

# Petrogenesis of McKinney (Snake River) olivine tholeiite in light of rare-earth element and Cr/Ni distributions

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## ABSTRACT

Samples of McKinney Basalt, including a pillow glass, are characterized by light rare-earth element-enriched abundance patterns with small positive Eu anomalies (relative to chondrites) and high Cr/Ni ratios. In particular, the positive Eu anomaly observed in the pillow glass is considered to be characteristic of the McKinney parental magma. These compositional features are apparently inconsistent with derivation of McKinney magma by partial fusion of garnet- or plagioclase-bearing lherzolite or clinopyroxenite or by crystal fractionation of likely liquidus phases at high or low pressure. Rather, partial melting calculations show that fusion of spinel peridotite or aluminous clinopyroxene peridotite can yield liquids with the rare-earth element patterns and Cr/Ni ratios of McKinney Basalt. An essential feature of the favored models is a relatively large contribution of clinopyroxene to the melt. This result suggests an origin of McKinney magma by fusion of mantle lherzolite at pressures between the stability fields of plagioclase peridotite (low *P*) and garnet peridotite or garnet clinopyroxenite (high *P*), that is, at depths within the continental lithosphere in this region.

## INTRODUCTION

From detailed mineralogic and petrochemical studies of McKinney Basalt, Leeman and Vitaliano (1976) concluded that this basalt was derived by partial melting of spinel (or aluminous clinopyroxene) peridotite at depths near 50 to 60 km. This conclusion is significant in that it apparently precludes the origin of Snake River and Yellowstone basalts, which typically resemble McKinney Basalt, directly from a deep mantle plume (Morgan, 1972; Smith and Sbar, 1974). This petrogenetic model, which is generally applicable to Snake River olivine tholeiite, may be tested to see if it is consistent with the observed trace-element abundances in these rocks.

## TRACE-ELEMENT CHARACTERISTICS OF MCKINNEY BASALT

Analyses of major- and trace-element contents of 17 samples of McKinney Basalt, including a pillow glass, are given, along with descriptions of analytical methods, in Leeman and Vitaliano (1976). The study reported here was concerned with the rare-earth elements (REE) and Cr and Ni contents of the McKinney pillow glass, because these elements are differentially incorporated in mineral phases that could have been in equilibrium with the parental magma of this glass. In particular, it is reasoned that these elements can yield information about the mineralogy of refractory residue remaining after extraction of this magma.

The average contents of several trace elements in McKinney Basalt and in 59 samples of Snake River olivine tholeiite are given in Table 1. The average for the McKinney Basalt closely resembles the average Snake River Basalt, but relative standard deviations on the latter averages are as large as 40 percent for some elements (for

example, Cr, Ni, REE). Nearly all analyzed samples, including McKinney pillow glass (see Table 1), have light-REE-enriched abundance patterns with small positive Eu anomalies relative to chondrites (see Fig. 1a). The ubiquitous Eu anomalies cannot be ascribed generally to plagioclase accumulation, because the pillow glass contains no feldspar and many of the other samples are nearly aphyric. Nor can they be ascribed to systematic analytical errors, because analyses of U.S. Geological Survey standard rocks performed concurrently are in good agreement with high-precision analyses by other investigators (Leeman, 1974; Leeman and Vitaliano, 1976). Cr/Ni ratios are characteristically high in McKinney and other Snake River Basalts (~2.5).

Assuming that the distinctive REE abundance patterns and Cr/Ni ratios of McKinney Basalt samples are determined by the mineralogy of their source region, it is of interest to examine a number of partial melting models to eliminate those that cannot produce liquids with such compositional characteristics.

## TRACE-ELEMENT MELTING MODELS

Schilling and Winchester (1967), Gast (1968), and Shaw (1970) presented theoretical models for the behavior of trace elements during partial fusion. Following their approach, I assumed that processes such as volatile or diffusive transfer are negligible under the *P-T* conditions of melting. This assumption may not be strictly true, but at present there are no means of evaluating the effects of

TABLE 1. TRACE-ELEMENT CONTENT IN SNAKE RIVER OLIVINE THOLEIITES

|       | McKinney Basalt<br>average* | SNAKE RIVER<br>Plain average† | McKinney Basalt<br>pillow glass |
|-------|-----------------------------|-------------------------------|---------------------------------|
| Ni    | 87                          | 104                           | 73                              |
| Co    | 51                          | 51                            | 43                              |
| Sc    | 31                          | 32                            | 34                              |
| Cr    | 215                         | 250                           | 173                             |
| Ba    | 380                         | 378                           | 425                             |
| Sr    | 321                         | 284                           | ..                              |
| Rb    | 17                          | 10                            | ..                              |
| Zr    | 278                         | 244                           | ..                              |
| La    | 24                          | 22                            | 26.5                            |
| Ce    | 54                          | 50                            | 61                              |
| Sm    | 7.6                         | 7.5                           | 8.43                            |
| Eu    | 2.6                         | 2.4                           | 2.95                            |
| Tb    | 1.2                         | 1.3                           | 1.39                            |
| Yb    | 3.4                         | 3.3                           | 4.05                            |
| Lu    | 0.56                        | 0.56                          | 0.70                            |
| K/Rb  | 400                         | 520                           | ..                              |
| K/Ba  | 17.5                        | 12.7                          | ..                              |
| Rb/Sr | 0.05                        | 0.03                          | ..                              |
| Cr/Ni | 2.5                         | 2.4                           | 2.4                             |

\* *n* = 16, excluding pillow glass.  
† *n* = 59.

such processes. It is also assumed that magma formation occurs in a single discrete step under equilibrium conditions, and that successive batches of magma are not "lost" or fractionated (that is, fractional melting does not occur). Under these assumptions, the concentrations of trace elements in a derived magma relative to those in the source material are dependent on (1) the crystal/liquid partition coefficients (which are themselves dependent to some degree on temperature, pressure, and composition), (2) the modal proportions of phases in the source material, (3) the composition of the relevant invariant minimum, and (4) the degree of melting.

The partition coefficients for most igneous crystalline phases are imperfectly known at present, but considerable empirical and experimental data are available. The values used in this study and their sources are given in Table 2. Of the elements considered, partition coefficients for the REEs are perhaps best determined for all the relevant phases. Clinopyroxene and amphibole, garnet, and plagioclase have distinctive relative partition coefficient patterns for the REEs. In addition, the behavior of Eu relative to the other REEs is known to depend on oxygen fugacity as well as crystalline structure factors (Philpotts and Schnetzler, 1968; Weill and Drake, 1973). It is also known that garnet and clinopyroxene structures strongly accept Cr relative to Ni, whereas olivine accepts Ni relative to Cr. Considerations such as these can aid in screening potential models of magma generation.

Relative concentrations of trace elements in hypothetical derived melts were computed using the equilibrium melting equations of Shaw (1970) and using a wide range of mantle compositions similar to naturally occurring ultramafic xenoliths (for example, Carter, 1970; Jackson and Wright, 1970). The postulated modal abundances for selected models are given in Table 3. The "melting modes" (that is, the proportions in which the mantle phases melt) used for olivine-orthopyroxene-clinopyroxene were modified from the 20-kb eutectic in the anhydrous system  $Mg_2SiO_4$ - $CaMgSi_2O_6$ - $SiO_2$  (Kushiro, 1969), whereas those involving hydrous phases were assumed. This assumption introduces little additional uncertainty in the model calculations as long as such hydrous phases are present in the model mantle only in small amounts. Because there are large uncertainties in the partition coefficients for the transition metals, these elements will not be discussed in detail. The partition coefficients for Rb, Sr, and Ba are sufficiently low for most phases that these elements are effectively partitioned into the melt, with the exception of Sr in plagioclase peridotite models and Rb in mica-bearing assemblages. In any case, Sr and Rb may behave as excluded elements as long as the proportions of residual plagioclase and mica are small. Calculated results for the REE, Cr, and Ni are presented in Table 3 as relative abundance ratios in order to avoid dependency on the source region composition.

The REE results are given as the ratios of Eu/Sm (as a measure of the Eu anomaly), La/Sm, La/Lu, and Tb/Lu, all of which reflect fractionation of light and heavy REEs. REE relative abundance patterns (which are comparable to chondrite-normalized patterns if the source material has chondritic relative abundances) for selected models are presented in Figure 1. In this figure it is apparent that peridotite and pyroxenite models yield liquids with slight, positive Eu anomalies, reflecting the partition coefficient pattern of clinopyroxene. Models involving residual plagioclase, even in small amounts, yield liquids with negative Eu anomalies. Garnet-bearing models produce liquids that are strongly enriched in the light REEs relative to the heavy REEs. These REE abundance patterns retain their characteristic features to relatively large degrees of partial melting (more than 30 percent) and appear to be diagnostic of the source region mineralogy. The effects of melting other phases are readily assessed. The presence of amphibole enhances the effect of clinopyroxene, since these minerals have similar relative partition coefficients for the REEs (see models 1, 2, and 3 in Table 3). Olivine, orthopyroxene, spinel, and phlogopite, judging from the limited data for these phases, strongly reject the REEs without

much interelement fractionation, compared with the effects of clinopyroxene, garnet, and plagioclase.

The model REE patterns (Table 3, Fig. 1) can be directly compared with that of the McKinney pillow lava (sample 70-15) if it is assumed that the mantle source region has chondritic relative abundances. For the purpose of calculations presented here, the average REE content of 20 chondrites (quoted in Haskin and others, 1968) was used; more recent chondritic averages differ slightly

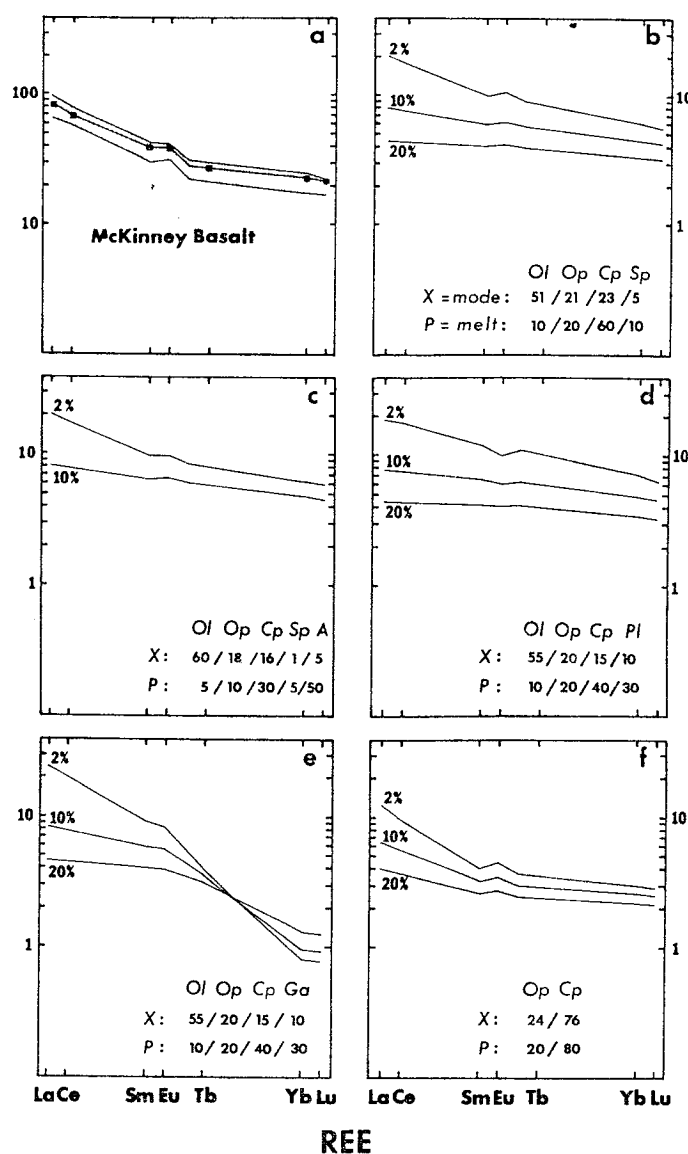


Figure 1. REE abundance patterns as a function of degree of fusion of some hypothetical mantle assemblages. a, Chondrite-normalized REE pattern for samples of McKinney Basalt; solid squares denote pillow glass; sample 70-15 GL. b through f, Vertical scale represents REE enrichment in derived liquids relative to initial concentrations ( $C_p/C_0$ ). Assuming chondritic relative abundances for the initial mantle source, these patterns may be directly compared with chondrite-normalized REE plots. Proportions of phases in the model source rock (X = mode) and in the assumed invariant minimum (P = melt) are given as a weight percentage for each model. Symbols for phases in mantle models are Ol = olivine, Op = orthopyroxene, Cp = clinopyroxene, Sp = spinel, Pl = plagioclase, Ga = garnet, and A = amphibole. b, Spinel lherzolite (model 2, Table 3). c, Amphibole-bearing spinel peridotite; at 10 percent fusion, amphibole was depleted (model 3). d, Plagioclase peridotite (model 4). e, Garnet peridotite (model 5). f, Clinopyroxene (model 8).

TABLE 2. PARTITION COEFFICIENTS USED IN TRACE-ELEMENT MELTING MODELS

| Element | Oliv/liq* | Opx/liq† | Cpx/liq§ | Amph/liq# | Garn/liq** | Spin/liq†† | Plag/liq§§ | Mica/liq# |
|---------|-----------|----------|----------|-----------|------------|------------|------------|-----------|
| La      | 0.01      | 0.02     | 0.07     | 0.16      | 0.01       | 0.10       | 0.14       | 0.03      |
| Ce      | 0.01      | 0.03     | 0.10     | 0.20      | 0.03       | 0.08       | 0.10       | 0.03      |
| Sm      | 0.01      | 0.05     | 0.29     | 0.50      | 0.30       | 0.05       | 0.07       | 0.03      |
| Eu      | 0.01      | 0.05     | 0.26     | 0.60      | 0.50       | 0.03       | 0.28       | 0.03      |
| Tb      | 0.01      | 0.12     | 0.31     | 0.65      | 1.7        | 0.02       | 0.05       | 0.03      |
| Yb      | 0.01      | 0.34     | 0.30     | 0.50      | 11.5       | 0.02       | 0.03       | 0.03      |
| Lu      | 0.01      | 0.42     | 0.30     | 0.45      | 11.8       | 0.02       | 0.03       | 0.04      |
| Ni      | 8.7       | 3.8      | 2.0      | 3.0       | 0.4        | 5.0        | 0.01       | 3.7       |
| Co      | 2.5       | 1.4      | 0.7      | 0.9       | 0.2        | 2.0        | 0.01       | 1.1       |
| Cr      | 0.2       | 2.0      | 10.0     | 12.0      | 2.0        | 10.0       | 0.01       | 7.0       |
| Sc      | 0.02      | 0.7      | 1.6      | 1.9       | 3.4        | 2.0        | 0.01       | 1.1       |
| Sr      | 0.01      | 0.01     | 0.03     | 0.3       | 0.04       | 0.01       | 1.2        | 0.1       |
| Ba      | 0.01      | 0.01     | 0.01     | 0.4       | 0.01       | 0.01       | 0.16       | 0.02      |
| Rb      | 0.01      | 0.01     | 0.01     | 0.4       | 0.02       | 0.01       | 0.10       | 3.0       |

Note: In all possible cases, data were selected from experimental studies extrapolated to 1300°C and assuming that oxygen fugacity was buffered near the quartz-fayalite-magnetite buffer. Otherwise, empirical data were used; in these cases, only data from basaltic or high-temperature ultramafic rocks were used. Estimates were used for a few elements in spinel, amphibole, and mica (notably Co and Sc).

\* Olivine — Ni and Co values from experimental studies (Leeman, 1974 and unpub. data), others from phenocryst-matrix data (Schnetzler and Philpotts, 1970; Philpotts and Schnetzler, 1970; Leeman and Scheidegger, unpub. data).

† Orthopyroxene — transition metal values calculated from opx/oliv (Mercy and O'Hara, 1967) and oliv/liq data; others from Schnetzler and Philpotts (1970), Philpotts and Schnetzler (1970), and Griffin and Murthy (1969).

§ Clinopyroxene — transition metal and REE values from experimental studies (Grutzeck and others, 1974; Lindstrom and Weill, 1974, and 1975, personal commun.); others from Griffin and Murthy (1969).

# Amphibole and mica — transition metal values calculated from amphib/cpx or mica/cpx (Griffin and Murthy, 1969; Dawson and others, 1970; Dawson and Smith, 1973) and cpx/liq data; others from Schnetzler and Philpotts (1970), Philpotts and Schnetzler (1970), Philpotts and others (1972), and Onuma and others (1968).

\*\* Garnet — all values calculated from garn/cpx (Taylor and others, 1969; Griffin and Murthy, 1969; Philpotts and others, 1972; Reid and Frey, 1971; Mercy and O'Hara, 1967) and cpx/liq data.

†† Spinel — REE values calculated from spin/cpx (Frey, 1970; with modified La and Ce) and cpx/liq data; all other values are intuitive guesses.

§§ Plagioclase — REE, Sr, and Ba values from experimental studies (Drake, 1972; Weill and Drake, 1973, and 1974, personal commun.); others from Schnetzler and Philpotts (1970), Philpotts and Schnetzler (1970), and Leeman (1974 and unpub. data).

from these values, but their use does not affect any of the conclusions drawn. Peridotite and clinopyroxenite models yield similar REE patterns to that of McKinney pillow lava, whereas the models involving even small amounts of residual plagioclase or garnet yield significantly different REE patterns. The small amounts of spinel, mica, and (or) amphibole that could be present in the mantle would have little effect on the calculated REE patterns, although their presence could significantly affect the content of other elements in derived melts. Therefore, of the mineral assemblages considered, only the garnet-free peridotite or clinopyroxenite models could yield liquids similar in REE content to McKinney pillow lava if the mantle has chondritic relative abundances of the REEs. Furthermore, the shapes of the calculated REE patterns for derived melts indicate that the McKinney REE pattern could have been obtained by limited (about 5 percent) melting of a peridotite or clinopyroxenite mantle. If the mantle source was actually enriched in light REEs relative to heavy REEs, more extensive melting would be allowed — the degree of melting depending on the degree of light-REE enrichment. Conversely, a light-REE-depleted mantle would allow only smaller degrees of melting, which seems rather improbable. If the source material was characterized by a negative Eu anomaly as the result of some early fractionation event, the conclusions drawn above would not be affected except that the inferred degree of melting could differ slightly.

A more remote possibility is that the mantle source for McKinney magma was a plagioclase cumulate assemblage characterized by a large positive Eu anomaly. Melting of such a material would result in liquids possibly characterized by a positive Eu anomaly of a magnitude smaller than that in the parent rock. This possibility is considered remote, because plagioclase is not stable above pressures of 8.6 to 11 kb, depending on its exact composition (Herzberg, 1972), and because petrologic and mineralogic considerations (Leeman and Vitaliano, 1976) suggest a greater pressure of

origin for McKinney magma. In any event, melting at shallow depths (<35 km) within the plagioclase peridotite stability field would require an exceptionally high geothermal gradient and would also preclude direct origin of such magma from a deep mantle plume.

Cr/Ni ratios calculated for the various melting models (Table 3) indicate that a clinopyroxenite source would yield liquids strongly depleted in Cr relative to Ni, whereas a source containing appreciable olivine would yield liquids with high Cr/Ni ratios. The McKinney pillow glass has a high Cr/Ni ratio (2.4) and, in addition, contains a trace of Cr-rich spinel microphenocrysts. If the McKinney magma was derived directly as a partial melt and underwent little crystal fractionation during its ascent, then its high Cr/Ni ratio is compatible with a peridotite rather than a pyroxenite source.

## EFFECTS OF FRACTIONAL CRYSTALLIZATION

The melting models just discussed are based on the assumption that fractional crystallization has not effected any significant changes in the composition of McKinney magma during its ascent. Yet there is evidence for some fractional crystallization in the presence of olivine and plagioclase phenocrysts (Leeman and Vitaliano, 1976), and it is important to assess the effects of this process.

Low-pressure crystallization of moderate amounts of olivine and plagioclase will tend to enrich the magma in all of the REEs and to cause a relative depletion in Eu. The net effect is to decrease the Eu anomaly of the melt. In the case of McKinney magma, the observed magnitude of the positive Eu anomaly would be minimal, and the original melt would be characterized by a larger Eu anomaly. High-pressure fractionation of a phase such as clinopyroxene, which has a slight, negative Eu anomaly in its partition coefficient

TABLE 3. 'TRACE-ELEMENT' MELTING MODELS

|                                                                | 1    | 2    | 3    | 4    | 5    | 6     | 7    | 8    |
|----------------------------------------------------------------|------|------|------|------|------|-------|------|------|
| <i>Model composition of initial mantle source (wt percent)</i> |      |      |      |      |      |       |      |      |
| Olivine                                                        | 65   | 51   | 60   | 55   | 55   | ..    | ..   | ..   |
| Orthopyroxene                                                  | 20   | 21   | 18   | 20   | 20   | ..    | 22   | 24   |
| Clinopyroxene                                                  | 15   | 23   | 16   | 15   | 15   | 50    | 71   | 76   |
| Garnet                                                         | ..   | ..   | ..   | ..   | 10   | 50    | 7    | ..   |
| Spinel                                                         | ..   | 5    | 1    | ..   | ..   | ..    | ..   | ..   |
| Plagioclase                                                    | ..   | ..   | ..   | 10   | ..   | ..    | ..   | ..   |
| Amphibole                                                      | ..   | ..   | 5    | ..   | ..   | ..    | ..   | ..   |
| <i>Melting mode (wt percent)</i>                               |      |      |      |      |      |       |      |      |
| Olivine                                                        | 15   | 10   | 5    | 10   | 10   | ..    | ..   | ..   |
| Orthopyroxene                                                  | 25   | 20   | 10   | 20   | 20   | ..    | 10   | 20   |
| Clinopyroxene                                                  | 60   | 60   | 30   | 40   | 40   | 50    | 60   | 80   |
| Garnet                                                         | ..   | ..   | ..   | ..   | 30   | 50    | 30   | ..   |
| Spinel                                                         | ..   | 10   | 5    | ..   | ..   | ..    | ..   | ..   |
| Plagioclase                                                    | ..   | ..   | ..   | 30   | ..   | ..    | ..   | ..   |
| Amphibole                                                      | ..   | ..   | 50   | ..   | ..   | ..    | ..   | ..   |
| <i>Trace-element relative abundances (equilibrium melting)</i> |      |      |      |      |      |       |      |      |
| <i>2 percent melt</i>                                          |      |      |      |      |      |       |      |      |
| Eu/Sm                                                          | 1.06 | 1.08 | 1.01 | 0.84 | 0.88 | 0.79  | 1.03 | 1.10 |
| La/Sm                                                          | 1.90 | 2.05 | 2.10 | 1.58 | 2.60 | 5.22  | 3.42 | 3.22 |
| La/Lu                                                          | 3.74 | 3.62 | 3.47 | 2.92 | 31.3 | 100.5 | 14.6 | 4.46 |
| Tb/Lu                                                          | 1.62 | 1.51 | 1.36 | 1.57 | 4.99 | 5.92  | 2.90 | 1.23 |
| Cr/Ni                                                          | 3.47 | 1.85 | 2.45 | 2.99 | 1.53 | 0.08  | 0.26 | 0.30 |
| <i>10 percent melt</i>                                         |      |      |      |      |      |       |      |      |
| Eu/Sm                                                          | 1.02 | 1.04 | 1.03 | 0.93 | 0.94 | 0.83  | 1.04 | 1.07 |
| La/Sm                                                          | 1.22 | 1.33 | 1.28 | 1.20 | 1.43 | 2.69  | 2.07 | 2.03 |
| La/Lu                                                          | 1.78 | 1.90 | 1.82 | 1.71 | 8.85 | 40.8  | 5.70 | 2.61 |
| Tb/Lu                                                          | 1.33 | 1.31 | 1.30 | 1.31 | 3.71 | 5.52  | 2.17 | 1.18 |
| Cr/Ni                                                          | 4.38 | 2.13 | 3.25 | 3.42 | 1.87 | 0.09  | 0.28 | 0.31 |
| <i>20 percent melt</i>                                         |      |      |      |      |      |       |      |      |
| Eu/Sm                                                          | 1.00 | 1.02 | ..   | 0.97 | 0.98 | 0.86  | 1.04 | 1.05 |
| La/Sm                                                          | 1.05 | 1.13 | ..   | 1.08 | 1.15 | 1.88  | 1.57 | 1.56 |
| La/Lu                                                          | 1.32 | 1.42 | ..   | 1.35 | 3.58 | 21.7  | 2.36 | 1.89 |
| Tb/Lu                                                          | 1.19 | 1.19 | ..   | 1.19 | 2.44 | 5.02  | 1.37 | 1.13 |
| Cr/Ni                                                          | 6.73 | 2.69 | ..   | 4.19 | 2.62 | 0.10  | 0.32 | 0.33 |

Note: Models 1 through 3 represent variants of a peridotite mineralogy; of the phases present, only clinopyroxene strongly fractionates the light and heavy REEs, whereas the others strongly exclude all the REEs. The models differ mainly with respect to the amount of clinopyroxene (and amphibole) present. In model 3 amphibole was depleted after 10 percent melting. Model 4 represents a plagioclase peridotite mineralogy; melting of plagioclase-bearing assemblages generally imparts a negative Eu anomaly (low Eu/Sm) to the derived liquid. Models 5 through 7 represent garnet peridotite, eclogite, and garnet pyroxenite mineral assemblages; melting of garnet-bearing assemblages generally produces a liquid that is depleted in the heavy REEs (high La/Lu and Tb/Lu). Model 8 represents a clinopyroxenite; melting of such a mineral assemblage will produce liquids with REE relative abundances not unlike those derived by melting peridotites, but with low Cr/Ni ratios. It is of particular interest to note how sensitive the relative REE abundances are to the presence of even small amounts of garnet or plagioclase. Minor amounts of mica will have little effect on the relative REE abundances of derived liquids, whereas amphibole will enhance the effect of melting clinopyroxene.

pattern, would tend to enrich Eu in the melt relative to the other REEs. However, it can be shown that removal of more than 70 percent of pure clinopyroxene is required to produce an anomaly of the magnitude observed in McKinney pillow glass under normal terrestrial redox conditions (that is, oxygen fugacities near the quartz-fayalite-magnetite buffer; Grutzeck and others, 1974). Such extensive fractionation seems unlikely, and if it occurred, it would grossly deplete the residual liquid of Cr and Sc relative to Ni. As noted above, such depletions are not observed, and it seems more likely that the positive Eu anomalies are features inherited during the partial melting process.

Low-pressure crystallization of olivine tends to rapidly deplete the host magma of Ni relative to Cr so that high Cr/Ni ratios can result. However, this effect is reduced if other phases that reject Ni crystallize simultaneously. In the McKinney Basalt samples studied, the phenocryst assemblage is composed of about 25 percent olivine (commonly containing Cr-rich spinel microphenocrysts) and 75 percent plagioclase. It can be shown that crystallization of olivine

and plagioclase in these proportions will increase the Cr/Ni ratio in the liquid by a factor of only two after 30 percent crystallization. This calculation does not consider the presence of Cr-rich spinel included in the olivines which would tend to counterbalance strongly the increase in Cr/Ni.

#### REE COMPOSITION OF THE MANTLE SOURCE

If it is assumed that the mantle source has chondritic relative abundances, it is possible to estimate the absolute abundances of REEs in the source for a given melting model. If it is assumed that the pillow glass closely represents the initial McKinney magma and that model 2 (Table 3, Fig. 1b) closely represents the source material, it can be inferred that for about 5 percent melting, the REE concentrations in the source region were about four to six times those in chondrites. If the pillow glass represents a fractionated liquid, as seems likely, these estimates are upper-limit values.

If it is assumed that McKinney magma formed by 20 percent

melting of model 2, a light-REE-enriched mantle is required that has 20 times the chondritic abundance of La and 7 times the chondritic abundance of Lu. These estimates seem unrealistically high and can be rationalized by considering that this degree of fusion is excessive and that the REE contents of the pillow glass are upper limits to the values for the primary magma. Nevertheless, the calculations suggest that the mantle source for this magma is not depleted in light REEs relative to heavy REEs, in contrast to estimates for the mantle source of normal ocean-ridge basalt (Schilling, 1975).

## CONCLUSIONS

The calculations described here are consistent with derivation of McKinney magma from a peridotitic mantle containing little or no garnet. A plagioclase-bearing source is conceivably possible but seems unlikely in view of other petrologic and experimental data (Leeman and Vitaliano, 1976). It is probable that the source region for this magma lies within the upper mantle in the continental lithosphere beneath the Snake River Plain. Alternatively, if the parental magma was derived at greater depths, within the garnet peridotite or eclogite stability field, it must be concluded that this magma re-equilibrated with garnet-free peridotite prior to its eruption. In either case, a direct origin from a deep mantle source (as in a plume) seems unlikely.

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