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GR Letter

Signatures of rift environment in the production of garnet-amphibolites and eclogites from Tso-Morari region, Ladakh, India: A geochemical study

D. Rameshwar Rao *, Hakim Rai

Wadia Institute of Himalayan Geology, 33 General Mahadeo Singh Road, Dehradun – 248 001, Uttaranchal, India

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Abstract

The geochemistry of eclogites and garnet-amphibolites from Tso-Morari region, Ladakh, India has been investigated to characterize their protoliths on the basis of immobile elements, especially trace elements including REE. The eclogites and garnet-amphibolites have coherent compositions, except for the UHP metamorphic minerals being preserved in eclogites. Compositionally, the metabasites range from 'depleted' to 'enriched', and span from within-plate basalts (WPB) to MORB fields, and match with various enriched or 'transitional' MORB types (e.g., on Ti–Zr–Y and Nb–Zr–Y ternary plots). Isotopically they have Sr_i ratio ~ 0.706 which is similar to some of the Ocean Island Basalt (OIB). The rocks under study suggest that the enriched components are probably derived by melting of a mantle source with an enriched OIB-type component rather than due to the crustal contamination. We propose a rift environment for their protoliths and relate to advanced intra-continental rift situation. Furthermore, our geochemical studies envisage an initial phase of plume activity (Cambrian or earlier) resulting in basaltic magma in the eclogitic layers at sub-lithospheric levels, wherein they were subjected to crystallization under ultra-high pressure conditions. At a later stage the reactivation of faults (probably during Permo-Triassic times) acted as channels for the emplacement of the high pressure rocks in the continental crust. Subsequently, the ultra-high pressure rocks got re-equilibrated as amphibolites, with some remaining as relict eclogites, which later got exposed to the surface during various phases of the Himalayan uplift.

Keywords: Eclogites; Garnet-amphibolites; Mantle plumes; Tso-Morari Crystalline Complex; Ladakh, India

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1. Introduction

The coesite-bearing UHP eclogites from Tso-Morari, India and Kaghan, Pakistan, prompted many workers to relate the existence of coesite to subduction beneath the Kohistan–Ladakh arc to depths of >90 km (Kaneko et al., 2003; O'Brien et al., 2001; Sachan et al., 2004). Much of the geological research on the Tso-Morari Crystalline Complex has so far been focused on petrological investigations, determining the metamorphic conditions (e.g., Sachan et al., 1999; Jain et al., 2003; de Sigoyer et al., 2004), and on the precise dating of UHP metamorphism through Sm–Nd, Lu–Hf, and U–Pb SHRIMP dating techniques (de Sigoyer et al., 2000, Leech et al., 2005, and the references therein). However, less focus has been drawn on the geochemical studies of garnet-amphibolites, some of which host the UHP minerals like coesite (cf. Mukherjee and Sachan, 2001).

It is well known that the metamorphosed basic and ultrabasic rocks are of substantial importance in establishing the tectonic evolution of mountain belts. Geochemical data, especially less mobile and immobile trace elements and rare earth elements (REE) can be used to provide information on the protolith character of these metamorphic rocks. The aim of this paper is to reveal the nature of the Tso-Morari protoliths and their possible geotectonic environment of emplacement with the support of geochemical data.

2. Geology of the area

The Tso-Morari Crystalline Complex in eastern Ladakh (Fig. 1) is considered to be an anticlinal domal structure with a double plunging cross-fold (Thakur, 1983). This NW–SE-trending corridor of metamorphic rocks, about 40 km wide and running

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* Corresponding author.
E-mail address: raodr@wihg.res.in (D. Rameshwar Rao).

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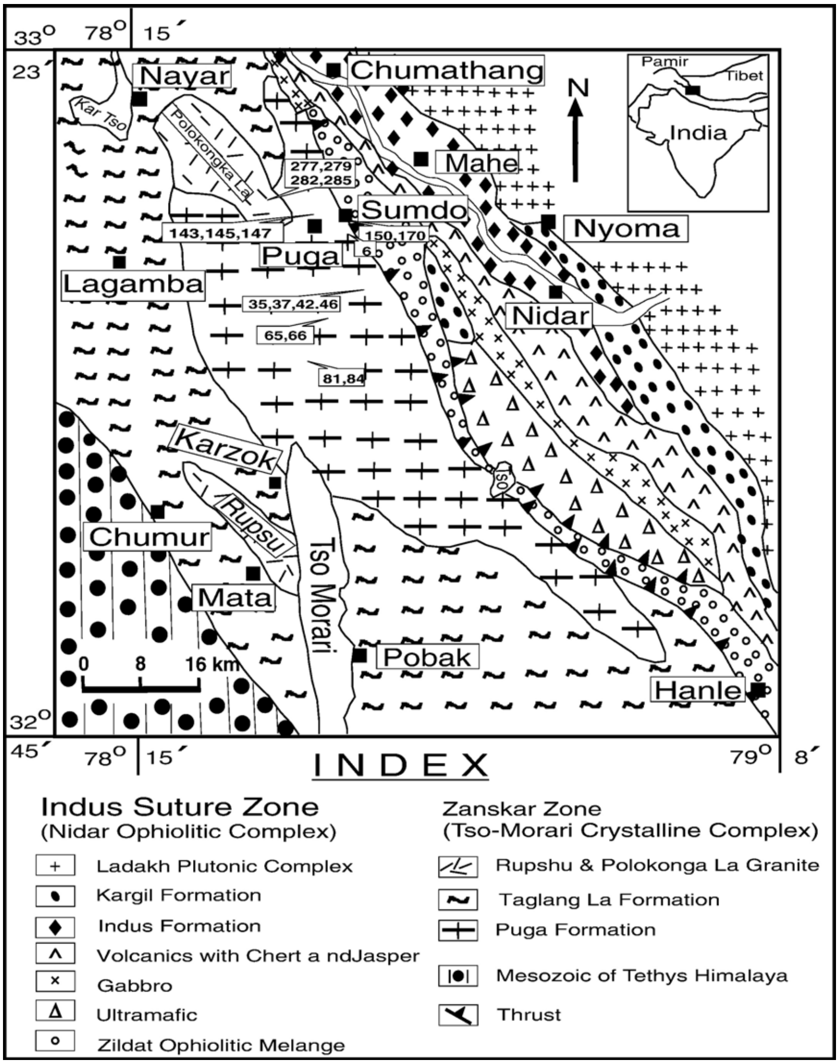

Fig. 1. General geological map of Tso-Morari region, Ladakh, India (after Thakur and Misra, 1984). The sample locations of garnet-amphibolites and eclogites are also shown on the map.

for nearly 100 km is separated by two contrasting lithologies. The ophiolites and ophiolitic mélange of the Indus Suture Zone lay on its entire northeastern margin, whereas the Tethyan Himalayan rocks are exposed along its southwestern margin. Some of the earlier workers considered the Tso-Morari Crystallines as a northern extension of the Higher Himalayan Crystallines (Hayden, 1904; Berthelsen, 1953; Gansser, 1964; Shankar et al., 1976). However, the presence of Palaeozoic to Lower Mesozoic metasediments indicates that Tso-Morari dome is not comparable with Precambrian rocks of the Higher Himalayan Crystalline rocks.

The Tso-Morari Crystalline Complex is divided into two main lithological units, which can be easily distinguished in the field: The medium- to low-grade metamorphosed Taglang La Formation to the south and the high-grade metamorphosed Puga Formation to the north. The Taglang La Formation is exposed in the south and west of the Puga Formation without any apparent visible break except at Karzok village. At Karzok, a narrow and localized ophiolitic mélange zone separates the two units. Argillaceous sediments with marly and calcareous sediments dominate the Taglang La Formation. Lenses and blocks of amphibolites and serpentinites are present in the western part of this formation. The Nyimaling and Rupshu granites of ~470 Ma intrude the metasediments in the west and east, respectively (Islam et al., in press). Fauna of Upper Carboniferous to Lower Triassic age has been reported from the limestone of this formation (Virdi et al., 1978). Thinly bedded carbonate-dominated sequence of Zanskar and Spiti Himalaya thrusts over this formation from the south.

The Puga Formation is dominated by the quartzo-feldspathic Puga gneiss. The gneisses and the Polokongka La granite found in this formation have been dated as ~480 Ma (Girard and Bussy, 1999; Rameshwar Rao and Hakim Rai, 2002). The Puga Formation contains metabasic rocks as lenses along with schists and marbles. Some of the metabasic bodies and gneisses have suffered eclogite–facies metamorphism (de Sigoyer et al., 1997; Guillot et al., 1997; Sachan et al., 1999). Much work has been carried out on the pressure–temperature conditions of the rocks of this formation (e.g., Sachan et al., 1999; de Sigoyer et al., 2000; Jain et al., 2003). Evidence for ultra-high pressure metamorphism has been recorded in coesite-bearing eclogite blocks and lenses (Mukherjee and Sachan, 2001). The studies carried out by de Sigoyer et al. (2004) in the region have indicated three main deformational stages associated with three stages of metamorphism. According to them the eclogite paragenesis has developed during D1, while the rocks were recrystallized to blueschist–facies conditions during D2, and the rise of the Tso-Morari dome through the crust took place during D3.

The eclogites (Fig. 2a) and garnet-amphibolites (Fig. 2b) under study are the most abundant and widespread mafic rock types of the Tso-Morari Crystalline Complex. They occur as dark lenses and blocks commonly running for a few meters within the Puga gneiss. The garnet-amphibolites are commonly associated with eclogites, and they are medium to coarse grained (around 3 to 14 mm). It is observed that lenses of eclogites have rims comprising of retrograde garnet-amphibolites. This corroborates the textural features of eclogites, which indicate that some amphibolites are formed by retrograde recrystallization of pre-existing eclogites (Figs. 2c and d). However, other amphibolite samples are devoid of textures indicating a prior eclogite stage and may represent metabasic rocks that recrystallized at relatively high-pressures, but less than those of eclogite–facies conditions (Figs. 2e and f).

Mineralogically the metabasites are comprised of porphyroblastic garnet, omphacite, augite, glaucophane, paragonite, phengite, muscovite and biotite. Some metabasites contain hypersthene, quartz, plagioclase, epidote, rutile, zircon, sphene, apatite, opaques, K-feldspar, aluminosilicates and carbonates as minor constituents. Mukherjee and Sachan (2001) have also reported ultra-high pressure minerals like coesite from the metabasites of the Tso-Morari region. The metabasites show wide variation in their mineralogical assemblage and can be grouped into three types based on the presence and absence of omphacite and garnet, e.g., eclogites, garnet-amphibolites and amphibolites. The rocks have undergone greenschist–facies retrogression as indicated by partial to complete replacement of garnet by chlorite, rutile by sphene, and pyroxenes by amphiboles (Fig. 2e). Some of the porphyroblastic garnets contain inclusions of glaucophane and omphacite indicating an earlier metamorphism under blueschist– and eclogite–facies conditions. Porphyroblastic glaucophane and epidote were formed after the rocks suffered ultra-high pressure metamorphism as indicated by the presence of relict garnet and pyroxene

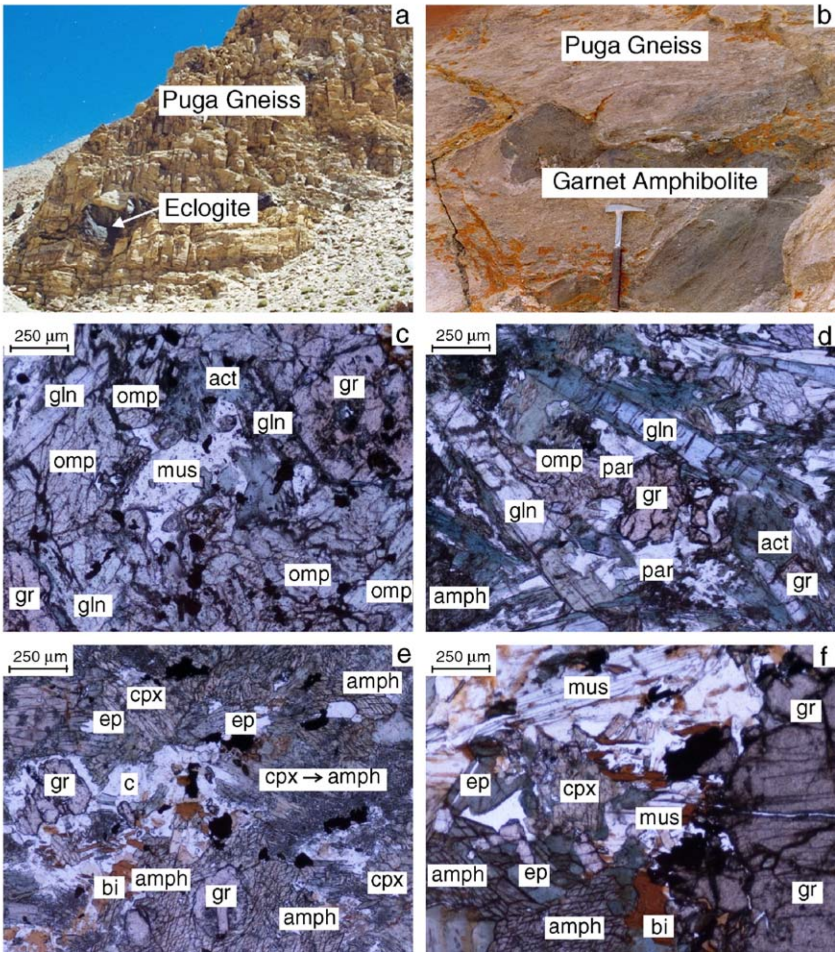

Fig. 2. Field photographs showing lenses of (a) eclogites and (b) garnet-amphibolites, within Puga Gneiss from Tso-Morari region. The photomicrographs (c) and (d) show the texture and mineralogy of eclogites, while photomicrographs (e) and (f) show those of garnet-amphibolites. The photomicrographs are under polarized light. Abbreviations used: gln – glaucophane; omp – omphacite; gr – garnet; amph – amphibole; mus – muscovite; cpx – clinopyroxene; chl – chlorite; ep – epidote; c – calcite; act – actinolite; par – paragonite; and bi – biotite.

inclusions in these minerals. Clinopyroxene–plagioclase symplectites have developed in eclogites and garnet-amphibolites. This type of intergrowth is considered to be due to the destabilization of omphacite. Amphibolites that lack garnet show more or less doleritic composition. The rock is dominated by pyroxene, amphibole, biotite, quartz and plagioclase. Pyroxene is mostly augite with scant hypersthene and shows replacement by amphibole along margins and cleavage traces. Hornblende and actinolite are dominant amphiboles, whereas development of chlorite and sericite is restricted.

3. Geochemistry

A representative selection of eclogites and garnet-amphibolites collected from widely separated localities from the Tso-Morari region was made into small pieces in steel mortar before converting them into small chips in Jaw-Crusher. The fine powdering to −200 meshes was carried out on Tema mill using tungsten–carbide tools. The fine powdered samples were used for the analyses of major elements, trace elements (including REE) and isotope determination of Rb and Sr at the analytical laboratories of Wadia Institute of Himalayan Geology, Dehradun. The major and trace elemental analyses of 18 samples were carried out on pressed pellets using XRF (SIEMENS SRS 3000) calibrated against both national and international standards. The major and trace elemental data of samples analyzed are given in Table 1 along with analyzed and reported values of the standard. A sub-set of 11 samples was also analyzed for REE using ICP–MS (Perkin-Elmer SCIEX) for which 40 mg of samples were treated with acids like HF, HNO_3 and $HClO_4$ in a Teflon beaker. The digested samples were made to 100 ml solution using 10% HNO_3, and subjected REE analysis on ICP–MS. The results of the samples analyzed are given in Table 2 along with analyzed and reported values of the standard. The isotopic composition of Rb and Sr were determined using isotopic dilution technique for garnet-amphibolites and eclogites. The analyses were carried out on VG-354 Thermal Ion Mass Spectrometer (TIMS). Samples weighing around 80 to 100 mg were treated with HF, HNO_3 and HCl acids. The digested samples were spiked with enriched ^{87}Rb and ^{84}Sr spikes. The Rb and Sr separates were obtained through cation-exchange columns following the procedure given in Rameshwar Rao and Hakim Rai (2002). The ^{87}Sr/^{86}Sr ratio was normalized to ^{86}Sr/^{88}Sr value of 0.1194. The reproducibility of the ^{87}Sr/^{86}Sr was tested by repetitive analyses of the NBS SRM-987 Sr standard. The sample regression was done using Provost (1990) program. The isotopic data of garnet-amphibolites are given in Table 3.

In general, it is observed that most major elements and many trace elements, mainly LIL elements, are mobile during the secondary alteration and metamorphism (Floyd and Winchester, 1975). On the other hand, the geochemical nature of mantle sources of mafic magmas can be examined through the ratios of trace elements having low bulk distribution coefficients, that is, incompatible trace elements (Cox et al., 1979). Ti, Y, Zr, Nb are generally considered as immobile; their stability is widely demonstrated during alteration. It is also generally assumed that the REE are reliable geochemical tracers due to their relative insolubility in seawater and their refractory nature, and as such are not much affected by eclogite–facies metamorphism (Bernard-Griffith et al., 1991). Hence, in the present study, emphasis is given to these elements in discussing the protoliths of garnet-amphibolites and eclogites. Even the positive correlation of the mobile Ba with the immobile P_2O_5 and the small range of K/Rb ratios (100–285) in these rocks, which can be used to test for a primary magmatic distribution of the mobile elements (cf. Dupuy et al., 1993) rules out secondary disturbance in these rocks.

The garnet-amphibolites and eclogites under study are found to have overlapping compositions and that the eclogites are clearly plotting along with garnet-amphibolites on all variation diagrams. Hence, they are discussed together in this paper. From Table 1, it is evident that the rocks are characterized by higher content of TiO_2 in the range nearly 1 to 4 wt.%, and lower Al_2O_3 content ranging between 10 and 14 wt.%, suggesting a normal basaltic composition. They show large variation in their K_2O wt.% (0.04 to 3.53) and P_2O_5 wt.% (0.12 to 1.33). The high P_2O_5 and TiO_2 concentrations observed in some of the samples, however, can be explained by the abundance of apatite, sphene, ilmenite and rutile. The Mg number using total Fe concentration ($mg\ \# = MgO/(MgO+FeO)*100$) ranges from 45 to 20, indicating no crystal fractionation. However, the rocks show regular variation of some major and trace elements with mg #, wherein for example, Na_2O, CaO, FeO^T, TiO_2, Y, Zr, Ba show negative correlation, while MgO, Cr, Ni show positive correlation. These trends shown by major and trace elements against mg # indicate that amphibolites were derived from igneous protoliths of tholeiitic nature.

The tholeiitic nature is apparent from $Zr/(P_2O_5*10\,000)$ vs. Nb/Y plot (Fig. 3a) and on AFM diagram (Fig. 3b). Also, on the ternary discrimination diagram of Jensen (1976) the protoliths of most of the garnet-amphibolites and eclogites can be characterized as high-Fe and Mg tholeiites. The low Nb/Y ratios (mean value of ~0.45) can be concluded to reveal a clear tholeiitic affinity in the samples under study (Floyd and Winchester, 1975). They emphasize that the tholeiitic rocks are prominently developed in zones of crustal extension or occur at intra-plate hot spots in both oceanic and continental regions, and are not volcanic rocks of island arcs related to subduction tectonics.

Chondrite-normalized abundances of REE of garnet-amphibolites and eclogites are shown in Fig. 4a which indicates no apparent Eu anomaly except for minor ones. The rocks show LREE abundance varying from 20 to 60 times chondrite, and HREE from 8 to 15 times chondrite. This suggests that the generation of this group cannot simply be explained in terms of different degrees of fractional crystallization of basaltic melts. Comparison of normalized REE patterns of eclogites and garnet-amphibolites under study with N-MORB, E-MORB and OIB rocks reveals that the LREE have an enriched pattern plotting between the E-MORB and OIB, while HREE match well with N-MORB (Fig. 4b).

In general, a multi-element spidergram provides useful means for comparing basalts of different tectonic settings since they include LIL elements, HFS elements and REE (for e.g., the

Table 1
Major and trace element data of ecologites and garnet-amphibolites from Tso-Morari Crystalline Complex, Ladakh, India

	Eclogites			Garnet amphibolites														Analysed values (reported values of standards)
	RH 46	RH 150	RH 170	RH 6	RH 35	RH 37	RH 42	RH 65	RH 66	RH 81	RH 84	RH 143	RH 145	RH 147	RH 277	RH 279	RH 282	RH 285	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
																			GSR-3
SiO_2	46.27	47.62	43.29	49.08	45.62	44.63	48.37	46.63	45.71	47.27	46.89	47.00	43.87	46.55	44.69	46.64	50.19	49.60	45.18 (44.64)
TiO_2	2.54	2.16	2.87	2.13	2.87	3.74	1.21	2.33	2.32	1.30	1.19	2.02	1.89	1.52	1.14	1.60	1.56	1.31	2.38 (2.36)
Al_2O_3	12.36	11.30	12.38	10.80	13.48	13.27	12.49	13.46	12.45	12.29	11.84	12.45	12.77	11.78	11.46	13.35	13.09	11.25	13.77 (13.83)
Fe_2O_3	14.30	13.99	17.19	15.76	14.97	15.14	14.14	13.84	13.73	12.66	12.85	16.32	12.40	15.43	13.68	13.41	13.05	13.82	13.33 (13.40)
MnO	0.22	0.19	0.14	0.25	0.20	0.26	0.20	0.19	0.19	0.16	0.16	0.27	0.20	0.20	0.16	0.18	0.21	0.17	0.17 (0.17)
MgO	7.78	7.47	8.13	7.28	7.78	7.06	9.26	8.25	8.38	11.09	11.96	4.70	9.57	6.40	12.74	9.73	10.62	10.36	7.46 (7.77)
CaO	10.58	10.91	9.05	10.06	8.51	8.96	7.49	10.79	11.22	9.05	9.29	8.31	9.31	12.30	8.82	9.21	5.55	9.22	8.65 (8.81)
Na_2O	2.81	2.48	1.91	2.03	2.80	1.43	1.98	2.34	2.34	1.34	1.08	1.61	1.82	2.95	1.38	2.03	1.37	1.42	3.51 (3.38)
K_2O	0.73	0.41	0.22	0.10	1.73	3.53	0.18	0.60	0.78	1.40	1.49	2.15	2.58	0.27	0.50	1.22	0.28	0.04	2.36 (2.32)
P_2O_5	0.36	0.26	0.63	0.34	0.38	0.58	0.14	0.27	0.35	0.22	0.18	1.33	0.20	0.16	0.12	0.24	0.16	0.15	0.86 (0.95)
Total	97.95	96.79	95.81	97.83	98.34	98.60	95.46	98.70	97.47	96.78	96.93	96.16	94.61	97.56	94.69	97.61	96.08	97.34	
																			JB-1a
Cr	266	296	122	227	214	225	140	252	296	305	318	187	288	240	266	239	187	288	435 (415)
Ni	84	78	76	63	93	82	434	85	101	301	372	57	78	57	357	179	319	294	133 (140)
Cu	63	109	193	130	98	19	100	76	87	83	55	31	81	102	109	111	169	93	60 (56)
Ga	20	20	19	18	20	20	17	20	20	18	17	19	20	20	17	19	18	18	19 (18)
Rb	44	24	15	3			15	18	23	84	79	107		9	23	83	13	3	38 (41)
Sr	313	271	153	176	224	88	101	263	258	129	79	183	105	172	242	300	180	163	448 (443)
Y	25	43	37	30	30	69	25	26	26	18	17	126	9	38	19	31	23	21	23.8 (24)
Zr	184	160	176	114	179	254	96	181	170	101	95		99	96	89	108	119	98	141 (146)
Nb	9	15	27	13	5	16	10	7	8	17	12	35	6	11	10	10	18	9	26 (27)
Ba	86	55			103	94		56	84	9	8	116	37			85	15		472 (497)
Pb	3	14	11	4	10	8	4	17	11	8	7	11	5	11	13	11	6	7	6.4 (7.2)
Th	3.5	3.7	5.0	2.2	2.6	3.7	3.2	2.6	0.9	3.0	3.8	4.1		2.5	3.5	3.2	0.6	2.7	9.6 (8.8)
Sc	35	45	46	47	33		29	38		25						31	29	25	29 (28)
mg #	32	31	29	28	31	29	36	34	34	43	44	20	40	26	44	38	41	39	

Table 2
REE data of eclogites and garnet-amphibolites from Tso-Morari Crystalline Complex, Ladakh, India

	Eclogites			Garnet amphibolites								Analysed values (reported values) of standard), JB-1a
	RH 46	RH 150	RH 170	RH 6	RH 35	RH 42	RH 65	RH 81	RH 279	RH 282	RH 285	
	1	2	3	4	5	6	7	8	9	10	11	12
La	12.99	15.76	15.96	12.57	8.03	11.45	11.25	15.40	7.56	14.03	9.46	36.17 (38.10)
Ce	34.53	35.97	34.47	28.12	23.99	21.57	29.95	32.47	18.02	28.55	20.98	63.60 (66.10)
Pr	5.18	4.93	4.49	3.89	4.21	3.12	4.54	4.06	2.69	3.60	2.72	7.09 (7.30)
Nd	22.98	21.49	18.80	17.32	21.83	13.08	20.81	16.45	12.98	15.22	11.51	26.06 (25.50)
Sm	5.67	5.33	4.43	4.37	6.64	3.33	5.29	3.87	4.17	3.63	3.03	5.26 (5.07)
Eu	2.04	1.69	1.52	1.63	2.39	0.92	1.88	1.27	1.54	1.26	1.06	1.62 (1.47)
Gd	5.99	6.61	5.86	5.49	6.92	4.16	5.71	4.30	5.03	4.17	3.62	5.29 (4.54)
Tb	0.93	1.21	1.03	0.93	1.11	0.75	0.87	0.66	0.89	0.66	0.61	0.72 (0.69)
Dy	5.34	7.82	6.60	5.78	6.54	4.53	5.10	3.85	5.79	3.99	3.72	3.99 (4.19)
Ho	1.07	1.61	1.41	1.20	1.28	0.88	1.02	0.76	1.21	0.81	0.74	0.79 (0.64)
Er	2.73	4.20	3.79	3.09	3.31	2.27	2.63	1.95	3.12	2.09	2.00	2.13 (2.18)
Tm	0.39	0.62	0.59	0.49	0.46	0.34	0.38	0.28	0.48	0.31	0.29	0.31 (0.31)
Yb	2.41	3.76	3.85	3.10	2.82	2.04	2.37	1.79	3.01	1.98	1.83	2.10 (2.10)
Lu	0.35	0.53	0.54	0.45	0.41	0.29	0.35	0.26	0.43	0.29	0.26	0.32 (0.32)

ocean island basalts, the N-, T- and P-type MORB). The relative enrichment and depletion of the elements provides valuable information about the petrogenetic process or source characteristics of any suite. Plotting of samples normalized to primitive mantle after Sun and McDonough (1989) show variable enrichment of the LIL elements with minor but significant negative anomalies in Nb and Sr and minor positive anomaly shown by P, while Zr and Ti do not show any anomalies as generally observed in case of island arc tholeiites (Fig. 5).

Further, the discrimination diagrams using immobile and incompatible elements have been plotted for the recognition of the tectonic setting of basaltic magmas for rocks under study. It was shown earlier that MORB could be subdivided into ‘depleted’ (N-type) and ‘enriched’ (E-type) varieties. Some workers (e.g., Sun et al., 1979; Wood et al., 1979; le Roex et al., 1983) on the basis of certain trace element ratios further subdivided the ‘enriched’ MORB into two varieties, e.g. T-type (transitional or intermediate) and P-type (plume or enriched). The ratios Zr/Nb, Y/Nb, Zr/Y and $(La/Yb)_N$ together with Sr, Nd and Pb isotopic ratios best serve to distinguish the N-, T- and P-type MORBs. The divisions are best illustrated in terms of Zr, Nb, Y and REE. Depicting the data of samples under study plotted on these diagrams Zr vs. Y, Zr vs. Nb and REE (Figs. 4 and 6), shows that the samples mostly spread over the fields defined for N- and T-type MORBs. The range of ratios of Zr/Nb (5.9 to 35.8), Y/Nb (1.1 to 6.00), Zr/Y (2.5 to 11.0) and $(La/Yb)_N$ (1.67 to 5.74) for the rocks under study are also similar to those of T- and N-MORB (le Roex, 1987). The ratios of Ba/Zr, Ba/Nb, Zr/Nb, Y/Nb, Zr/P_2O_5, Ti/Zr for the samples under study compare well with T-type MORB defined after Wood et

Table 3
Rb–Sr isotopic data of garnet-amphibolites from Tso-Morari crystalline complex, Ladakh, India

S no.	Sample nos.	$^{87}Rb/^{86}Sr$	1% error (*X*-axis)	$^{87}Sr/^{86}Sr$	2σ error (*Y*-axis)
1	RR-37	6.097	0.061	0.73964	0.00016
2	RR-65	0.213	0.002	0.70720	0.00010
3	RR-66	0.233	0.002	0.70681	0.00016
4	RR-84	2.7	0.027	0.72078	0.00008

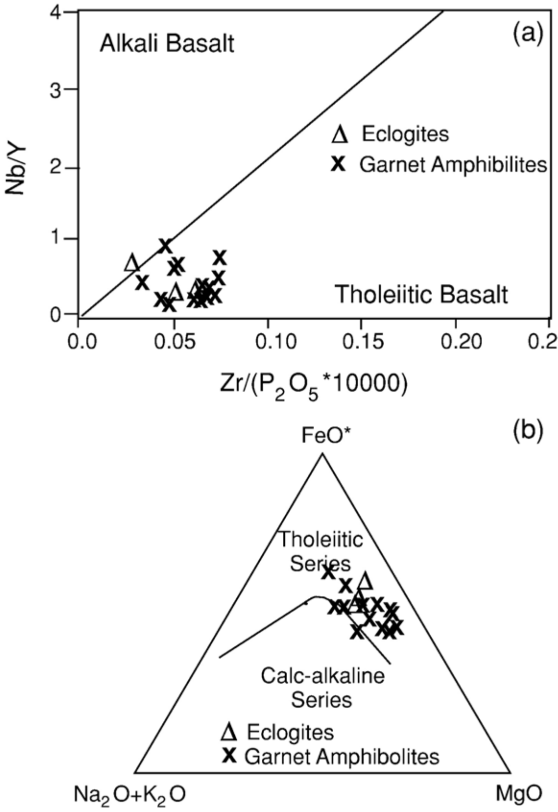

Fig. 3. Characterization of eclogites and garnet-amphibolites from Tso-Morari region on (a) Zr/P_2O_5 vs. Nb/Y discrimination diagram (after Floyd and Winchester, 1975) and (b) AFM diagram (after Barker and Arth, 1976).

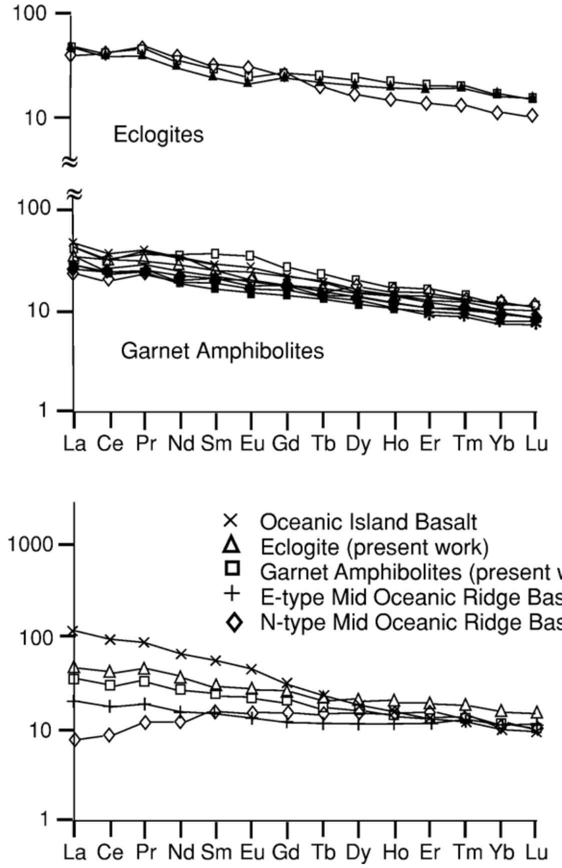

Fig. 4. The plots showing (a) REE spidergram of eclogites and garnet-amphibolites from Tso-Morari region and (b) comparison of their mean REE composition with OIB, E-MORB and N-MORB compositions (data after Sun and McDonough, 1989).

al. (1979). According to Barberi et al. (1975) the transitional basalts have been considered as specific to rift zones where the crust is intermediate between oceanic and continental in composition and structure.

For constraining the geotectonic environment of emplacement basic modern volcanics from known tectonic regimes are compared with the rocks under study. For example, on Ti–Zr–Y and Nb–Zr–Y diagrams (Fig. 7), the samples spread over within-plate basalts (WPB) and MORB fields. A similar tectonic setting is also suggested on many other binary and ternary plots (e.g., Ti–Zr–Sr, and also on Cr vs. Y, Zr vs. Zr/Y, TiO_2 vs. FeO∗/MgO, Zr vs. TiO_2) defined by Pearce (1982), Pearce and Cann (1973), Meschede (1986) and Miyashiro (1974), and preclude a volcanic arc-type tectonic setting (cf. Pearce, 1983). In addition, the Zr/Y vs. Zr/Nb plot after Kampunzu and Mohr (1991) can be used to demonstrate the different stages of rift “maturity” in time and space. The garnet-amphibolites and eclogites under study plot in the proto-oceanic rift fields on this diagram (Fig. 8a). The ratio of LIL elements and REE also resemble to MORB values, as shown by the Sm/Ce and Sr/Ce data in Fig. 8b.

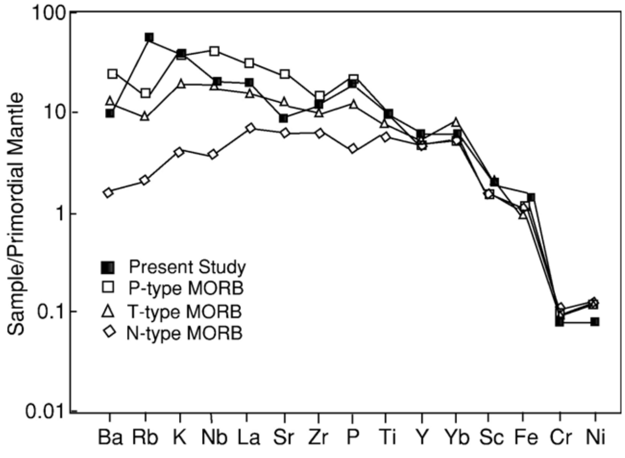

Fig. 5. Trace element pattern of eclogites and garnet-amphibolites from Tso-Morari region normalized to primitive mantle of Sun and Nesbitt (1977). The representative compositions of N-, T- and P-type MORB are from the Southern Ocean after le Roex (1987).

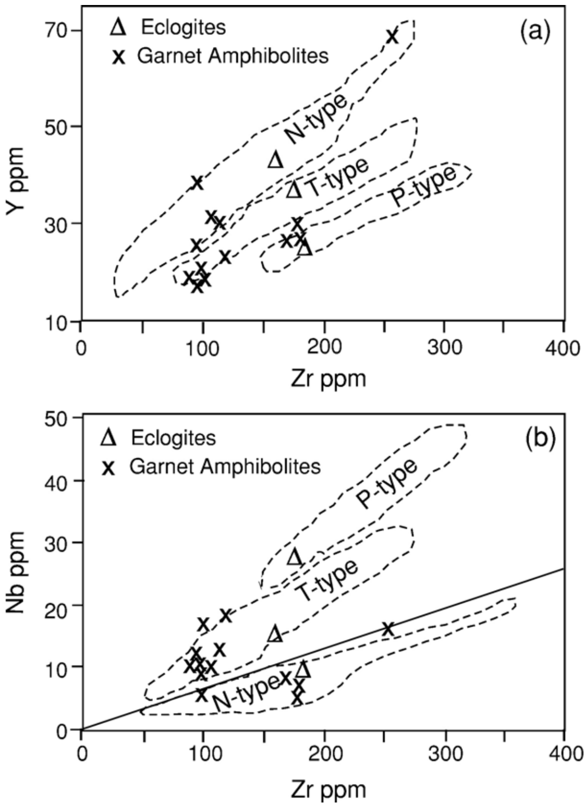

Fig. 6. Covariation of (a) Zrppm vs. Yppm, and (b) Zrppm vs. Nb ppm of eclogites and garnet-amphibolites from Tso-Morari region. The N-, T- and P-type MORB fields are from Southern Ocean after le Roex (1987).

4. Discussion

The eclogites and garnet-amphibolites are preserved as lenses within quartzo-feldspathic rocks dating ~480 Ma (Girard and Bussy, 1999; Rameshwar Rao and Hakim Rai, 2002) and metapelites of the Tso-Morari region (Fig. 2). They have identical geochemical characteristics and indicate sub-alkaline tholeiitic chemistry (Fig. 3a and b). Their low mg # (45 to 20), and narrow range of REE variations in eclogites and garnet-amphibolites (Fig. 4) do not indicate different degrees of fractional crystallization of the melts. The rocks do not represent cummulate nature which is evident from their TiO_2 vs. Al_2O_3

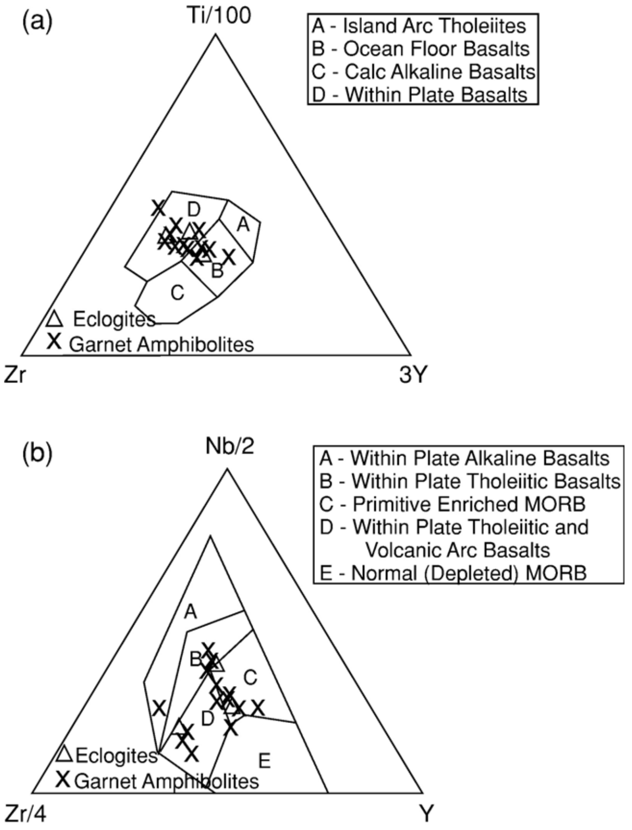

Fig. 7. Characterization of eclogites and garnet-amphibolites from Tso-Morari region on (a) Ti–Zr–Y diagram (after Pearce and Cann, 1973) and (b) Nb–Zr–Y diagram (after Meschede, 1986).

(after Pearce, 1983) and mg # vs. TiO_2 diagrams (not shown). The chondrite normalized REE patterns display LREE enrichment and have non-depleted or even slightly HFSE-enriched patterns, which may be indicative of some mantle enrichment. Their mantle normalized trace-element patterns do not show Ti negative anomaly which is one of the attributes of the mafic rocks. A negative Nb anomaly is observed in some samples. Similar negative anomaly of Nb, which is not coupled to Ti negative anomaly, is commonly recorded in continental tholeiites (Dupuy and Dostal, 1984). Also, most of the mafic rocks have P/Ce ratio comparable to mantle value of 75±15 (Sun and Hanson, 1975). The narrow range of $(La/Yb)_N$ (1.67–5.74) is consistent with a generation by partial melting of a mantle source in which garnet does not remain as a residual phase. Absence of pronounced negative Eu anomaly in these samples suggests plagioclase did not fractionate, while a marked positive correlation of mg # with Ni and Cr confirms the possibility of olivine fractionation of mantle melts.

In discrimination diagrams using immobile major and trace elements, the rocks under study are observed to spread over within-plate basalts (WPB) and MORB fields (Figs. 5–8). Interestingly, the samples plot outside the volcanic arc basalts (VAB) field and suggest a rift environment instead of subduction related environment for their protoliths. The composition of metabasites ranges from ‘depleted’ to ‘enriched’ as result of which the garnet-amphibolites and eclogites of the study area fall in the T-MORB field defined by le Roex (1987) on the binary variation diagrams of Zr vs. Y and Zr vs. Nb (Fig. 6) and on Ce/Y vs. Zr/Nb and Y/Nb vs. Zr/Nb (not shown). The $\varepsilon_{Nd}(t)$ reported by Spencer et al. (1995) for eclogites from Higher Himalaya range from +4.9 to −10, which also indicates depleted to enriched source for these rocks. Thus, an enriched source component superimposed on an overall MORB chemistry is observed (Figs. 5–8). Hence, a more enriched source is required to explain the shift towards higher Ce/Yb (6–18), Ce/Nb (1.3–4.8), Ti/Y (95–1250), Zr/Y (2.5–11), Th/Nb (0.03–0.5), Th/Yb (0.3–1.7), and Nb/Yb (1.8–9.5), and to lower Zr/Nb (6–36) and Y/Nb (1–6) ratios (Table 1). The enrichment of source could be an OIB (plume-related) or an E-MORB component present in the asthenosphere source, or alternatively, a subcontinental lithospheric mantle (SCLM) or derived from continental material in a subduction zone.

The presence of both high- and low-Ti metabasites may advocate for the existence of several lines of magmatic evolution from different magmatic parental batches. It is to be noted that since fractional crystallization cannot produce significant variations in incompatible element ratios (e.g., Zr vs. Nb and Zr vs. Y), such variations are most likely to be due to different degrees of partial melting from a homogeneous source. The enrichment factor can be looked upon by using Ti/Y vs. Zr/Y and Nb/Yb vs. Th/Yb plots. It is noteworthy that most of the samples plot on the mantle array between the composition of typical E-MORB and OIB (Fig. 9). Increase in the Th/Yb ratio

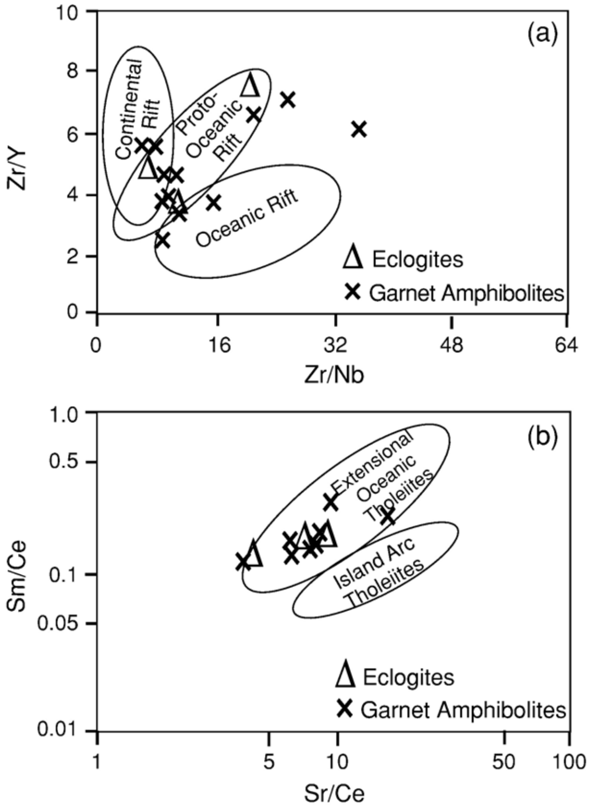

Fig. 8. Discrimination of eclogites and garnet-amphibolites from Tso-Morari region on (a) Zr/Nb vs. Zr/Y diagram (fields after Kampunzu and Mohr, 1991) and (b) Sr/Ce and Sm/Ce diagram (fields after Kampunzu et al., 1993).

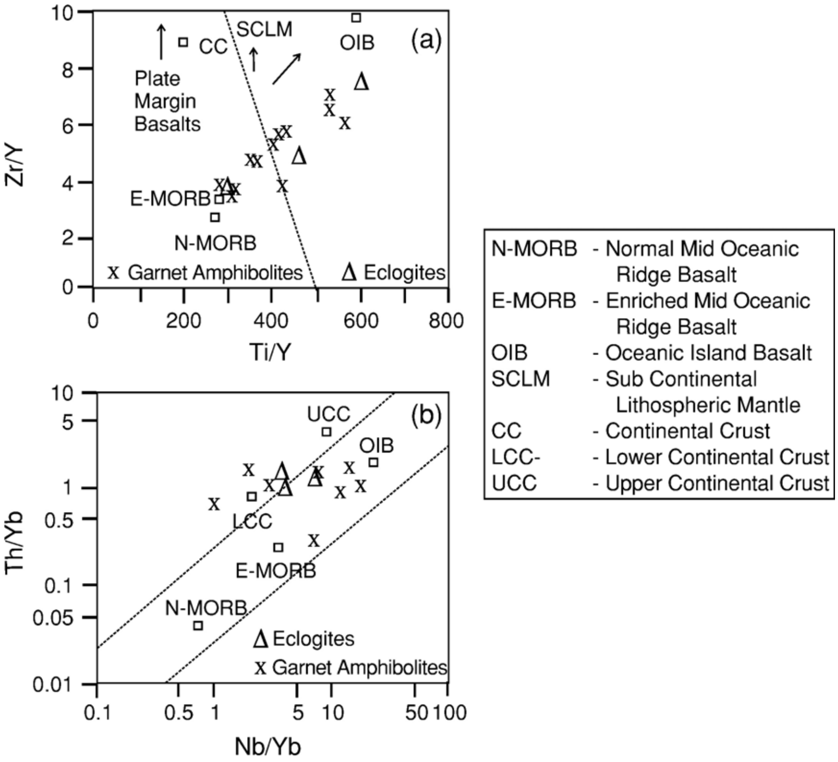

Fig. 9. Plotting of eclogites and garnet-amphibolites from Tso-Morari region on (a) Ti/Y and Zr/Y diagram (mantle array field after Pearce and Gale, 1977) and (b) Nb/Yb vs. Th/Yb diagram (fields after Pearce, 1982). The compositions of E-MORB, N-MORB, OIB, Continental Crust, Lower Continental Crust, Upper Continental Crust are from Sun and McDonough (1989) and Taylor and McLennan (1985).

(0.3–1.7) may suggest the involvement of crustal component. From Th/Yb ratios and Figs. 8 and 9, it can be inferred that the enrichment is not because of the incorporation of ‘subduction’ component, or due to mixing of asthenosphere with lower crust or upper crustal rocks. The enriched component could probably be the result of mixing of melts generated at different levels and can be attributed to a plume component present in the asthenosphere (OIB or E-MORB) which is reflected in Fig. 8. The ‘enriched pattern’ is almost exactly matching with the more enriched types of MORB, especially ‘transitional type’ MORB (T-MORB). Interaction between the plume and the MORB reservoir produces E-MORB along some segments of the ridge (e.g., le Roex et al., 1983; Kampunzu et al., 2000). According to Holm (1985), basalts ranging from depleted to slightly enriched can be generated in an intra-continental rifting stage (including intra-continental back-arc settings). Floyd (1989) showed that the oceanic plateau basalts of Nauru Complex have T-type composition derived from melting of a dominant N-type MORB source that mixed with melts derived from a sparsely distributed OIB source. Likewise, the within-plate nature of the earliest igneous rocks in the Gariep belt has been interpreted to mark the involvement of a mantle plume in continental break-up (Frimmel et al., 1996).

The Rb and Sr isotopic data of the garnet-amphibolites and eclogites show scatter. This probably indicates either mobility of Rb, or a possible pulsating magmatic activity in the region. The isotopic data of the garnet-amphibolites (Table 3), however, define a four point isochron (Fig. 10) which suggests an emplacement age of around 388 ± 11 Ma, with Sr_i ratio of 0.70587 ± 0.00017, and MSWD around 13. The Sr_i ratio of 0.706 is similar to some of the typical Ocean Island Basalt (OIB). Spencer et al. (1995) have also reported Sr_i ratios in the range of 0.7053–0.7073 for eclogites from Higher Himalaya. Further, the geochemical data such as Ti/Y ratio (95–1250) and the narrow range of $(La/Yb)_N$ (1.67–5.74) suggest that the melts are generated in depths greater than 60–80 km within the spinel-peridotite field.

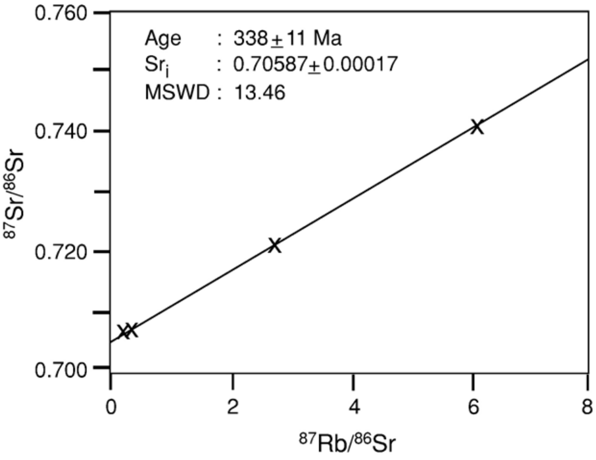

Fig. 10. Rb–Sr isochron of garnet-amphibolites from Tso-Morari region, Ladakh, India.

Following the possible pattern of convection in the Earth the return flow from the mantle may be in the form of scattered upwelling that forms clusters of hot spots rather than single large convection cells. Based on this argument, and from the present studies we envisage that the garnet-amphibolites and eclogites which show signatures of rift-related setting are probably generated in an advanced stage of intra-continental rift or an intra-continental back-arc setting (hot spot theory; Hofmann and White, 1982; Holm, 1985). In the initial stage, the oceanic intraplate volcanism resulted due to localized partial melting (i.e., hot spots) within the upper mantle beneath an advancing edge of the Indian plate or distal part of the Indian continental margin (to support this, zircon core ages for metabasite rocks have been dated to range from Precambrian to Cambrian, i.e., between 1750 and 450 Ma, e.g., Leech et al., 2005). Also, Steck et al. (1998) believe that the Tso-Morari Crystalline is the extension of North Indian Crust of Precambrian to Cambrian age. The hot mantle melts generated by plume activity have simply risen to form eclogitic layers in sub-lithosphere.

At a later stage, the northward movement of India in response to initial opening of the Indian Ocean might have not only provided necessary compression along the northern margin of India, the subduction of the Neo-Tethys oceanic crust and the initiation of the island arc in the Ladakh (Sharma, 1991), but also facilitated the reactivation of listric faults (cf. Dubey and Bhatt, 1986) during Permo-Triassic rifts. During northward subduction of the Indian Plate the continental part of the plate underwent tectonic deformation. This and the activated fault planes might have influenced the intrusion of the metabasites and eclogites from the eclogitic layer in the sub-lithosphere levels to the present day host continental crust and got preserved within it as lenses. The ultra-high pressure rocks got re-equilibrated here as amphibolites and some remained as relict eclogites. There are also evidences of alkaline magmatism at ~160 Ma observed in Agglomeratic Slate-Panjal Trap sequence of the Kashmir Himalaya (Rameshwar Rao et al., 1995). Also, based on bulk geochemistry and isotopic data of eclogites of the Higher Himalaya, Spencer et al. (1995) have also suggested that the rocks could be equivalents of the Permian Panjal Traps and proposed some protolith contamination from the evolved Higher Himalayan continental crust.

A number of papers report the age of UHP metamorphic rocks. Leech et al. (2005) studied 78 zircons from quartzo-feldspathic gneiss to eclogites from Tso-Morari region by U–Pb SHRIMP analyses. Most of core–mantle spot analyses yielded Ordovician ages (462 ± 9 to 477 ± 10 Ma), while analyses of light-coloured rim gave age of around 53.3 ± 0.7 Ma which has been related to UHP metamorphism. It is to be noted that the coesite reported in garnets of eclogites in the study area are not confined at garnet rims (cf. Sachan et al., 2004), which suggest that the Himalayan subduction event of Late Cretaceous is not responsible for the production of ultra-high pressure minerals in metabasites. Also, from the present study, we have not found any signatures of the subduction event. From this background, the major question that comes to the fore is whether UHP metamorphism is a result of collision event that took place around 55 Ma, or it is an older event (preceding Permian)? From the present studies, we believe that the eclogites and garnet-amphibolites represent the high-pressure crystallization of basaltic magma under eclogite–facies conditions at sub-lithospheric levels and that the ages of around 55 Ma (cf. Leech et al., 2005, and reference therein) probably represent the imprints of continental collision and initiation of Himalayan metamorphism. The eclogites and amphibolites got exposed to the surface during the Himalayan uplift.

5. Conclusions

The garnet-amphibolites along with UHP eclogites occur as lenses within the quartzo-feldspathic gneisses and metapelite rocks of the Tso-Morari region in the Ladakh Himalaya. The eclogites and garnet-amphibolites have consistent compositions with UHP metamorphic minerals like coesite being preserved in the former. The rocks have generated in an intra-continental rift predating the Himalayan subduction and collision event, and represent the present-day surface exposure of the deep mantle plumes. The injection of magma in pulses might have contributed to the complexity of the chemical features and explain the scatter observed in the geochemical plots. No geochemical signature of subduction related tectonic environment has been found hence the authors doubt in relating the UHP metamorphism to subduction related processes. We therefore feel that these aspects need to be investigated in greater detail and constrain the UHP metamorphism to either Himalayan or pre-Himalayan event, before giving various models of subduction theories for the development of UHP metamorphism of eclogites.

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