Characterization of fluid involved in ultramafic rocks along the Rakhabdev Lineament from southern Rajasthan, northwest India

Harsh Bhu1, Arindam Sarkar2, Ritesh Purohit1,* and Amlan Banerjee2

1Department of Geology, M. L. Sukhadia University, Udaipur 313 002, India
2Stable Isotope Laboratory, Indiana University, Bloomington, Indiana, 47405-1405, USA

The communication reports characterization of fluid involved in the process of serpentinization of the ultramafic rocks from the Rakhabdev–Kherwara sector constrained along the Rakhabdev Lineament, in southern Rajasthan, northwest India, at a temperature of around 350°C. The relatively low water/rock ratio in the rocks suggests the possibility of extensive isotopic exchange over a long period of time in a completely fluid buffered system. The isotopic data suggest possible involvement of at least two different fluid systems, either involving highly evolved meteoric water or a mixture of hydrothermal fluids with the meteoric water. The presence of extensive chloritization in the metamorphic country rocks suggests involvement of low degree of metamorphism during the alteration. Additional isotopic studies are required to understand the role of different fluid sources in altering the ultramafic rocks of the studied region.

Keywords: Fluid characterization, hydrogen isotopes, Rakhabdev Lineament, serpentines.

AN ensemble of ultramafic rocks occurs in different parts of the Proterozoic Aravalli Supergroup around Udaipur–Kherwara–Dungarpur sector in southern Rajasthan, northwest India. The dominant outcrops occur along a prominent lineament, the Rakhabdev Lineament, that runs from southwest of Udaipur to the north of the Barwania (22°55′: 74°56′), south of the Narmada river. Major outcrops of the ultramafic bodies occur in the region between Rakhabdev (24°50′: 73°40′) and Kherwara (23°59′: 73°35′) (Figure 1). This belt of ultramafic bodies coincides roughly with the boundary between the shelf and the deep-sea sedimentary facies associations of the Aravalli Supergroup. Based mainly on this geological setting of the ultramafic bodies of the Rakhabdev–Kherwara belt, several workers proposed an ophiolite evolution of these rocks. On the other hand, some others have grouped them as intrusive bodies. South of Kherwara the ultramafic bodies occur as isolated linear bodies giving a picture of a dyke swarm. The post-orogenic character of these bodies is abundantly clear in the sector south of Dungarpur (22°55′: 73°45′), where these bodies are seen to cross-cut the complexly folded rocks of the Aravalli Supergroup. If we correlate this complex deformation pattern in the southern Aravalli (mountain) belt with the Satpura Orogeny1, then the age of these ultramafic bodies would be quite young, Neoproterozoic to be precise. In contrast to the occurrence of ultramafic rocks along the Rakhabdev Lineament, those which occur in the deep-water facies sedimentary belt of the Aravalli Supergroup in the Jharol belt, west of Udaipur, are generally considered as the syn-sedimentary bodies occupying the uppermost stratigraphic level (Table 1)2. Looking into the diverse field relationship in different parts of the Aravalli basin, it is difficult to rule out the possibility of at least two periods of ultramafic emplacement, one during the Aravalli Orogenic cycle and the other at a late stage which could even have post-dated the Neoproterozoic Satpura Orogeny.

Looking into the intensity of controversy based on field data, we tried to address the problem from a different angle by understanding the nature of fluids that were involved in the generation of serpentinites, the primary constituent of the ultramafic ensemble. It is now well known that the nature and extent of serpentinization in ultramafic rocks depend on factors like nature of fluid, temperature, water-to-rock ratio and type of alteration process. Studies by a number of workers3-9 indicated how the rela-

*For correspondence. (e-mail: ritesh_purohit@rediffmail.com)
tive importance of these factors, especially the nature of the serpentinizing fluid is reflected in the variation of isotopic composition of hydrogen and oxygen. Information based on stable isotopic study therefore is likely to provide us an indirect clue to the mode of emplacement of the ultramafic bodies of the Rakhabdev–Kherwara belt, which is the most controversial sector in terms of the emplacement mode of these rocks.

The studied ultramafic rocks of the Rakhabdev–Kherwara belt predominantly comprise serpentinites, which show extensive alteration to talc-carbonate, talc and chlorite-schist rocks. The rocks occur as large, irregular lensoid bodies, some of which are more than 5 km in length along the strike. The general trend of these bodies is N–S. Outcrops around Kherwara are scattered in the form of a ring (Figure 1). ‘Country rocks’ of the ultramafic rocks consist of dolomitic carbonates, quartzo-feldspathic schist, amphibolite and quartzite, which show three phases of folding deformation. Locally, thermal metamorphism has been noted in dolomitic carbonates that occur adjacent to the ultramafic rocks.

The serpentinites appear as compact, fine-to-medium grained rocks with a splintery to conchoidal fracture having smooth, greasy and wax-like appearance. Weathering has produced a pitted surface and cavity filled with reddish-brown limonite. In the field, the serpentinites show three distinct variants:

(i) Tough, massive, pale yellow, greenish-yellow to greyish-green serpentinite, generally very fine-grained and often rich in opaque minerals.

(ii) Pale green, pistachio green, apple green and slaty black, highly foliated and at places sheared, medium-to-coarse grained, showing development of carbonate, chlorite, steatite and crysolite. The latter mineral shows slip-fibre type growth.

(iii) Massive, deep green, very fine-grained and rich in fibrous tremolite. Opaque grains of sphene, magnetite and chromite are scattered in the massive serpentinites.

Sheared serpentinites showing development of mylonitic cleavage associated with hydrothermal fluid-induced retrogressive metamorphism formed pockets of talc and crysolite deposits. In thin sections, the serpentinites appear as an altered mass forming a network of short prismatic laths, fibres or flakes of antigorite (Figures 2 c–d and 3).

Laboratory studies of serpentinite samples drawn from the studied region included XRD and isotopic measurements made at the Department of Geological Sciences, Bloomington, Indiana, USA. Hydrogen was analysed using a Thermo-Finnigan Delta-plus-XP stable isotope ratio mass spectrometer. Oxygen isotope studies were made following the method of Clayton and Mayeda10, while hydrogen isotope studies were conducted according to the method of Sharp et al.11. Both the oxygen and hydrogen isotopic compositions are reported in standard δ notation relative to Vienna Standard Mean Ocean Water (VSMOW).

The results are listed in Table 2, which are indicated by two varieties of serpentines; one is a fine, single, homogenous phase (Figure 2 a) and another is included within the fine homogenous host (Figure 2 b). The single homogenous phase is mainly antigorite. The included phase within the fine homogeneous phase (serp-10, serp-12) is also antigorite variety (Figure 3). The δ18O and δD values of the fine, homogenous and included phases are listed in Table 2 and illustrated in Figure 4. The results show a restricted range of oxygen and hydrogen isotopic values. The isotopic compositions of homogenous serpentine show a narrow range of δD values but a relatively wide range of δ18O values. Values of δ18O and δD range between 6.1 and 7.9‰ (δ18O mean: 6‰) and between −73 and −80‰ (δD mean is −75‰; Table 2) respectively. Two samples, one with relatively low δD value of −94‰ and another with a lower δ18O value of 4.7‰, fall outside the range. The included phase and homogenous groundmass show similar isotopic values, which appear close to single, homogenous serpentine phases observed in other samples. One chlorite sample associated with serpentine was also analysed. It
showing relatively low $\delta^{18}O$ (5.9‰) and high $\delta D$ (~70‰) values. The combined data are plotted on a $\delta^{18}O$ versus $\delta D$ plot (Figure 4). Interestingly, isotopic data for our samples are from the Rakhabdev Lineament sector plot within the field observed by Wenner and Taylor\textsuperscript{4}, and Burkhard \textit{et al.}\textsuperscript{8} for continental chrysotile and antigorite (Figure 4).

Looking into the possible complex history of evolution, we employed the conventional method of temperature estimation by studying the mineral assemblages. Considering the absence of the prehnite–pumpellyite assemblage\textsuperscript{12,13} and the formation of serpentinite through the alteration of Fe-olivine, the formational temperature\textsuperscript{9,14,15} of serpentinite is assumed to remain below 350°C.

Understanding that the mineral-water fractionation is important in computing isotopic values of water in equilibrium with silicate minerals, we used the apparently most
acceptable hydrogen serpentine-water fractionation factor of Wenner and Taylor\(^4\). Figure 5 illustrates the effects of a close system isotopic exchange on mineral water $\delta^{18}O$ and $\delta D$ values calculated from serpentine water fractionation factor at a temperature of 350°C. The values show a range between 5.4 and 7.8‰ and between –61 and –82‰ respectively. We have also calculated fluid $\delta^{18}O$ and $\delta D$ for the included phases present in massive homogeneous host. The $\delta^{18}O_{\text{fluid}}$ values range between 6.7 and 6.8‰, while the $\delta D_{\text{fluid}}$ values are between –68 and –71‰. The small range of $\delta^{18}O_{\text{fluid}}$ and relatively wide range of $\delta D_{\text{fluid}}$ values computed from serpentine suggest involvement of at least two different fluids in the alteration process of the Rakhabdev–Kherwara ultramafics. The fluid equilibrated with chlorite is different ($\delta^{18}O_{\text{fluid}}$: 5.9‰, $\delta D$: –70‰) than other serpentines, but both values of $\delta^{18}O$ are in close proximity.

Before understanding the role and nature of the fluid, it is important to know the fluid paths. Figure 5 illustrates isotopic exchange of fluid with rocks at variable, effective and time-integrated water-to-rock ratio. The ratio depends on the nature of rock porosity and fluid flow rate. Figure 5 also illustrates change in isotopic composition of fluid by exchanging with rocks over a long period of time. Generally un-evolved, short pathlength fluid is characteristic of fluid-buffered system and high time-integrated water/rock ratio. The relatively low water/rock ratio possibly suggests that the fluids were already in equilibrium with serpentine for a long period of time prior to reaction with mafic–ultramafic rocks.
Table 2. Oxygen and hydrogen isotopic data of serpentine and equilibrated fluid value at 350° C from ultramafics of Rakhabdev Lineament, Rajasthan, India

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>δD</th>
<th>δ¹⁸O</th>
<th>δ¹⁸O_{water}</th>
<th>δD_{water}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serp-1</td>
<td>Antigorite</td>
<td>-73</td>
<td>6.2</td>
<td>6.9</td>
<td>-61</td>
</tr>
<tr>
<td>Serp-6</td>
<td>Antigorite</td>
<td>-75</td>
<td>7.9</td>
<td>8.6</td>
<td>-63</td>
</tr>
<tr>
<td>Serp-7</td>
<td>Antigorite</td>
<td>-73</td>
<td>7.1</td>
<td>7.8</td>
<td>-61</td>
</tr>
<tr>
<td>Serp-9</td>
<td>Antigorite</td>
<td>-73</td>
<td>6.4</td>
<td>7.1</td>
<td>-61</td>
</tr>
<tr>
<td>Serp-10</td>
<td>Antigorite</td>
<td>-94</td>
<td>6.4</td>
<td>7.1</td>
<td>-82</td>
</tr>
<tr>
<td>Serp-11</td>
<td>Antigorite</td>
<td>-71</td>
<td>6.9</td>
<td>7.6</td>
<td>-59</td>
</tr>
<tr>
<td>Serp-12</td>
<td>Antigorite</td>
<td>-86</td>
<td>6.9</td>
<td>7.6</td>
<td>-74</td>
</tr>
<tr>
<td>Serp-13</td>
<td>Antigorite</td>
<td>-78</td>
<td>4.7</td>
<td>5.4</td>
<td>-66</td>
</tr>
<tr>
<td>Serp-14</td>
<td>Antigorite</td>
<td>-76</td>
<td>6.4</td>
<td>7.1</td>
<td>-64</td>
</tr>
<tr>
<td>Serp-UNK</td>
<td>Antigorite</td>
<td>-76</td>
<td>6.1</td>
<td>6.8</td>
<td>-65</td>
</tr>
<tr>
<td>Serp-9 (inclusive)</td>
<td>Antigorite</td>
<td>-67</td>
<td>6.2</td>
<td>6.9</td>
<td>-55</td>
</tr>
<tr>
<td>Serp-10 (inclusive)</td>
<td>Antigorite</td>
<td>-80</td>
<td>6.1</td>
<td>6.8</td>
<td>-69</td>
</tr>
<tr>
<td>Serp-11 (inclusive)</td>
<td>Antigorite</td>
<td>-73</td>
<td>7.4</td>
<td>8.1</td>
<td>-62</td>
</tr>
<tr>
<td>Serp-12 (inclusive)</td>
<td>Antigorite</td>
<td>-82</td>
<td>6.0</td>
<td>6.7</td>
<td>-71</td>
</tr>
<tr>
<td>Serp-13 (brown)</td>
<td>Chlorite</td>
<td>-67</td>
<td>3.5</td>
<td>4.2</td>
<td>-56</td>
</tr>
<tr>
<td>Serp-8</td>
<td>Chlorite</td>
<td>-70</td>
<td>5.9</td>
<td>6.6</td>
<td>-58</td>
</tr>
</tbody>
</table>

Figure 5. δ¹⁸O_{water} vs δD_{water} plot showing isotopic composition of water in equilibrium with serpentine from Uitkomst complex at 350°C. The illustrated exchange path of meteoric water at various water-to-rock weight ratios is computed for exchange with basaltic rocks with δ¹⁸O_{water} ~ -6‰ and δD_{water} ~ -75‰, 1% water, Δ¹⁸O_{rock-water} and ΔD_{rock-water} being -0.194 and -12.73 respectively.

Extensive serpentinization observed in the thin and polished sections implies requirement of at least 10% water for the process of mineral conversion. The isotopic data (Figure 5) fall within the magmatic water box, suggesting the involvement of magmatic water. However, the mineral assemblages of ultramafic rocks and their geological history do not rule out the possibility of involvement of water from other sources. Formation of serpentine from sea water is well established by several authors. Keeping the isotopic data in mind, there are two different possibilities on nature of the fluid involved in the serpentinization process. One is that the meteoric water of δ¹⁸O ~-5‰ and δD ~-70‰ calculated to be in equilibrium with serpentine may apply to fluids that had already undergone extensive isotopic change in the flow system prior to interaction with pyroxene and/or olivine-bearing primary igneous rocks and magmatic rocks of δD ~-70‰ and δ¹⁸O ~-6‰ at the Rakhabdev–Kherwara ultramafics. Another reasonable alternative is that the meteoric water exchange with country rocks at depleted water–rock ratios (0.005 to 0.001, Figure) for a long period of time, and then stays there and mix with lately generated magmatic or hydrothermal water along the fluid path (Figure 5). Additional isotopic studies of serpentine over a broad area at the Rakhabdev Lineament sector are, however, required to differentiate the role of individual fluid sources.

Summarizing, both mineralogical and stable isotopic data suggest a complex history of serpentinization of the Rakhabdev–Kherwara sector. Oxygen and hydrogen isotopic studies of serpentines indicate that isotopic compositions are the result of rock interaction with one or two distinct fluid types. Oxygen and hydrogen isotopic data of serpentine and chlorite are consistent with the involvement of fluid with characteristics similar to evolved meteoric water and hydrothermal fluid. Although metamorphic water cannot be ruled out, the fluid source can be better explained either as evolved meteoric water or as the product of mixing between evolved meteoric water and hydrothermal fluids which were generated at a later stage. The range in serpentine δD values may be explained by mixing of already equilibrated meteoric with primary igneous rocks. The actual source and nature of the fluid involved in the Rakhabdev–Kherwara sector is difficult to suggest.
without a detailed understanding of serpentine species and their spatial O and H isotopic distribution. This necessitates further detailed study for better characterizing the serpentinization process in the Rakhabdev–Kherwara region constrained along the Rakhabdev Lineament.


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In situ observations on preferential grazing of seaweeds by some herbivores

M. Ganesan*, S. Thiruppathi¹, Nivedita Sahu¹, N. Rengarajan¹, V. Veeragurunathan¹ and Bhavanath Jha²

¹Marine Algal Research Station, Central Salt and Marine Chemicals Research Institute, Mandapam Camp 623 519, India
²Marine Algae and Marine Environment, Central Salt and Marine Chemicals Research Institute, Bhavnagar 364 002, India

Grazing of seaweed tissues by herbivores causes inconsistent crop yields that make commercial seaweed farming a less economically viable venture. In most situations, about 10% of available seaweed biomass is removed by the herbivores. To identify the seaweeds that are preferred by the herbivores, a study was carried out near the experimental seaweed farming site at Krusadai Island (9°14.823′N; 79°12.921′E), southeast coast of India. Abundant populations of grazer fishes, namely Siganus javus (Rabbit fish), Acantthursus sp. (Surgeon fish), Cetoscarus sp. (Parrot fish) and sea urchin Tripneustes sp. were observed near this site. Twenty different seaweed species tested for this study include Caulerpa racemosa, C. taxifolia, Halimeda gracilis, H. macroloba (all Chlorophyceae), Sargassum wightii, Turbinaria conoides, Dictyota dichotoma, Padina boergesennii, Pococikella vaigata, (all Phaeophyceae), Hypnea musciformis, H. valentiae, Chama pnia parvula, Acanthophora spicifera, Gelidiella acerosa, Gracilaria crassa, G. edulis, G. dura, G. corticata, Laurencia papillo sa and Kappaphycus alvarezii (all Rhodophyceae). Among these, only five species of Rhodophyceae were grazed. G. edulis was the preferred choice of herbivores and 72 ± 17.8% of its biomass (P < 0.03) was grazed from the initial biomass of 5 g fresh wt. The corresponding grazing value for G. dura was 57.4 ± 28% (P < 0.02), for G. corticata, 47.2 ± 27.2% (P < 0.02), for L. papillosa, 41 ± 21% (P < 0.01) and for K. alvarezii, 34 ± 10.4% (P < 0.01) against their original

*For correspondence. (e-mail: ganesanddr@yahoo.com)