Most known komatiites, including all of the Archaean examples, have been subjected to hydrothermal activity of one sort or another, as evidenced by the presence of secondary hydrous minerals such as chlorite, serpentine and tremolite. A combined oxygen isotopic and petrographic study of a single komatiite flow in Munro Township indicates that the degree of mineralogical alteration is inversely correlated with $\delta^{18}O$. All of the samples lie on a mixing line between fresh komatiites ($\delta^{18}O = +5.7 \pm 0.3$) and serpentinite ($\delta^{18}O \approx +3.0$). The fresh komatiite value is similar to that of Phanerozoic ultramafic rocks, and suggests that $\delta^{18}O$ of the Earth's mantle has not changed appreciably through geological history. Using a final metamorphic temperature of 300–330°C, the serpentinite value suggests that the hydrothermal fluid had $\delta^{18}O$ values between $-2$ and $+2$. This fluid was very likely a metamorphic pore fluid that evolved from Archaean sea water during burial metamorphism of the greenstone belt. The water:rock ratios during oxygen isotopic exchange appear to have been high ($>1$). Although some of this water–rock interaction may have taken place immediately upon extrusion of the komatiite into the ocean, most of the alteration was accomplished by sea water circulating deeply into the volcanic pile as the komatiites were buried and heated.

18.1 INTRODUCTION

In the first decade since the recognition of the significance of komatiites (Viljoen & Viljoen 1969a, b), considerable effort has been expended to characterize both the igneous petrology and the chemistry of this unusual suite. With the possible exception of the Gorgona Island examples, however, all komatiites are presently metamorphic rocks containing small varying amounts of relict igneous minerals. The fact that komatiites are hydrothermally altered is hardly surprising; it is a property they share with nearly all the other volcanic rocks that make up Archaean greenstone belts.

In all epizonal igneous environments, the magmas serve as heat engines that drive hydrothermal convection cells which involve the local groundwaters. These heated waters react with the rocks, typically producing abundant secondary hydrous minerals (depending on the temperature), and invariably exchanging oxygen isotopes.

The altered komatiites in the Archaean geological record, therefore, should record evidence of ancient hydrothermal systems. Study of these ancient hydrothermal processes can lead to an increased understanding of the nature of the komatiite volcanism, as well as information regarding water–rock interactions in general and the evolution of the hydrosphere. It is likely that the altered komatiites
can be profitably studied using the techniques of oxygen isotope geochemistry together with the petrographic microscope.

Among Archaean komatiites, a sample locality with a very high degree of preservation is in Munro Township, Ontario. There, although structural and textural preservation is essentially perfect, the primary igneous minerals have been largely pseudomorphed by secondary, hydrous minerals such as serpentine, tremolite and brucite. The excellent preservation of the Munro komatiites is in part related to the fact that the surrounding greenstone belt has been subjected to only two principal metamorphic events, both of which are well understood. In addition, the metamorphic grade is relatively low (prehnite–pumpellyite facies). These two conditions greatly simplify the interpretation of the isotopic data and make Munro Township an ideal place for studying water–komatiite interactions. The degree of preservation in Munro Township also permits calculation of $\delta^{18}O$ of the initial komatiite magma, allowing certain constraints to be placed on models of komatiite genesis.

18.2 SAMPLING AND EXPERIMENTAL TECHNIQUE

A set of six samples was collected across a single komatiite flow that crops out on Pyke Hill, the prominent monadnock in Munro Township (Arndt et al. 1977). This particular flow ranges from 2.5 to 3.0 m thick, and has a well developed upper chilled and fractured flow top. Beneath the flow top, textural changes progress through fine-grained spinifex, coarse-grained spinifex, a foliated zone, fine- to medium-grained peridotites, and finally a basal chilled zone (Fig. 18.1). The six
samples were selected to span most of the textural variations present, hence they are not evenly spaced through the flow (Fig. 18.1). In addition, single samples of two other komatiite flows in the Abitibi greenstone belt (Lamotte Township, Quebec, and Skead Township, Ontario) were collected for comparison with the Munro Township samples and with other published komatiite analyses.

Oxygen was liberated from silicates using the fluorine technique described by Taylor and Epstein (1962). The results are reported in δ-notation in parts per mil (‰), where

\[
\delta^{18}O_{\text{sample}} = \left( \frac{(^{18}\text{O} : ^{16}\text{O})_{\text{sample}}}{(^{18}\text{O} : ^{16}\text{O})_{\text{standard}}} - 1 \right) \times 1000.
\]

Precision is better than 0.2‰ and raw δ\(^{18}\)O values are corrected to the SMOW scale using Caltech rose quartz δ\(^{18}\)O = +8.45. NBS-28 has δ\(^{18}\)O = +9.60 on this scale.

### 18.3 Metamorphic Petrology

Megascopically there is little sign of hydrothermal activity at Pyke Hill. There are rare chrysotile veins, but the megascopic textures and structures of the komatiites are perfectly preserved. Similarly, although quartz veins are common, deformation is absent in the basalts of the surrounding volcanic pile.

In thin section, the relict igneous textures of the komatiites are also well preserved, even though largely pseudomorphed by secondary hydrous minerals (Fig. 18.2a, b, c). The komatiites originally consisted of relatively large olivine crystals set in a matrix ranging from pyroxene and devitrified glass to fine-grained intergrowths of pyroxene and plagioclase. The principal alteration effect is the replacement of olivine by fine-grained metamorphic minerals. The alteration assemblage, however, varies from grain to grain in response to the differential reactivities of the three main igneous minerals. About half of the olivine is partially replaced by the assemblage antigorite + brucite + magnetite (Fig. 18.2c). Adjacent to these pseudomorphs the groundmass is relatively fresh.

The other olivine pseudomorphs contain variable amounts of tremolite (ranging up to 100%), antigorite, magnetite and an absence of brucite (Fig. 18.2a, b). Adjacent to these pseudomorphs the pyroxene, devitrified glass and plagioclase have been variably replaced by chlorite, the intensity of chloritization decreasing away from the olivine pseudomorph. The local abundance of chlorite is proportional to the local abundance of tremolite, and the chloritization of plagioclase and glass is more extensive than that of pyroxene. The largest concentrations of tremolite and chlorite are along veins and fractures (e.g. Fig. 18.2d), and the tremolitic alteration appears to cross-cut the antigorite–brucite alteration. Talc is possibly also present along the veins. The tholeiitic basaltic lavas (greenstones) associated with the komatiites at Pyke Hill are recrystallized to an assemblage which includes prehnite, pumpellyite and chlorite (Arndt et al. 1977, p. 347).
Figure 18.2 Photomicrographs from Munro Township. (a) Br-3, transmitted light. (b) Same view, crossed polars. An intensely altered portion of a komatiite in which the olivine has been replaced by tremolite, and the groundmass has been largely replaced by chlorite. In spite of the wholesale recrystallization during which the oxygen isotopes have exchanged, note the excellent state of textural preservation. (c) Br-5, transmitted light. An equant olivine crystal which has been partially replaced by antigorite and magnetite. The small rounded grains with high relief are relict olivine. (d) Br-3, crossed polars. Close up view of the tremolite (prismatic) and chlorite (black).
These textural observations suggest that the relative susceptibility to recrystallization in the komatiites increased in the order pyroxene, plagioclase, olivine. The glass was also undoubtedly very susceptible to alteration, probably even more so than olivine. Wherever plagioclase (and glass) broke down, the Ca and Al released appear to have stabilized tremolite and chlorite, respectively, at the expense of olivine and pyroxene. The reaction describing this process is

\[
2\text{CaAl}_{2}\text{Si}_{2}\text{O}_{8} + 9\text{Mg}_2\text{SiO}_4 + 2\text{MgCaSi}_2\text{O}_6 + 10\text{H}_2\text{O} + 5\text{SiO}_2 \rightarrow \\
\text{anorthite} \quad \text{olivine} \quad \text{pyroxene}
\]

\[
2\text{Mg}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8 + 2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2 \rightarrow \\
\text{chlorite} \quad \text{tremolite}
\]

This suggests that silica has been added to the rock, consistent with the predominance of chlorite and tremolite (and possibly talc) along fractures, and the ubiquitous presence of quartz veinlets in the nearby basalts. As would be expected, hydrothermal alteration of the Abitibi volcanic pile surrounding Pyke Hill has produced silica-bearing solutions, and these fluids evidently have reacted chemically as well as isotopically with the komatiites.

An additional complexity is the fact that brucite and tremolite are not stable together under any conditions (Evans & Trommsdorff 1970), perhaps suggesting two metamorphic events. As long as the groundmass phases are not participating in the reactions, however, antigorite and brucite are the stable breakdown products of olivine. Although polymetamorphism is a possibility, the data are adequately explained by a single progressive metamorphism involving a low-temperature olivine and glass destructive stage, and a later high-temperature olivine, pyroxene, plagioclase and glass destructive stage. In the basalts associated with the komatiites, no evidence for polymetamorphism was observed.

Figure 18.3 Petrogenetic grid used to determine the maximum temperature of alteration. Sources of data are: (1)–(4) Evans and Trommsdorff (1970); (5)–(7) Nitsch (1971). The location of the invariant point in the iron-free system is thought to be about 2 kb and 345 ± 20°C (Winkler 1979). The komatiites have no diagnostic assemblage, but the assemblage prehnite + pumpellyite + chlorite in the associated basalts places an upper limit of 300–330°C on the temperature. Because of the probable progressive nature of the alteration, no lower temperature limit is drawn.
These observations are consistent with the volcanic rocks near Pyke Hill all being recrystallized in a single hydrothermal metamorphic event. The metamorphic style is typical of that of the Abitibi greenstone belt as a whole, which is thought to have been subjected to sub-seafloor burial metamorphism (Dimroth & Lichtblau 1979, Beaty & Taylor 1979, Jolly 1980). Subsequent to this hydrothermal event, the Abitibi rocks were locally subjected to dehydration contact metamorphism associated with the intrusion of the Kenoran granitic batholiths (Jolly 1974, 1980). The nearest of these batholiths to Pyke Hill crops out about 15 km to the north-east, but this later metamorphic episode did not produce any obvious dehydration at Pyke Hill. Mineral-chemical and phase equilibria data (Jolly 1980) indicate a high geothermal gradient during burial metamorphism, which suggests (Fig. 18.3) that the maximum temperature experienced during hydrothermal alteration at Pyke Hill was about 300–330°C. Because of the submarine origin of the volcanic pile, the hydrothermal fluid for this metamorphic event was almost certainly sea water which had penetrated into the volcanic pile.

18.4 OXYGEN ISOTOPIC DATA

18.4.1 Isotopic structure of the flow

The oxygen isotopic composition of the Pyke Hill komatiite flow ranges from $\delta^{18}O = +3.65$ to $+5.25$. The variation as a function of depth is shown in Figure 18.4. The lowest $^{18}O$ values occur in the centre and at the top of the flow, with higher $^{18}O$ values in between and at the base. Also shown on Figure 18.4 are the amounts of modal secondary minerals. The two curves are obviously correlated, indicating that $\delta^{18}O$ depends directly on the abundance of secondary minerals. Both variables are demonstrably related to the degree of alteration. By plotting the two against one another (Fig. 18.5), it is possible to extrapolate to the compositions of both the original fresh komatiite and the total secondary assemblage. Both of these end members are highly significant, and are discussed in detail below.

It seems inevitable that komatiites, like the associated tholeiitic basalt flows, were
erupted into the ocean and crystallized on the sea floor. Not only are greenstone belts characterized by an abundance of pillow lavas, but interflow sedimentary rocks (including chemical precipitates such as chert) are common. This suggests that the ubiquitous chilled and polyhedrally jointed flow tops (Arndt et al. 1977, p. 328) in the komatiites formed by the rapid loss of heat to the overlying water. As soon as such a fractured flow top had formed, sea water would have entered the rock, and if the temperature were high enough (because of conduction from the centre of the hot flow) serpentinization would immediately have begun to take place. One might anticipate, therefore, somewhat larger oxygen isotopic (and alteration) effects in the fractured flow tops than in the unfractured central and basal zones of the flow. In partial support of this prediction, the least altered rocks present are from the base of the flow, and in the upper portions $\delta^{18}O$ steadily decreases towards the flow top (Fig. 18.4). The most altered rock in the sampled section, however, is from the core of the flow. This indicates that although an alteration gradient may initially have been imposed on the komatiite, the serpentinizing process ultimately had access to all parts of the flow.

18.4.2 $\delta^{18}O$ of fresh komatiite

Figure 18.5 indicates that the oxygen isotopic composition of the original komatiitic liquid was in the range $+5.7 \pm 0.3\%_o$. This is indistinguishable from $\delta^{18}O$ of basalts presently being erupted from mid-ocean spreading centres ($5.7 \pm 0.2\%_o$). The coincidence of these values may at first appear rather surprising; simple calculations suggest that komatiites should have lower $^{18}O$. In fresh basalt with $\delta^{18}O = +5.7$ containing 50% plagioclase, 40% pyroxene and 10% olivine, the $\delta^{18}O$ values of these minerals are about $+6.0$, $+5.5$ and $+5.1$ respectively (Taylor 1968, Taylor & Epstein 1970, Onuma et al. 1970, Anderson et al. 1971). If similar mineral compositions were present in komatiites, where the respective proportions are 20, 30 and 50% (Arndt
et al. 1977, Table 7), the whole rock $\delta^{18}O$ would be +5.4. This is, in fact, marginally within the projected Pyke Hill value of $+5.7 \pm 0.3\%_O$. This calculation also indicates that igneous fractionations can be responsible for only a small part of the observed $\delta^{18}O$ spread on Figure 18.4. The loss of 40% olivine would change the komatiite’s whole rock $\delta^{18}O$ value by only 0.3\%_O.

Komatiites, however, have considerably higher liquidus temperatures than basalts. The data of Arndt (1976) on the Pyke Hill komatiites, for example, indicate a liquidus (olivine saturation) temperature of about 1500°C, followed by the appearance of spinel (1350°C), pyroxene (1200°C) and plagioclase (1200°C), and a solidus of about 1150°C. Because the isotopic fractionation factor $\Delta$ between two phases is typically proportional to $1/T^2$ (e.g. Javoy 1977), the olivine in komatiites may be richer in $^{18}O$ than basaltic olivine. Preliminary work by Kyser and O’Neil (1978) and Kyser (1979) suggests that the olivine–pyroxene fractionation may even reverse at high temperature. This effect might account for the high extrapolated Pyke Hill whole rock value. On the other hand, Hoefs and Binns (1978) have reported olivine with $\delta^{18}O = +4.5$ and pyroxene with $\delta^{18}O = +5.6$ to $+5.9$ in the Australian komatiites. Further resolution of this problem must await the preparation and analysis of more mineral separates.

18.4.3 Source region

Because oxygen isotopic fractionations are independent of pressure, the assumptions of equilibrium partial melting and adiabatic rise to the surface permit estimation of the composition of the mantle through analysis of the magmas produced there. In this regard $\delta^{18}O$ of the Pyke Hill komatiites (+5.7 ± 0.3\%_O) is remarkably similar to $\delta^{18}O$ of a variety of ultramafic rocks, including nodules in Hawaiian basalts, +5.8\%_O (Kyser & O’Neil 1978); Beni Bousera, Lherz, Cassou and Lanzo, +5.56 ± 0.05\%_O (Javoy 1978); and assorted peridotites, pyroxenites and dunites (including the south-eastern Alaskan ultramafics) +5.6 ± 0.2\%_O (Taylor 1968). Whether or not these materials could be in equilibrium with +5.7\%_O tholeiitic basalt depends on the nature of the olivine–pyroxene–liquid fractionation at high temperature, as discussed above. In any case, the komatiite data (see also Hoefs & Binns 1978) suggest that mantle-derived magmas in the Archaean had oxygen isotopic compositions similar to those derived during more recent episodes in the Earth’s history.

18.4.4 $\delta^{18}O$ of secondary minerals

The extrapolated $\delta^{18}O$ of all the secondary minerals in the komatiite taken together (Fig. 18.5) is about +3.0\%_O. None of the five main secondary minerals (antigorite, magnetite, tremolite, brucite, chlorite) could be separated from these rocks because of their fine grain size (typically 1–50 µm) and textural complexity (Fig. 18.2). Assuming final equilibration at 300°C and the presence of antigorite, magnetite, tremolite and chlorite in the proportions 60:5:30:5, these minerals would have $\delta^{18}O$ values of about +3.2, −3.7, +3.8 and +3.2, respectively (Friedman & O’Neil
This calculation is admittedly speculative because of the uncertainty in the temperature and the somewhat variable proportions of the secondary minerals (Table 18.1). However, the calculated antigorite value is similar to that of a 1–2 mm wide chrysotile vein which cuts Pyke Hill (+3.8), and to chrysotile from two nearby asbestos mines (+3.5, +4.6) (Fig. 18.5).

18.4.5 Fluid composition and water:rock ratio

Because $^{18}$O and $^{16}$O are both non-radiogenic isotopes, their total amounts in the water–rock system are fixed, and the conservation of mass defines an equation governing the exchange of $^{18}$O between the water and rock. The open-system equation is (Taylor 1977)

$$W:R = \log \frac{\delta^{1}H_2O + \Delta - \delta^{1}rock}{\delta^{1}H_2O - (\delta^{1}rock - \Delta)}$$

where $W:R$ is the water:rock ratio in atom per cent oxygen, $\delta^{1}H_2O$ is the initial water composition, $\Delta$ is the fractionation between water and rock, and $\delta^{1}rock$ and $\delta^{1}rock'$ are the initial and final rock compositions, respectively. In the case of the Munro komatiites, the initial and final rocks are known (Fig. 18.5). $\Delta$ for the serpentinization reaction has been estimated by Wenner and Taylor (1973) as a function of temperature, so three unknowns describe the hydrothermal alteration: $T$, $W:R$ and $\delta^{1}H_2O$.

The most convenient way to represent these three variables is by using a plot of $\delta^{1}H_2O$ versus $W:R$ on which the isotherms are contoured (Fig. 18.6). Although

| Table 18.1 Data from single komatiite flow, Pyke Hill, Ontario. |
|------------------|----------------|----------------|----------|--------|--------|--------|
| height above base (m) | 2.9 | 2.1 | 2.6 | 1.1 | 0.05 | 0.2 |
| $\delta^{18}$O (%) | 4.6 | 4.9 | 4.9 | 3.5 | 3.8 | 4.9 |
| $\delta^{18}$O yield (μmoles mg$^{-1}$) | 14.66 | 13.72 | 14.81 | 14.34 | 14.43 | 13.93 |
| Mode § | olivine | secondary after olivine | groundmass (pyx + plag + chlorite) + opaque | total secondary | antigorite | magnetite | tremolite | brucite | chlorite | talc |
| (1) | (43) | (56) | (45) | (23) | (3) | (15) | (2) | (2) | (2) |
| 13 | 28 | 59 | 31 | 13 | 2 | 11 | 2 | 1 | 0 |
| 7 | 37 | 56 | 38 | 20 | 3 | 12 | 2 | 1 | (tr.?) |
| 6 | 74 | 20 | 75 | 64 | 8 | (tr.?) | <1 | (tr.?) | (tr.?) |
| 27 | 22 | 51 | 24 | (13) | 1 | 8 | 1 | 2 | 0 |
| 32 | 17 | 51 | 19 | (7) | (1) | 9 | <1 | (2) | 0 |

† Replicate analysis were performed on splits of the same sample.

‡ Low oxygen yields are probably due to incomplete fluorination of olivine.

§ Values in parentheses are visual estimates, others determined by point counting in transmitted light.
the mineral assemblages suggest a metamorphic temperature of about 300°C, there
is little assurance that all or even most of the water flux took place at that tem­
perature. It is perfectly possible that the rocks were altered at a lower temperature, such
as 200°C, and then isochemically heated to 300°C. Most probably the water–rock
interaction took place over a range of temperatures.

Because the rocks have lost \(^{18}\)O during alteration, if the water:rock ratio were
very small the fluid would have had to be very \(^{18}\)O-depleted to have produced such
a transformation. On the other hand, if the water:rock ratio were greater than about
two, the fluid would have had a \(^{18}\)O value in the vicinity of 0\%\textsubscript{o} and the isotopic
shifts would be essentially independent of W:R (Fig. 18.6). In that case, there
would be much more oxygen in the water than in the rock, so increasing W:R would
have little effect.

Several lines of evidence indicate that this alteration took place under conditions
of high water:rock ratio, indicating \(^{6}\)H\textsubscript{2}O close to 0\%\textsubscript{o}. The basaltic rocks associated
with the komatiites (e.g. Theo's flow = +6.3\%\textsubscript{o}) are also extensively hydrothermally altered, but show \(^{18}\)O enrichments instead of depletions (Beaty & Taylor 1979). Similar water–rock calculations on those samples indicate possible hydrothermal fluids in the range \(-2 \text{ to } +2\) at high W:R, increasing to \(>8\) at low W:R (Beaty 1980). Inasmuch as the two rock types were altered together, the Abitibi hydrothermal fluid must lie within the field of coincidence, which spans \(^{6}\)H\textsubscript{2}O =
\(-2 \text{ to } +2\), and W:R \(>1\).

High water:rock ratios have also been calculated by White (1968) on the meta­
morphically similar Keweenawan basalts, and by McCulloch \textit{et al.} (1981) for the
sub-seafloor alteration of the Samail ophiolite. Independently, Taylor (1977), in
his study of granitic batholiths, found evidence that $\delta^{18}O$ of ocean water has remained relatively constant (close to 0) over the last 2.5 Ga. At the Amulet mine within the Abitibi greenstone belt (2.85 Ga) there is also good evidence that sea water had $\delta^{18}O = +0.5 \pm 1.0$ (Beaty & Taylor 1980). Thus the data in this paper are consistent with the interpretation that the komatiites were hydrothermally altered by sea water, and that sea water has not changed in $\delta^{18}O$ since the Archaean. In this regard it is interesting to note that modern oceanic antigorite (Wenner & Taylor 1973) is similar in $\delta^{18}O$ to the komatiitic serpentine (Fig. 18.7).

18.4.6 Komatiites from other areas

Two samples of komatiites from elsewhere in the Abitibi greenstone belt have been studied. A sample of coarse spinifex-textured komatiite from Spinifex Ridge in Lamotte Township, Quebec (Lajoie & Gélinas 1978) has $\delta^{18}O = +4.5$ (Fig. 18.7). This rock is completely recrystallized to an assemblage of tremolite + chlorite + serpentine + magnetite, and is thus mineralogically and isotopically similar to the Munro komatiites. The degree of alteration is greater, but as in Munro the assemblage suggests an addition of silica to the rock.

By contrast, a komatiitic basalt (identified by Jensen (1978) on the basis of texture and composition) from Skead Township, Ontario, has $\delta^{18}O = +8.4$ (Fig. 18.7). The metamorphic assemblage of this rock, however, is tremolite + chlorite + haematite + epidote + sphene. This basalt differs from the komatiites in Munro and Lamotte Townships, in that it contains only 14% MgO (versus 20–35%), 15% CaO
(versus 3—9%) and 1.8% $K_2O$ (versus 0.01—0.10%). The $K_2O$ concentration, the presence of haematite + epidote instead of magnetite, and the absence of serpentine suggest that this rock has been subjected to more complex hydrothermal processes than the Munro komatiites. This makes interpretation of the isotopic data very difficult. The high $^{18}O$ character may be partially related to the mineralogy because tremolite and epidote (?) have a greater tendency to concentrate $^{18}O$ than serpentine and magnetite (O'Neil 1977). However, the Skead Township basalt must also have been altered either at a lower temperature or by a higher $^{18}O$ fluid.

Three analyses of Archaean ultramafic rocks from the greenstone belts around Despair Lake, Ontario, range in $\delta^{18}O$ value from +5.3 to +6.8 (Longstaffe et al. 1977). These samples are from a serpentinized dunite emplaced in the basalt sequence (F. J. Longstaffe, personal communication), which may have undergone a hydrothermal process similar to that which has affected the komatiites.

Some $\delta^{18}O$ data have also been collected for Australian komatiites by Hoefs and Binns (1978). In those samples the komatiites range from $\delta^{18}O = +5.0$ to +9.4 (Fig. 18.7). If fresh komatiites were erupted with $\delta^{18}O = +5.7 \pm 0.3$, then these rocks show both increases and decreases in $\delta^{18}O$ value, similar to the Canadian results. The significance of these values is not clear, however, because of the incomplete petrographic data.

### 18.5 CONCLUSIONS

Oxygen isotopic investigation of the Munro Township komatiites has led to the following conclusions. First, in spite of the excellent state of textural preservation, all of the komatiites analysed have undergone oxygen isotopic exchange with very large quantities of hydrothermal fluid. This exchange manifests itself principally in the serpentinization of olivine. Second, the hydrothermal fluid was apparently sea water or marine-derived pore fluids with $\delta^{18}O \sim 0 \pm 2$. Although the komatiite flows may have interacted directly with the ocean water they flowed into, probably most of the alteration was accomplished by sea water circulating deeply into the volcanic pile as the komatiites were buried and heated. It is important to emphasize that the serpentinization was caused by a flow of water through the komatiites and involved exchange with considerably more water than that needed to make stoichiometric serpentine. Third, the $\delta^{18}O$ of the original komatiite magma was apparently $+5.7 \pm 0.3$. This value is indistinguishable from $\delta^{18}O$ of a wide variety of modern ultramafic rocks, including nodules in basalts, high-temperature peridotites, and the south-eastern Alaskan intrusives. This suggests that $\delta^{18}O$ of the Earth's mantle has not changed appreciably throughout geological history.
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D. W. BEATY AND H. P. TAYLOR JR


