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Protolith of the Stak eclogite in the northwestern Himalaya

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ABSTRACT

This paper reports the major, minor and trace element abundances and Nd isotope compositions of bulk rock samples of eclogites from the Stak Valley in northwestern Himalaya and discusses their protolith. Major element compositions confirm the basaltic nature of the protolith. Trace element abundances normalized to the primitive mantle show almost flat patterns at ten times the primitive mantle values with slightly high concentrations of Th and light rare earth elements. These patterns are similar to those of enriched MORBs. Neodymium isotope compositions are chondritic and the values of εNd lie between those of MORB and old Indian continental crust. Immobile trace element contents of Stak eclogites are similar to those of the Permian Panjal Traps and significantly different from those of the Deccan Traps erupted at 73–66 Ma in the northwestern Indian plate, suggesting that the Panjal Traps is the protolith of the Stak eclogites. The protoliths of ultra-high pressure eclogites in the Kaghan and Tso Morari massifs in northwestern Himalaya are also interpreted to be the Panjal Traps. The results of this study suggest that a large Permian igneous province developed at the northwestern margin of the Indian plate before the collision with the Eurasian continent.

KEYWORDS: *Stak Valley, eclogite, trace element, neodymium isotope, India-Eurasia collision.*

INTRODUCTION

In the western Himalaya, high-pressure (HP) and ultrahigh-pressure (UHP) eclogites have been reported from three locations: in the Kaghan, Tso Morari, and Stak Massifs. In the Upper Kaghan Valley, northern Pakistan (CHAUDHRY & GHAZANFAR, 1987; POGNANTE & SPENCER, 1991), coesite inclusions were reported in omphacite by O'BRIEN *et alii* (2001). UHP metamorphism in the Tso Morari massif in the northwest India is confirmed by the occurrence of coesite in eclogite lenses surrounded by pelitic rocks (SACHAN *et alii*, 2004; MUKHERJEE & SACHAN, 2009). Based on the bulk rock composition and isotopic data, the protoliths of the Kaghan and Tso Morari eclogites are interpreted as Permian Panjal Trap basalts (e.g., SPENCER *et alii*, 1995; LUAIS *et alii*, 2001), and the protolith of the metapelites surrounding the eclogites of the Tso Morari massif are interpreted as shallow water Permo-Triassic sediments deposited at the northern margin of the Indian continent (GUILLOT *et alii*, 2001).

In the Stak Valley, about 120 km northeast of the Kaghan eclogite occurrence, highly retrogressed eclogites are reported by LE FORT *et alii* (1997). LANARI *et alii* (2013) recently evaluated the peak metamorphic conditions of the Stak eclogites to 2.5 GPa and 750 °C, but geochemical data were not obtained and the protolith was still uncertain. In the present study, we carried out the bulk rock and Nd isotope analysis of the Stak eclogites. We compare the data to the basaltic rocks in the vicinity of the study area and discuss the protolith of the Stak eclogites.

GEOLOGICAL SETTING

Northwestern Himalaya represents an example of continent–continent collision following the subduction of the Tethyan oceanic lithosphere. Just before the initial India-Eurasia contact, the northern margin of the current Indian continent was located at 7 ± 3°N (PATZELT *et alii*, 1996) whereas the southern Eurasian continental margin was probably located at 19–21 ± 4°N (SUN *et alii*, 2012; HUANG *et alii*, 2013). At ca. 57 Ma, the northern edge of Greater India collided with the intra-oceanic arc with the formation of ophiolite bodies (GUILLOT *et alii*, 2003; MAHÉO *et alii*, 2004; GUILLOT *et alii*, 2008). From 57 to 45 Ma, the ongoing continental subduction of the Greater India was associated with the final closure of the Tethyan sea and the onset of the continent-continent collision (GUILLOT & REPLUMAZ, 2013).

The Stak Valley is situated in the northwestern part of the Himalayan range (Fig. 1a), within the Higher Himalayan Crystalline and the gneisses of the Nanga Parbat-Haramosh Massif (NPHM) (Fig. 1a). The Higher Himalayan Crystalline is bounded by the Main Central Thrust (MCT) to the south and the Main Mantle Thrust (MMT) to the north (Fig. 1a). Highly metamorphosed sedimentary rocks with metric to decametric boudins of eclogites are exposed in the Stak Valley, defining the "Stak massif", which is approximately 2 km wide and 10 km long. The Stak massif is located on the northern edge of the Indian continental plate within the Higher Himalaya Crystalline, between the Ladakh units to the southeast and the NPHM gneisses to the northwest (Fig. 1a).

LANARI *et alii* (2013) evaluated the peak metamorphic conditions of the Stak eclogite as 2.5 GPa at 750 °C based on X-ray mapping of a single thin section. The U-Pb zircon ages of Stak eclogites are reported as ca. 36–30 Ma (KOUKETSU *et alii*, 2014).

SAMPLES

We determined major and trace element abundances in seven eclogitic samples in the Stak massif, and car-

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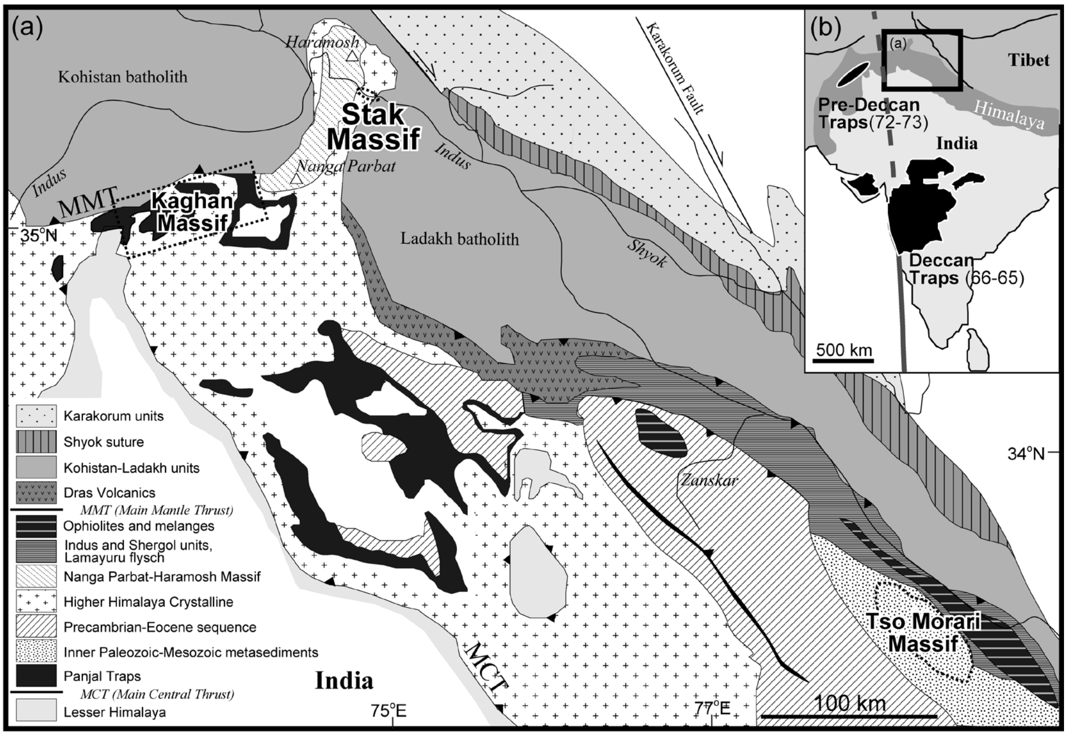


Fig. 1 - (a) Geological map of northwestern Himalaya showing the locations of Stak, Kaghan, and Tso Morari massifs (modified from CHAUVET *et alii*, 2008). The Siwalik molasse deposits are in the white blank area. (b) Distribution of the Deccan Traps (black area in the insert) and the track of the head of the Réunion mantle plume (thick dashed and solid line in the insert). The dashed line shows pre-Deccan path of the head of the Réunion mantle plume based on the 83.5 and 99 Ma plate reconstructions reported by KENT *et alii* (2002), and the solid line is the post-Deccan path proposed by DUNCAN (1990). Solid ellipsis in Pakistan shows the area of pre-Deccan volcanic rocks reported by MAHONEY *et alii* (2002). Numbers correspond to ages in million years.

ried out Nd isotope analyses of three representative samples in the study area; one foliated sample (SK6-38), one highly retrogressed sample (SK6-41), and one with coarse-grained euhedral crystals of garnet (SK8-53) (Fig. 2). The eclogites consist mainly of garnet, omphacite, amphibole, biotite, plagioclase, quartz and rutile. The garnet grains are commonly elongated up to 500 µm in length (Fig. 2a), and contain inclusions of quartz, rutile, dolomite, apatite, and rare omphacite and zircon. The highly retrogressed sample contains abundant symplectite of clinopyroxene, amphibole, and plagioclase after omphacite (Fig. 2b). Sample SK8-53 contains abundant euhedral garnet grains more than 500 µm in diameter including abundant quartz and needle shaped apatite in the core (Fig. 2c).

ANALYTICAL METHODS

BULK ROCK COMPOSITION

The concentrations of major and trace elements were determined with a Philips PW 2400 X-ray fluorescent spectrometer at the University of Ottawa after fusing bulk rock powder with a flux composed of 78.5% $Li_2B_4O_7$ and 21.5% $LiBO_2$. Loss on Ignition (LOI) is determined by weighing samples before and after heating them in air at 1050 °C for over 1 hour. Trace element abundances were determined with an inductively coupled plasma-mass spectrometer after HF-HNO_3-HCl digestion at Actlabs, Ancaster, Canada.

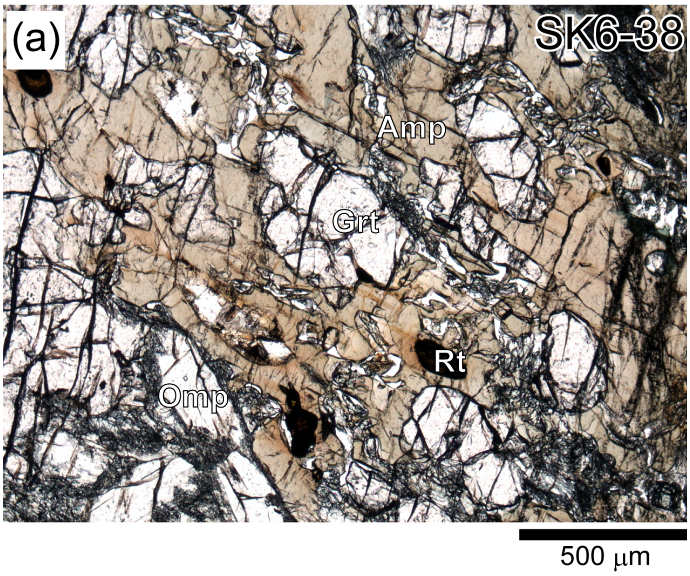
NEODYMIUM ISOTOPE COMPOSITIONS

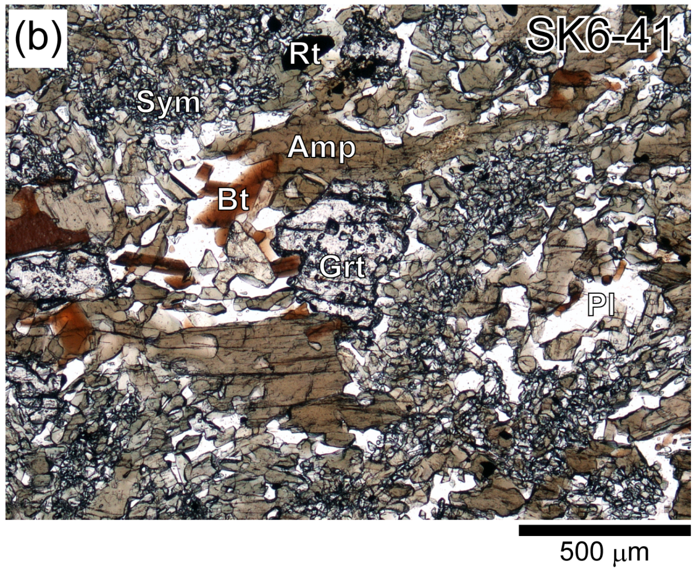
Approximately 50 mg of powdered samples were dissolved in HF-HNO_3 mixture at 180 °C overnight, then HNO_3 was added and finally HCl, following dryness in between steps. Neodymium was separated by a routine procedure with an alkali resin (Bio-Rad AG50W, 100 mesh) followed by separation of REE using Eichrom Ln Resin. Neodymium was eluted using 0.26 N HCl. Samples were loaded with H_3PO_4 on one side of a Re double filament and run at temperatures of about 1700–1800 °C with a thermal ionization mass spectrometer Thermo-Finnigan Triton at Carleton University in Ottawa. Digestion and analysis of the USGS reference BCR-2 during the analysis of samples yielded $^{143}Nd/^{144}Nd$=0.512640±14 (n=2). The mass spectrometer condition was verified by running a working Nd standard solution ($^{143}Nd/^{144}Nd$ =0.511823-0.511837) at the beginning of each analytical session and the solution has been calibrated with La Jolla standard (0.511855 ± 9).

RESULTS

The Stak samples contain SiO_2 ranging from 47 to 51 wt.% (Fig. 3a, Table 1). MgO contents are from 7 to 9 wt.% in most samples. The sample SK8-53, that contains abundant coarse-grained euhedral garnet, contains slightly low MgO (5 wt.%) and high SiO_2 (50.4 wt.%; Table 1). The total Fe expressed as Fe_2O_3 ranges from 11 to 14 wt.%, except for sample SK8-53 which contains high Fe, 17 wt.% Fe_2O_3. CaO contents of all samples are within 9–11 wt.%. The Na_2O and K_2O contents are 2–3 wt.% and 0.3–1.0 wt.%, respectively, with the exception of the sample SK8-53 that contains low contents, 0.3 and 0.06 wt.%, respectively (Fig. 3a, Table 1). TiO_2 and P_2O_5 contents are 1.2–1.7 wt.% and 0.1–0.2 wt.%, respectively, whereas the sample SK8-53 has 3.8 wt.% and 0.7wt.% (Fig. 3b, Table 1). The trace element contens such as Zr, Nb, and Y are 80–235 ppm, 4–19 ppm, 25–52 ppm, respectively (Fig. 3b, Table 1).

The primitive mantle-normalized trace elements abundances show a flat pattern at about ten times the primitive





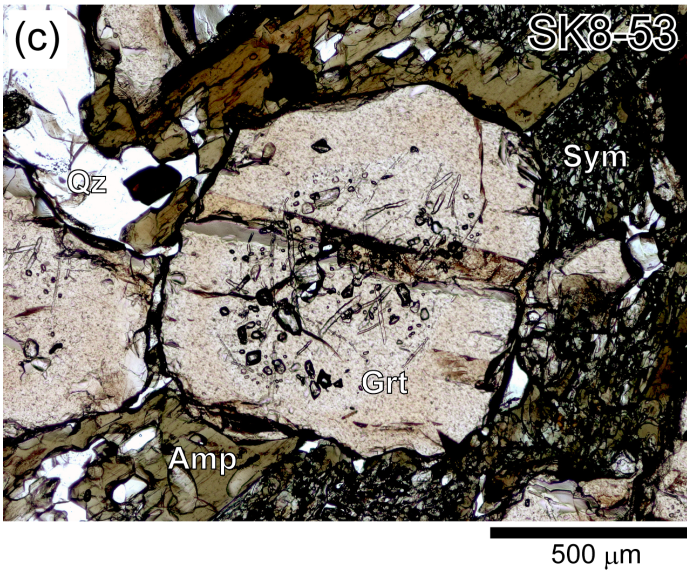


Fig. 2 - Photomicrographs of representative samples. (a) Elongated garnet grains in sample SK 6-38. (b) Highly retrogressed eclogite in sample SK6-41. (c) Coarse-grained (> 500 μm in diameter) euhedral garnet grain including quartz and apatite needles in sample SK8-53. Scale bars are 500 μm. Abbreviations; Amp=amphibole, Bt=biotite, Omp=Omphacite, Grt=garnet, Pl=plagioclase, Rt=rutile, and Sym=symplectite of clinopyroxene, amphibole, and plagioclase after omphacite.

mantle values with minor enrichment in Th and light rare earth elements (LREE; Fig. 4a). The trace element values of the sample SK8-53 are higher than the other samples and Th abundance is more than 100 times the primitive mantle value.

$^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios of three samples, SK6-38, SK6-41, and SK8-53, range between 0.1313–0.1745 and 0.512369–0.512647 (Table 2). For the samples SK6-38 and SK6-41, the $^{143}Nd/^{144}Nd$ values are close to the bulk silicate Earth; εNd at present values (εNd_0) are close to 0: +0.2 and -2.0, respectively (Fig. 5; Table 2). Since ^{147}Sm decays very slowly with a half-life of 106 b.y., the $^{143}Nd/^{144}Nd$ of the samples and the bulk silicate earth did not change much in the past 300 m.y. Therefore, the age-corrected εNd values are also close to 0; in paticular, +0.3 and -1.7 at 57 Ma, when the Indian continental plate collide with the Eurasian plate, and +1.0 and -0.7 at 289 Ma, when the Panjal Traps, one of the older possible protolith rocks of Stak eclogites, erupted (Table 2). The εNd values of sample SK8-53 are lower than the other two samples; -5.2 at present, -4.8 at 57 Ma, and -2.8 at 289 Ma (Table 2).

DISCUSSION

Geochemical characteristics of Stak eclogite

All measured samples in the Stak massif plot within the basalt field in the discriminating diagram by Le Bas *et alii* (1986) (Fig. 3a). The trace element patterns of Stak samples, except for sample SK8-53, are similar to E-MORB (enriched mid-ocean ridge basalt) pattern (Fig. 4a). The bulk chemical compositions and Nd isotope values are not significantly different among the measured samples, excluding sample SK8-53, even though some samples were highly retrogressed (Fig. 2). Sample SK8-53 contains slightly higher concentrations of Th, Nb, LREE, Fe_2O_3, and SiO_2 and low MgO and εNd value compared to the other samples (Figs. 3,4,5). These data suggest a contribution of ancient crustal material to the rock. It is likely that the parental magma of SK8-53 assimilated country silicic rocks either ancient granites or sedimentary rocks derived from such a granitic protolith.

TABLE 1

Major and trace element values of whole rock analysis.

	SK6-37	SK6-38	SK6-40	SK6-41	SK8-45	SK8-46	SK8-53
Major (wt.%)							
SiO_2	47.54	46.93	47.90	48.76	47.80	48.00	50.60
Al_2O_3	16.05	15.71	15.42	16.01	16.10	15.80	13.00
Fe_2O_3	12.93	12.86	13.90	10.50	13.20	13.70	17.00
MnO	0.19	0.20	0.21	0.17	0.19	0.20	0.27
MgO	9.22	9.19	7.21	7.97	7.92	7.55	4.61
CaO	9.13	10.16	10.31	10.52	10.28	10.02	9.56
Na_2O	3.09	3.09	1.99	3.20	2.50	2.30	0.30
K_2O	0.53	0.47	0.27	0.95	0.47	0.40	0.06
TiO_2	1.40	1.37	1.71	1.15	1.58	1.74	3.83
P_2O_5	0.13	0.13	0.15	0.11	0.14	0.19	0.74
LOI	0.20	0.30	0.62	1.09	0.30	0.40	0
Total	100.41	100.41	99.69	100.43	100.48	100.30	99.97
Trace (ppm)							
Sc	32.6	32.3	47.6	33.6			
V		210	294	179	222	231	169
Cr	385	371	226	345	135	135	
Co	49.2	53.4	49.0	42.3	56.1	59.1	44.7
Ni	145	176	65.0	56.3	122	115	14.9
Cu	74.4	89.7	101	25.3	107	149	36.6
Ga	19	18	13	15.9	21.1	22.2	20.3
Rb	26.4	33.7	7.9	45.8	12.9	5.6	0.9
Sr	95.2	72.4	149	96.8	137	155	95.3
Y	25.7	24.5	36.7	24.7	28.2	32.7	51.9
Zr	82.6	79.9	100	81.0	84.0	91.0	235
Nb	4.4	4.9		4.0	7	7	19
Cs	0.05	6.54	0.53	9.81	1.73	1.14	0.73
Ba	102	64.2	86.0	89.3	112	75.0	50.0
La		7.0	9.7	7.6	7.2	9.2	36.9
Ce		15.9	21.9	16.7	16.9	21.3	77.1
Pr		2.4	3.2	2.4	2.5	3.1	10.6
Nd		10.4	14.1	9.9	10.7	13.5	40.5
Sm		3.1	4.1	2.7	3.3	3.8	8.8
Eu	0.05	1.22	1.65	1.09	1.33	1.44	2.69
Gd		4.2	5.2	3.7	4.5	5.0	9.1
Tb		0.7	0.9	0.7	0.8	0.9	1.4
Dy		4.3	6.0	3.9	5.2	6.0	9.1
Er	0.1	3.0	3.7	2.9	3.1	3.5	5.2
Yb	0.1	2.7	3.4	2.4	2.7	3.1	4.2
Lu	0.1	0.4	0.5	0.3	0.4	0.5	0.6
Hf	0.1	0.6	0.1	0.6	0.3	1.0	1.3
Th		1.0	1.2	0.8	3.9	2.0	8.9
Pb		32.6	1.5	69.2	4.2	7.6	3.5
U	0.1	0.3	0.4	4.6	1.0	1.0	1.0

Total Fe expressed as Fe_2O_3

PROTOLITH OF THE STAK ECLOGITES

Possible protolith

The initial contact of the Indian continent with the Eurasian continent is considered to have taken place in the northwestern part of the Himalaya based on the biostratigraphy of collision-related sediments on both sides of the Indus–Tsangpo suture zone and on paleomagnetic data (e.g. KLOOTWIJK *et alii*, 1992; ROWLEY, 1996; GUILLOT *et alii*, 2003). The age of this collision, however, is debated. It is inferred to be at ca. 57 Ma based on paleomagnetic data showing an abrupt slowdown in the northward velocity of the Indian plate (KLOOTWIJK *et alii*, 1992; GUILLOT *et alii*, 2003) and to be as recent as 50–51 Ma based on the termination of marine carbonate deposition (GAETANI & GARZANTI, 1991; GARZANTI *et alii*, 1996; ROWLEY, 1996; NAJMAN *et alii*, 2010). Therefore, any mafic igneous rocks older than these ages are possible protoliths of the Stak eclogite.

The northern margin of Indian continent experienced two episodes of basaltic magmatism before the collision with Eurasia: Panjal Traps during the Permian and pre-Deccan Traps during the late Cretaceous. The Panjal Traps cover a large area of ~10^4 km^2 exposed along the Pir Panjal and Zanskar mountain ranges in the region of northwestern India and Pakistan (SHELLNUTT *et alii*, 2011; Fig. 1a). They consist mostly of basaltic rocks with minor amounts of basaltic-andesites, rhyolites, and dacites (GANJU, 1943; BHAT *et alii*, 1981; SHELLNUTT *et alii*, 2012). Zircon LA-ICP-MS U–Pb dating of a rhyolite from the lower-middle volcanic sequence of the Panjal Traps yielded ages of 289 ± 3 Ma (SHELLNUTT *et alii*, 2011).

The igneous activity of the Deccan Traps started in northern Pakistan, about 500 km southwest of the studied area, at about 73–72 Ma, and then rapidly propagated southwards to central and southern India (BASU *et alii*, 1993; SHETH *et alii*, 2001; MAHONEY *et alii*, 2002; CHENET *et alii*, 2007; SEN *et alii*, 2009) (Fig. 1b). The voluminous lavas (~95% of the total) were erupted at 66–65 Ma in west-central India and an additional area offshore of western India, and they cover an area of more than 5×10^5 km^2 (SEN *et alii*, 2009; Fig. 1b). The igneous activity is related to the activity of the Réunion mantle plume, still active in the Réunion Island located in the southwestern Indian Ocean. The geochemical characteristics of pre-Deccan Traps are similar to those of the Deccan Traps and Réunion hotspot lavas (MAHONEY *et alii*, 2002; KERR *et alii*, 2010). Given that the main igneous activity related to the plume is far, > 1000 km, from the study area, in this study, we focus on the early igneous activity of Deccan Traps (the so-called pre-Deccan Traps) whose locations are close to the Stak massif.

TABLE 2

Neodymium isotope compositions of eclogites from the Stak massif.

Samples	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (present)	2σ	εNd (present)	εNd (57Ma)	εNd (289Ma)
SK6-38	14.01	4.04	0.1745	0.512647	12	0.2	0.3	1.0
SK6-41	12.98	3.50	0.1631	0.512538	14	-2.0	-1.8	-0.7
SK8-53	40.5	8.8	0.1313	0.512369	15	-5.2	-4.8	-2.8

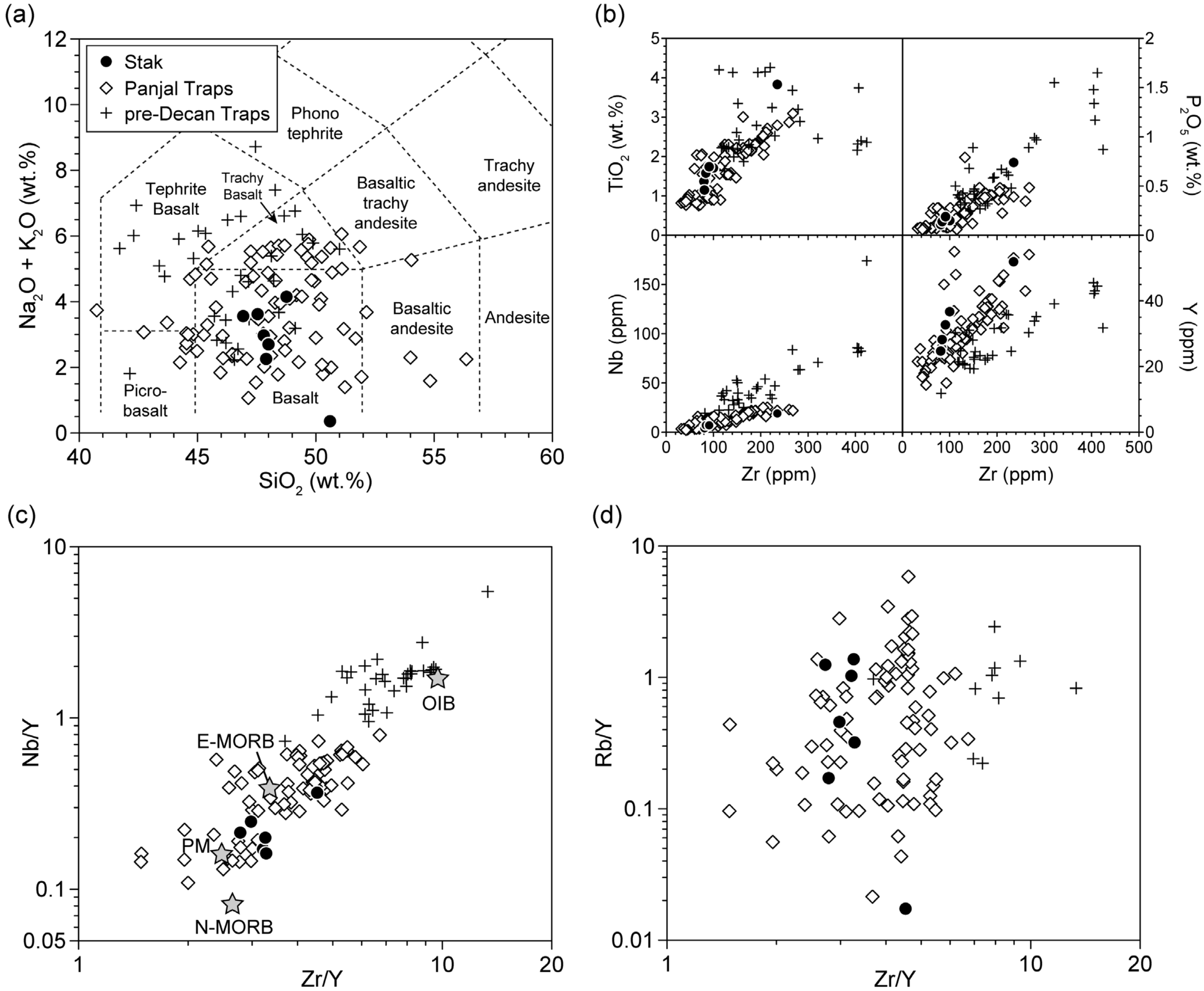


Fig. 3 - (a) Classification diagram of volcanic rocks by LE BAS *et alii* (1986). (b) Zr versus TiO_2, P_2O_5, Nb, and Y diagrams. (c) Zr/Y versus Nb/Y diagram. (d) Rb/Y versus Nb/Y diagram. Stak samples are plotted as solid circles. The major element compositions of Panjal Traps (BHAT *et alii*, 1981; HONEGGER, 1982; VANNAY & SPRING 1993; SPENCER *et alii*, 1995; SHELLNUTT *et alii*, 2014; SHELLNUTT *et alii*, 2015), and pre-Deccan Traps (MAHONEY *et alii*, 2002; KERR *et alii*, 2010), are plotted for comparison. N-MORB (normal MORB), E-MORB (enriched MORB), PM (primitive mantle), and OIB (ocean island basalt) values are from MCDONOUGH & SUN (1995).

Comparison of the Stak eclogites with the Panjal and pre-Deccan Traps

The measured bulk rock compositions of the Stak samples are compared to those of the Panjal Traps and the pre-Deccan Traps. In the discrimination diagram of LE BAS *et alii* (1986), the samples of the Panjal Traps and pre-Deccan Traps fall in the basalt, picro-basalt, tephrite basalt, trachy basalt, phonotephrite, basaltic trachy andesite, and basaltic andesite (Fig. 3a). We focus our discussion on the abundances of high field strength elements such as Ti, Zr, Y, and Nb, because they are generally considered relatively immobile during regional metamorphism and alteration. In addition, we will also focus on the large ion lithophile element Rb that is mobile and easily removed or added by hydrothermal fluids (e.g. JENNER, 1996).

The Zr abundance of Stak samples range from 80 to 235 ppm, and that of the Panjal Traps shows a similar range between 32–268 ppm whereas the Zr abundance of the pre-Deccan Traps shows a more wide range between 82–424 ppm (Fig. 3b). The contents of TiO_2 (0.8–3.1 wt.%) and P_2O_5 (0.1–0.8 wt.%) for the Panjal Traps are lower than those of the pre-Deccan Traps (1.4–4.3 wt.% and 0.1–1.6 wt.%, respectively). These trace element in the Stak samples are similar to those of the Panjal Traps (Fig. 3b). Niobium (Nb) abundances are similar between the Stak samples (4–19 ppm) and Panjal Traps (2–25 ppm), whereas the pre-Deccan Traps (19–174 ppm) contain higher values (Fig. 3b). Yttrium (Y) abundances of Stak samples (25–52 ppm), Panjal Traps (14–55 ppm), and pre-Deccan Traps (12–45 ppm) are similar. However, the values of the pre-Deccan Traps show a trend different from the other two

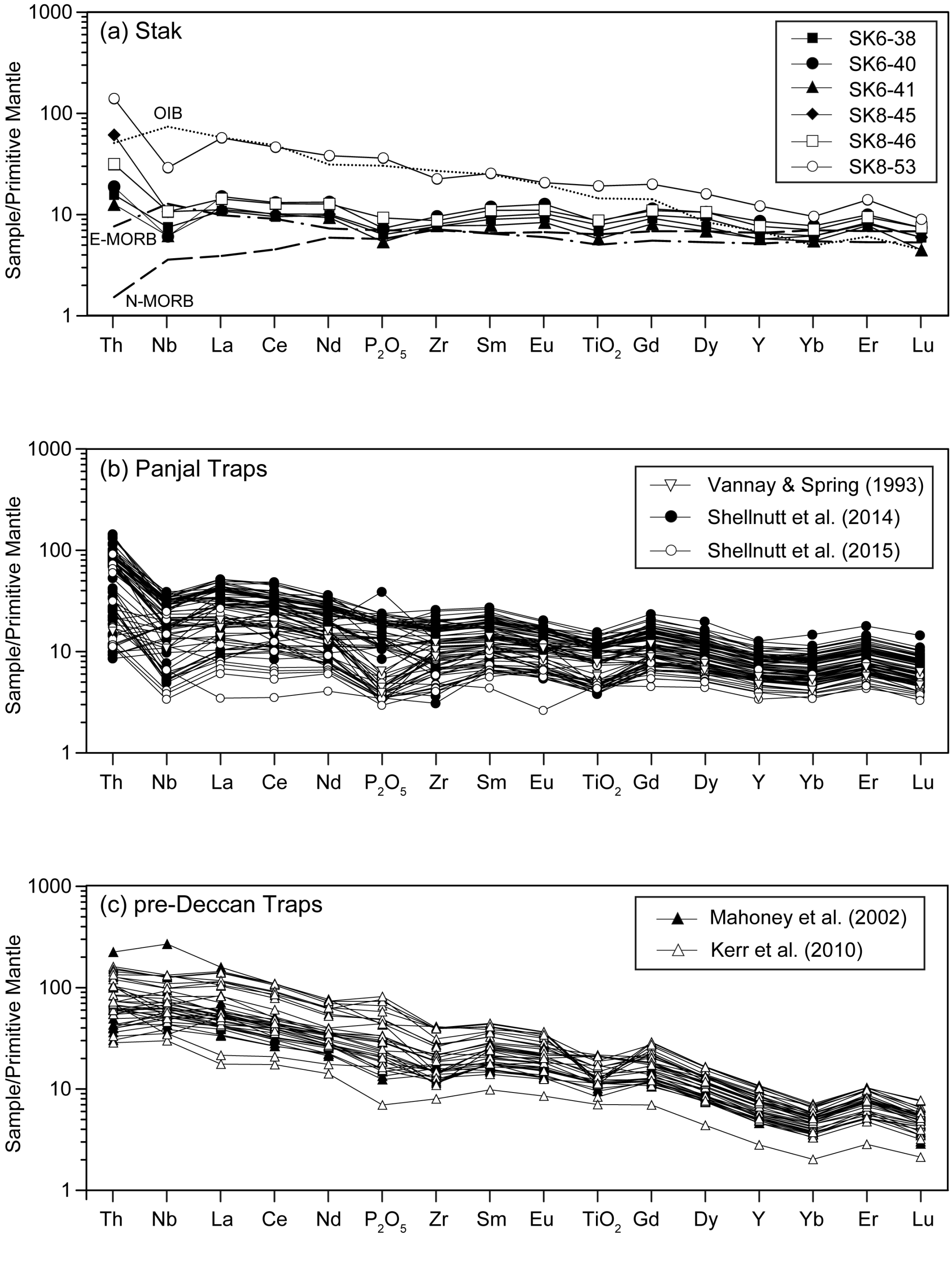


Fig. 4 - Primitive mantle-normalized trace element patterns of immobile elements. (a) Stak samples measured in this study. (b) Panjal Traps reported by VANNAY & SPRING (1993), SHELLNUTT *et alii* (2014), and SHELLNUTT *et alii* (2015). (c) Pre-Deccan Traps reported by MAHONEY *et alii* (2002) and KERR *et alii* (2010). The global average N-MORB, E-MORB, and OIB patterns reported in MCDONOUGH & SUN (1995) are shown in (a) for comparison.

groups on the Y-Zr diagram with the pre-Deccan Traps showing low Y for a given Zr content (Fig. 3b).

The similarity between the Stak samples and Panjal Traps is further demonstrated by the ratios of certain trace elements. Garnet concentrates the heavy rare earth elements and Y and is stable at mantle depth, > 75 km (GREEN & RINGWOOD, 1970). Therefore, the presence of garnet in the magma source region produces partial melts with low concentrations of heavy rare earth elements and Y. Thus, our chemical data compared with data from possible protoliths on diagrams of Nb/Y vs. Zr/Y and Rb/Y vs. Zr/Y may be useful in evaluating the type of mafic magmas as protolith of our eclogites (Figs. 3c,d). The low ratios of Nb/Y and Zr/Y observed in the Stak samples suggest that the parental melt formed with no residual garnet; the partial melting took place at a shallow depth (spinel facies peridotite) or with very high degrees of partial melting of a garnet peridotite to remove the entire garnet. The ratios of Nb/Y and Zr/Y of Stak samples are similar to the ratio of a typical E-MORB (Fig. 3c). The Panjal Traps also plot around the E-MORB and Primitive mantle end-members in the Nb/Y vs. Zr/Y diagram (Fig. 3c). The Panjal Traps formed by partial melting of mantle peridotite at relatively shallow depth (< 75 km; SHELLNUTT *et alii*, 2014), and they show relatively low ratios of Nb/Y and Zr/Y (Fig. 3c). On the other hand, the majority of the pre-Deccan Traps show high Nb/Y and

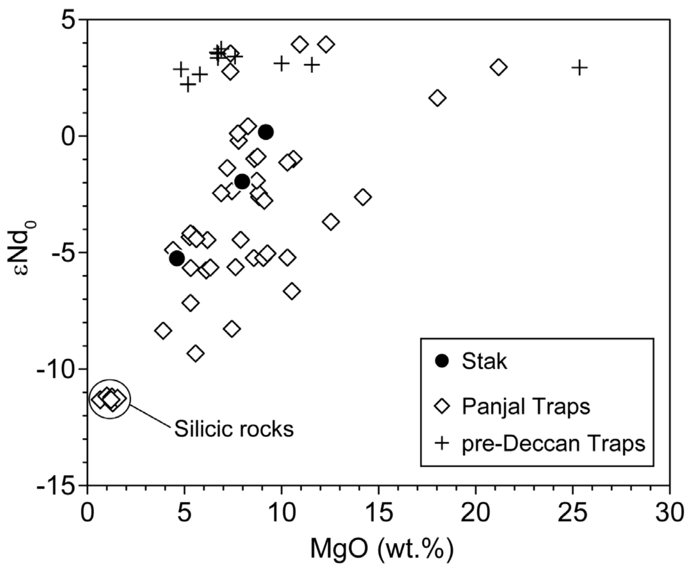


Fig. 5 - Present-day εNd values versus MgO diagram for the Stak samples, Panjal Traps (CHAUVET *et alii*, 2008; SHELLNUTT *et alii*, 2012; SHELLNUTT *et alii*, 2014; SHELLNUTT *et alii*, 2015) and pre-Deccan Traps (MAHONEY *et alii*, 2002; KERR *et al*., 2010).

Zr/Y and plot around the average ocean island basalt (OIB) (Fig. 3c), suggesting partial melting in the garnet-facies mantle peridotites. Many samples of the Stak and Panjal Traps show Rb enrichment at a given Zr/Y ratio that reflects hydrothermal alteration (Fig. 3d).

The primitive mantle normalized trace element patterns of Stak samples are almost flat with minor enrichments in Th and LREE (Fig. 4a). The Panjal Traps also show trace elements patterns similar to those of the Stak samples, but with a wider range (Fig. 4b). The patterns of Stak and Panjal Traps are similar to the E-MORB end-members (VANNAY & SPRING 1993). The Nb and P negative anomalies of some samples of Panjal Traps are interpreted as minor assimilation of crustal rocks and are also present in the Stak samples (Fig. 4a,b). The trace element patterns of the pre-Deccan Traps show higher content of LREE than the Stak samples and are similar to the global average OIB pattern (Fig. 4c).

The present day εNd values of the Stak samples range from +0.2 to -5.2 (Fig. 5; Table 2), whereas the the present day εNd values of the basaltic Panjal Traps and pre-Deccan Traps are between +3.9 and -9.3 (SPENCER *et alii*, 1995; CHAUVET *et alii*, 2008; SHELLNUTT *et alii*, 2014; SHELLNUTT *et alii*, 2015) and +3.9 and +2.2 (MAHONEY *et alii*, 2002; KERR *et alii*, 2010), respectively (Fig. 5). The εNd_0 values of silicic rocks of rhyolite and dacite in the Panjal Traps are reported around -11 (Fig. 5; SHELLNUTT *et alii*, 2012). Combined with the MgO trends, the εNd_0 values of the Stak samples fall within the range of the Panjal Traps (Fig. 5). The sample SK8-53 shows the lowest εNd_0 value of -5.2 in the measured the Stak samples and the this lowering is most likely due to the assimilation of surrounding sedimentary rocks as they are essentially derived from Archean granitic rocks. SHELLNUTT *et al*. (2014) reported εNd_0 values ranging from +0.4 to -8.3 for the Panjal Traps, and the values are similar to those of the Stak samples. The authors suggested the contribution of partial melt of crustal rocks less than 20 %. The recent paper by SHELLNUTT *et alii* (2015) reported more depleted samples in the Panjal Traps with εNd_0 up to +3.9 (Fig. 5). If this is the value for the primary melt of the Panjal Traps, much higher degree of assimilation of silicic rocks is required to explain the low εNd for sample SK8-53.

In summary, bulk chemical compositions, trace element patterns, and Nd isotope data suggest that the Stak eclogite is more akin to the Panjal Traps rather than the pre-Deccan Traps.

EXTENT OF THE PANJAL TRAP PROVINCE

In northwestern Himalaya, coesite-bearing eclogites are reported from the Kaghan and the Tso Morari massifs (Fig. 1a). The present day εNd values of Kaghan eclogites are between +4 and -3 (SPENCER *et alii*, 1995; REHMAN *et alii*, 2008), whereas those of Tso Morari eclogite lenses range between +5 to -6 (LUAIS *et al*, 2001; Fig. 6). The εNd_0 values of metapelites surrounding the eclogite lenses in the Tso Morari massif are low, -18, reflecting the Archean granitic provenance for the metapelites (DE SIGOYER *et alii*, 2000). The εNd_0 values of Stak samples plot within the range of the other two eclogites. Taken together all eclogites in the northwestern Himalaya fall between the N-MORB end-member and the old Indian continental crust field (Fig. 6). The protoliths of the Kaghan and Tso Morari eclogites are interpreted as the Panjal Traps (e.g., SPENCER *et alii*, 1995; DE SIGOYER *et alii*, 2000; LUAIS *et alii*, 2001). These results suggest that all eclogites identified so far in the northwestern Himalaya share a similar protolith, most likely the Panjal Traps.

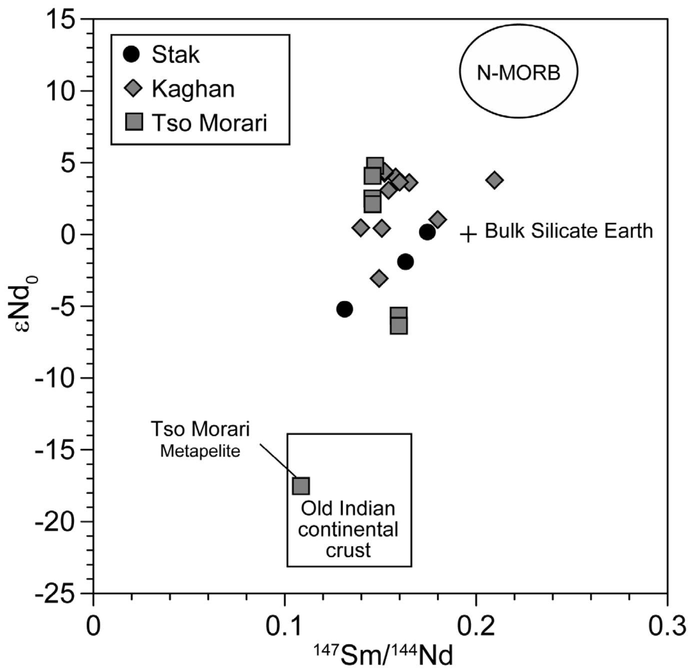


Fig. 6 - εNd values versus $^{147}Sm/^{144}Nd$ diagram for the eclogite samples from the Stak massif (solid black circle), Kaghan massif (gray diamond), and Tso Morari massif (gray square). The metapelite from the Tso Morari massif is also plotted for comparison. The data of Kaghan eclogites are from SPENCER *et al*. (1995) and REHMAN *et alii* (2008) and Tso Morari eclogites and metapelite are from de SIGOYER *et al*. (2000) and LUAIS *et al*. (2001). N-MORB and old Indian continental crust fields are from SPENCER *et al*. (1995).

The Panjal Traps covers the area of ~10^4 km^2 at the present (SHELLNUTT *et alii*, 2011) whereas the approximate areal distribution of eclogites originate from the Panjal Traps in the northwestern Himalaya at the present is at least ~ 500 km long and ~ 150 km wide: ~ 7.5×10^4 km^2 (Fig. 1). In addition, the paleo latitude of the Panjal Traps exposed at the present day is around 5°N while those of UHP eclogites in the northwestern Himalaya of Kaghan and Tso Morari massifs are considered to be at around 10°N in the greater India at ~ 55 Ma (GUILLOT *et alii*, 2007). Therefore the width of the Panjal Traps province at around 55 Ma is estimated ~ 600 km with ~ 500 km long, and the area is simply calculated to be ~ 3×10^5 km^2, which is consistent to the study of ERNST & BUCHAN (2001) that they estimated the total area of the Panjal Traps and other related Permian volcanic rocks of the Himalaya to be ~ 2×10^5 km^2. These estimations are comparable to the size of the Deccan Traps: ~ 5×10^5 km^2. These results imply that the paleo Panjal Traps in the northwestern margin of the Indian plate was several to several tens of times larger in size before the India-Eurasia collision.

CONCLUSIONS

The bulk rock chemical compositions of Stak eclogites fall within the basalt field in the discriminating diagram by LE BAS *et alii* (1986) and have trace element pattern similar to a typical E-MORB. Based on major and trace element and Nd isotope composition, the northwestern Himalayan eclogites at Stak, Kaghan, and Tso Morari massifs derive from the same protolith: the Permian Panjal Traps. Our data suggest that the extent of the Permian igneous province, before the collision with the Eurasian plate, was larger than the area exposed at present at the northwestern margin of the Indian plate.

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