) and the equations of Shaw (1970) allow us to define the REE characteristics of the liquids shown in figures 3 and 4. Their K, Rb, and Sr contents are similar to those of alkali basalts, and at 5 to 10 percent melting, the La/Sm ratio (for example, 9.2) is compatible with the liquid being alkline in nature. Similarly, under the assumption of isotopic equilibrium during anatexis (Hofmann and Hart, 1978), the liquids produced by melting of Ataq and Nunivak hydrous mantle will have a Sr isotopic composition identical to those of the amphiboles (table 1). Eruption of such partial melts would produce alkali basalt flows isotopically indistinguishable from the present-day alkali basalts on Nunivak Island or at Ataq.

Nunivak Island, Alaska.—Mark (ms) noted that Nunivak Island comprises two chemically and isotopically distinct suites of basalts, namely basanites (0-1.7 m.y.) and less alkalic basalts (3-6 m.y.). The younger basanites tend to be richer in total alkalis (6.09-9.20 percent Na₂O + K₂O; Mark, ms), and have lower ⁸⁷Sr/⁸⁶Sr ratios than the bulk of the older less alkalic basalts (3.7-5.8 percent Na₂O + K₂O; Mark, ms). Perhaps the differing Sr isotopic composition of the basalts can be correlated with multiple mantle metasomatic events below Nunivak Island. The mantle metasomatic events preserved in the Nunivak nodules have isotopic signatures identical to those of the alkaline basalts. Francis (1976) commented on the similarity of Na/Na⁺ + K ratios of the basalts at Nunivak and the interstitial amphibole and implied that the metasomatic fluids and basalts were genetically related. This is compatible with their Sr and Nd (Menzies and Murthy, 1979) isotopic data. It can be tentatively suggested that continual influx of metasomatic fluid, perhaps caused by diapirism, modified the mantle below Nunivak prior to or synchronous with, alkali basalt volcanism. The older, more radiogenic basalts on Nunivak may be associated with multiple events, now preserved as pargasite and kaersutite in the Nunivak nodules, while the occurrence
of mica in other Nunivak nodules may relate to yet another isotopically distinct mantle event. The mica is perhaps a remnant of the metasomatic event(s) associated with the production of recent basanites.

Kirish volcano, Ataq.—Alkali basalt volcanism along the south Arabian coast has been dated using K-Ar and Rb-Sr methods (Dickinson and others, 1969; Carter and Norry, 1976). Volcanic rocks, ranging from rhyolite to olivine basalt, exhibit a significant correlation between initial \(^{87}\text{Sr}/^{86}\text{Sr}\) and \(^{87}\text{Rb}/^{86}\text{Sr}\) ratios. The Rb-Sr age is, however, 20 to 30 m.y. greater than the K-Ar age for the same volcanic rocks. The K-Ar age of eruption (5.0-6.0 m.y.) is compatible with a Pliocene to upper Miocene period of volcanic activity and the existence of angular unconformities in the Kham and Yemen volcanics. Dickinson and others (1969) and Carter and Norry (1976) resolve the age discrepancy by suggesting that a fractionation event occurred in the mantle source region prior to eruption of the basalts. Could this event be related to a precursory metasomatic or enrichment event in the mantle? A closer examination of the regression analyses reveals that the y-axis intercept is in the range of \(^{87}\text{Sr}/^{86}\text{Sr} = 0.70352\) to \(0.70391\). This would represent the “initial ratio” of the mantle material that was more recently involved in alkali basalt volcanism. Ironically such a mantle isotopic composition compares favorably with that of the metasomatic minerals from the Ataq nodules \((^{87}\text{Sr}/^{86}\text{Sr} = 0.70344-0.70498)\). Also amphibole lherzolites from Ataq have an average \(^{87}\text{Sr}/^{86}\text{Sr} = 0.70383\) (Menzies, unpub. data) and as such represent suitable candidates for mantle involved in the production of alkaline magmas along the south Arabian coast. During initial rifting and fragmentation of the continental crust, in and around the area now occupied by the Red Sea, localized mantle degassing spawned by diapirism resulted in extensive metasomatism of the upper mantle. This enrichment event is recorded in the recent volcanics of south Arabia. However, a more complex origin for these basalts is revealed by Sm-Nd data (Menzies and Murthy, 1979).

Metasomatism and enrichment events.—Many recent petrogenetic models involve contaminated or modified mantle. Kay (1977), in a study of Aleutian arc magmas, proposed a two-stage mixing model similar to that of Ringwood (1975), in which metasomatic fluids originating in the subducted oceanic crust (quartz eclogite?) penetrate the mantle overlying the subducted slab. Since this mantle is light REE depleted, infiltration of fluids with \((\text{La}_N = 94.07-28.3\) and \(\text{Yb}_N = 6.82-3.17\) will produce a light REE enriched mantle. Moderate degrees of melting (5-10 percent) will then produce volcanic arc magmas.

Enrichment events have also been invoked by Carter and others (1978) for tholeiites from Mt. Etna, Sicily. The light REE depleted character of the source peridotite, as revealed by \(^{143}\text{Nd}/^{144}\text{Nd}\) isotopic studies, is in direct contrast to the light REE enriched nature of the tholeiites. Clearly a metasomatic event occurred in the mantle in this area so recently that it is not reflected in the Nd–isotopic data. Similarly, a recent metasomatic event may alleviate the need for low degrees of
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Melting in the production of extremely light REE enriched lavas from the East-Eifel district of Germany. Staudigel and Zindler (1978) reported a light REE depleted source for several light REE enriched East-Eifel lavas ($La/Yb = 15-30$). They proposed ~1 percent melting of garnet lherzolite ($2\times$ chondrite) to explain the concentration of light REE in the liquid. A recent enrichment event, occurring sufficiently close to the time of eruption of the lavas, may be a viable alternative. Frey, Green, and Roy (1978) similarly evoked a recent enrichment event within the source region of basanites, nephelinites and melilites, such that higher degrees of partial melting (4-25 percent) could be accommodated. Frey, Green, and Roy (1978) argued that although these volcanic rocks can be generated by 0.4 to 1.0 percent partial melting of a source with chondritic relative REE abundances at 2 to 5$\times$ chondrite, this low degree of melting is in direct conflict with the high degrees ($\geq 15$ percent) of melting deduced from major element and experimental data. Similarly, it can be shown (figs. 3 and 4) that high degrees of partial melting (5-20 percent) can produce liquids with the K, Rb, and Sr content of alkaline magmas, if the source region experienced an enrichment episode prior to the melting event.

The dominant constituent of the sub-oceanic (and perhaps the sub-continental) mantle appears to be a light REE depleted peridotite that contains sufficient major and minor elements to satisfy the requirements for alkaline and basaltic magmas. Prior to (or synchronous with) the eruption of alkaline and basaltic magmas, however, an influx of metasomatic fluids must occur to provide the requisite amount of some lithophile trace elements.

CONCLUSIONS

Isotopic and trace element studies of metasomatized sub-oceanic and sub-continental mantle and host alkaline magmas indicate:

A. Mantle metasomatism, or the gain of a K, REE, P, et cetera component, is a precursor to the genesis of alkaline magmas. Metasomatic minerals from Nunivak Island ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70270-0.7033$) and Ataq ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70346-0.70408$) are isotopically identical to the host alkaline magmas erupted on Nunivak Island ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70251-0.70322$) and at Ataq ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70353-0.70395$).

B. The high content of K, Rb, Sr, and total REE in melts produced by 5 to 20 percent anatectic of metasomatized mantle indicates that kaersutite and pargasite are both related to alkaline magmatism. Assuming isotopic equilibrium during anatexis the liquids calculated for Nunivak and Ataq correspond to the observed composition of host alkaline magmas.

C. Metasomatic events vary in their Sr isotopic composition between and within individual eruptive centers. Multiple pulses of metasomatic fluid, from isotopically distinct sources, can penetrate and contaminate the underlying mantle. Different enrichment events may be related to the production of isotopically different magmas on Nunivak Island and elsewhere.
D. Previous metasomatic events can be swamped by later events, or vice-versa, leading to the production of isotopically different magma batches. Dependent on the isotopic composition of amphiboles and micas, they may represent single or multiple metasomatic pulses.

E. Mantle peridotites can experience loss and gain of fluids enriched in K, REE, P, Ti, et cetera throughout geologic time, revealing the transitory nature of these migrating fluids that scavenge incompatible elements from one part of the mantle and deposit them elsewhere, for example, South Arabian Coast and San Quintín, Baja California.

F. The age of mantle enrichment events may be recorded as an $^{87}$Sr/$^{86}$Sr vs Rb/Sr positive correlation amongst the nodules or later erupted magmas (for example, South Arabian coast). The initial $^{87}$Sr/$^{86}$Sr ratio of the mantle deduced from regression analyses of the Arabian volcanic rocks is identical to that of the metasomatized mantle at Ataq.

G. An enrichment or metasomatic episode occurring prior to a melting event will enhance the light REE and LIL element content of the mantle source region, such that alkali basalts can be produced by 5 to 20 percent melting, thus eliminating the need for extremely low degrees of melting (that is < 1.0 percent).

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