

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

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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 to 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 workers^{3–9} indicated how the rela-

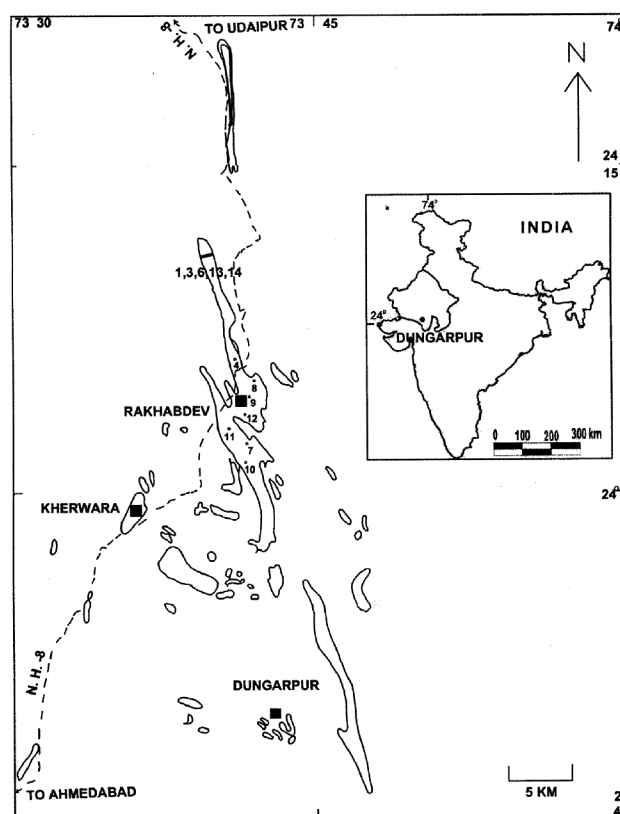


Figure 1. Outcrops of ultramafic bodies showing sample location from Rakhabdev, southern Rajasthan, northwest India.

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Table 1. Stratigraphic classification of the Aravalli Supergroup in the type area after Roy *et al.*²

Shelf sequence		Deep-water sequence	
Upper Aravalli Group	Ultramafic intrusives Lakhawalli Phyllite Kabita Dolomite Debari Formation	Jharol Formation Formation Conglomerate, arkose and quartzite	Mica schist and thin beds of quartzite, ultramafics
-----Unconformity-----			
Middle Aravalli Group	Tidi Formation Bowa Formation Mochia Formation Udaipur Formation		
-----Unconformity-----			
Lower Aravalli Group	Jhamarkotra Formation Delwara Formation		
-----Unconformity-----			
Mewar Gneiss		(Archaean)	

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 Rakhadev–Kherwara belt, which is the most controversial sector in terms of the emplacement mode of these rocks.

The studied ultramafic rocks of the Rakhadev–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 bodies.

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:

- Tough, massive, pale yellow, greenish-yellow to greyish-green serpentinite, generally very fine-grained and often rich in opaque minerals.
- 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.
- 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, homogeneous phase (Figure 2 *a*) and another is included within the fine homogeneous host (Figure 2 *b*). The single homogeneous phase is mainly antigorite. The included phase within the fine homogeneous phase (serp-10, serp-12) is also antigorite variety (Figure 3). The $\delta^{18}\text{O}$ and δD values of the fine, homogeneous 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 homogeneous serpentine show a narrow range of δD values but a relatively wide range of $\delta^{18}\text{O}$ values. Values of $\delta^{18}\text{O}$ and δD range between 6.1 and 7.9‰ ($\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ value of 4.7‰, fall outside the range. The included phase and homogeneous groundmass show similar isotopic values, which appear close to single, homogeneous serpentine phases observed in other samples. One chlorite sample associated with serpentine was also analysed. It

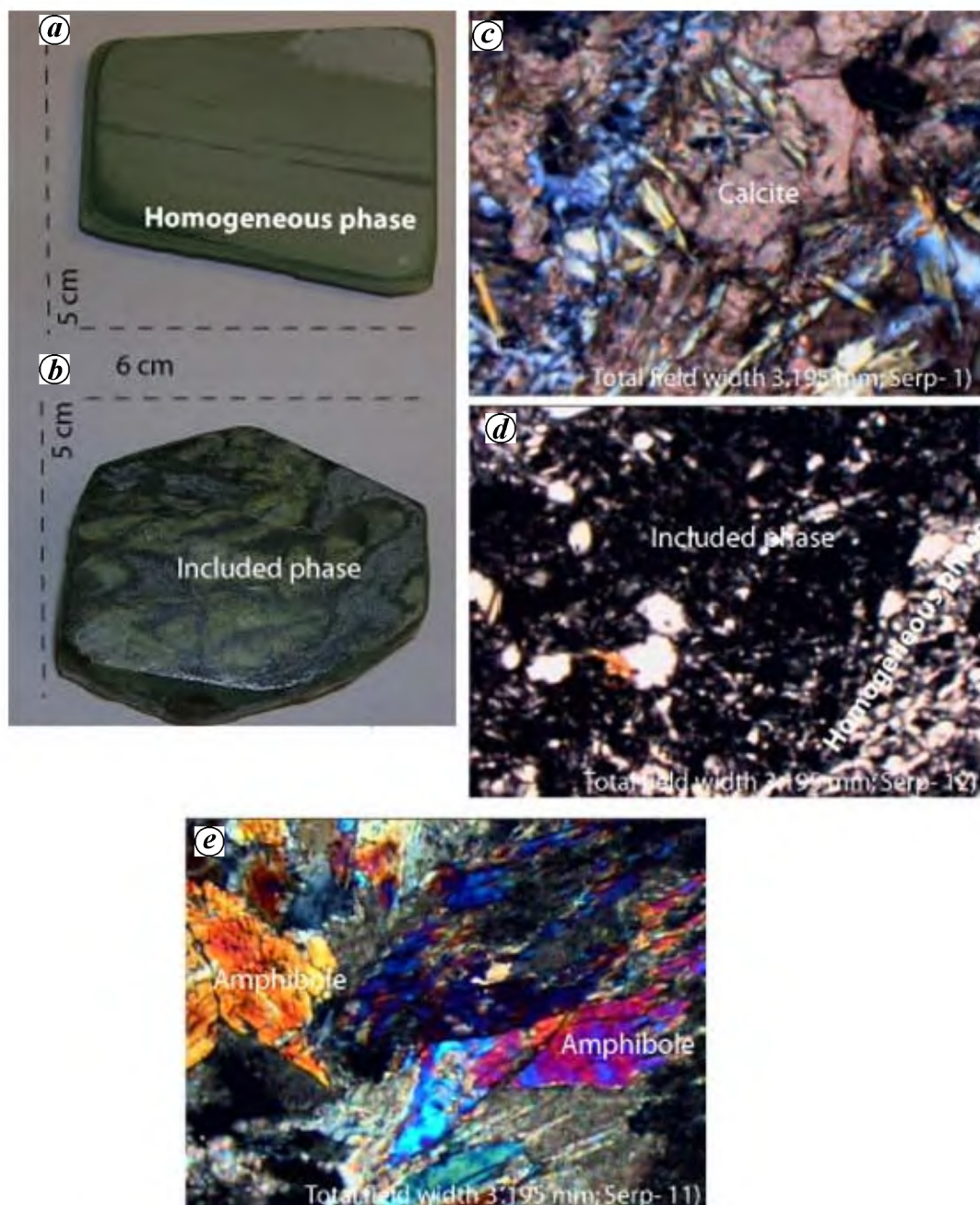


Figure 2. *a*, Fine, single phase homogenous serpentinite. *b*, Two phase serpentinite; one phase is included within another. *c*, Photomicrograph of serpentinite unit containing serpentine and calcite. Serpentine found as thin flakes, associated with calcite (serp-1; cross polar). *d*, Photomicrograph of second-generation serpentinite within a serpentinite host. Serpentine host is identified by fresh and homogenous phase, whereas included phase is identified by strong optical discontinuity (serp-12; cross polar). *e*, Photomicrograph of relict amphibole observed within serpentinite host. Relict amphibole probably indicates the presence of olivine and/or pyroxene before whole-sale serpentinization (serp-11; cross polar). (Total field width 3.195 mm for all five photomicrographs).

shows relatively low $\delta^{18}\text{O}$ (5.9‰) and high δD (−70‰) values. The combined data are plotted on a $\delta^{18}\text{O}$ versus δD plot (Figure 4). Interestingly, isotopic data for our samples are from the Rakhadev Lineament sector plot within the field observed by Wenner and Taylor⁴, and Burkhard *et al.*⁸ for continental chrysotile and antigorite (Figure 4).

Looking into the possible complex history of evolution, we employed the conventional method of temperature esti-

mation by studying the mineral assemblages. Considering the absence of the prehnite–pumpellyite assemblage^{12,13} and the formation of serpentinite through the alteration of Fe-olivine, the formational temperature^{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

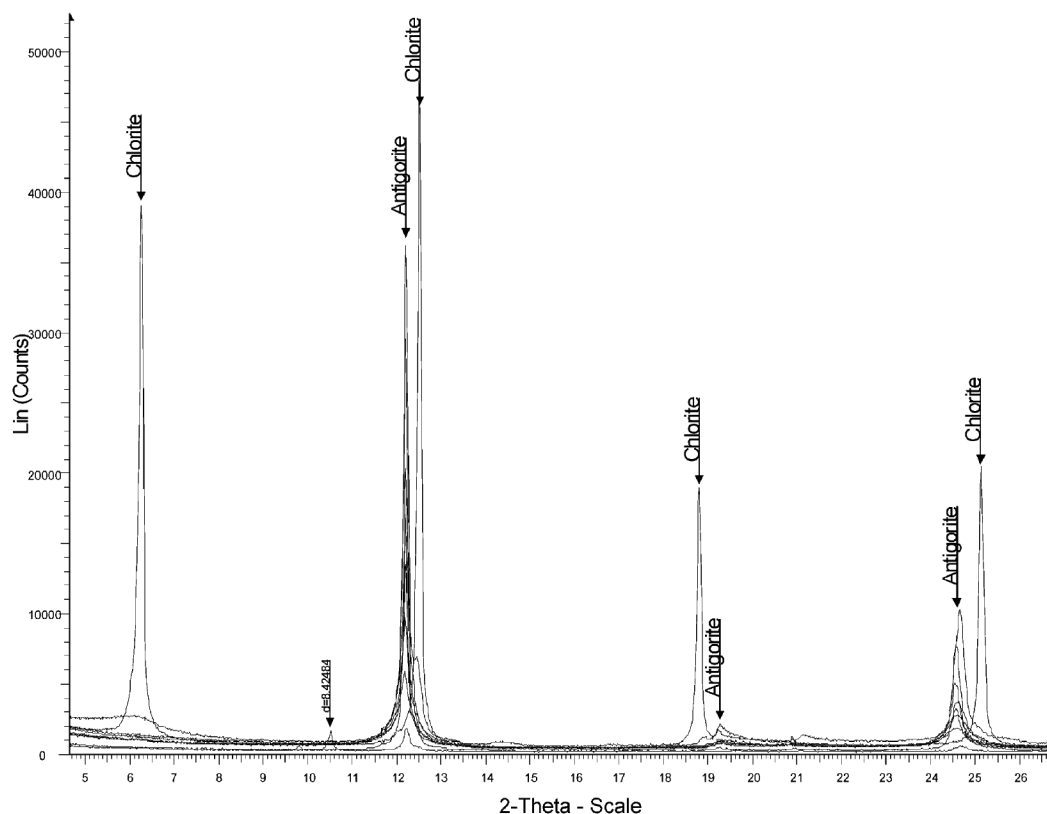


Figure 3. X-ray diffraction data of various serpentine and chlorite minerals.

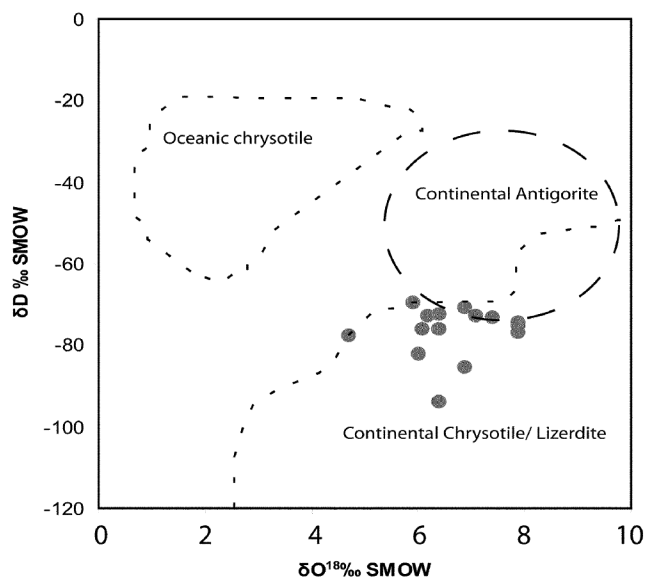


Figure 4. Isotopic data of serpentine showing various tectonic environments⁷. Dotted field is after Wenner and Taylor⁴, and dashed field is after Burkhard *et al.*⁸.

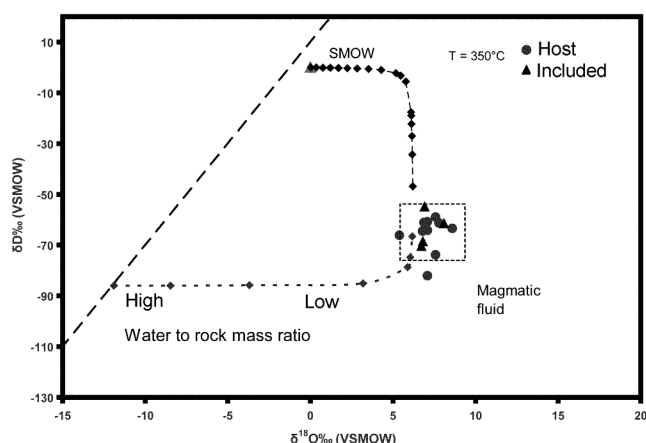
acceptable hydrogen serpentine-water fractionation factor of Wenner and Taylor⁴. Figure 5 illustrates the effects of a close system isotopic exchange on mineral water $\delta^{18}O$

and δD 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 δD 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 δD_{fluid} values are between -68 and -71‰. The small range of $\delta^{18}O_{\text{fluid}}$ and relatively wide range of δD_{fluid} values computed from serpentine suggest involvement of at least two different fluids in the alteration process of the Rakhadev-Kherwara ultramafics. The fluid equilibrated with chlorite is different ($\delta^{18}O_{\text{fluid}}$: 5.9‰, δD : -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

Sample	Mineral	δD	$\delta^{18}O$	$\delta^{18}O_{\text{fluid}}$	δD_{fluid}
Serp-1	Antigorite	-73	6.2	6.9	-61
Serp-6	Antigorite	-75	7.9	8.6	-63
Serp-7	Antigorite	-73	7.1	7.8	-61
Serp-9	Antigorite	-73	6.4	7.1	-61
Serp-10	Antigorite	-94	6.4	7.1	-82
Serp-11	Antigorite	-71	6.9	7.6	-59
Serp-12	Antigorite	-86	6.9	7.6	-74
Serp-13	Antigorite	-78	4.7	5.4	-66
Serp-14	Antigorite	-76	6.4	7.1	-64
Serp-UNK	Antigorite	-76	6.1	6.8	-65
Serp-9 (inclusive)	Antigorite	-67	6.2	6.9	-55
Serp-10 (inclusive)	Antigorite	-80	6.1	6.8	-69
Serp-11 (inclusive)	Antigorite	-73	7.4	8.1	-62
Serp-12 (inclusive)	Antigorite	-82	6.0	6.7	-71
Serp-13 (brown)		-67	3.5	4.2	-56
Serp-8	Chlorite	-70	5.9	6.6	-58

**Figure 5.** $\delta^{18}O_{H_2O}$ vs δD_{H_2O} 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 $\delta^{18}O_{H_2O} \sim 6\text{‰}$ and $\delta D_{H_2O} \sim -75\text{‰}$, 1% water, $\Delta^{18}O_{\text{rock-water}}$ and $\Delta D_{\text{rock-water}}$ being -0.194 and -12.75 respectively.

Extensive serpentinization observed in the thin and polished sections implies requirement of at least 10% water¹⁶ 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^{4,9}. But in the present case it appears that sea water conditions have to be ruled out, considering the geological setting of the serpentinites. The isotopic data also (Figure 4) categorically suggest the continental origin of antigorite and chrysotile. The third possibility for serpentinization could be metamorphic fluid. Most of the metamorphic country rocks at the

Rakhabdev–Kherwara sector are chlorite-rich and could be responsible for serpentinization, as suggested by Kyser *et al.*¹⁷.

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 $\delta^{18}O \sim 5\text{‰}$ and $\delta D \sim -70\text{‰}$ 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 $\delta D \sim -70\text{‰}$ and $\delta^{18}D \sim 6\text{‰}$ 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.

structural facilities for field work and preparation of thin and polished sections. Isotopic determination studies were carried out at Stable Isotope Lab, Indiana University, Bloomington, USA. We thank Dr E. M. Ripley, Indiana University, for guidance during data interpretation. We also thank the anonymous reviewer for comments and suggestions.

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***In situ* observations on preferential grazing of seaweeds by some herbivores**

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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), *Acanthurus* 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 boergesenii*, *Pocockiella vaiegata*, (all Phaeophyceae), *Hypnea musciformis*, *H. valentiae*, *Champia parvula*, *Acanthophora spicifera*, *Gelidiella acerosa*, *Gracilaria crassa*, *G. edulis*, *G. dura*, *G. corticata*, *Laurencia papillosa* and *Kappaphycus alvarezii* (all Rhodophyceae). Among these, only five species of Rhodophyceae were grazed. *G. edulis* was the preferred choice of herbivores and $72 \pm 17.8\%$ 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 $57.4 \pm 28\%$ ($P < 0.02$), for *G. corticata*, $47.2 \pm 27.2\%$ ($P < 0.02$), for *L. papillosa*, $41 \pm 21\%$ ($P < 0.01$) and for *K. alvarezii*, $34 \pm 10.4\%$ ($P < 0.01$) against their original

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