

Geochemistry of the Panjal Traps basalts (NW Himalaya): records of the Pangea Permian break-up

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Key words. – Panjal Traps, Continental flood basalts, Geochemistry, Neotethys, Rifting.

Abstract. – The late Lower to Middle Permian Panjal Traps (NW Himalaya, India-Pakistan) represent the greatest magmatic province erupted on the northern Indian platform during the Neotethys opening. New geochemical and isotopic analyses were performed on basalts from the eastern borders of the traps (SE Zaskar-NW Spiti area) in order to characterize this volcanism, to discuss its compositional variations in comparison to Panjal counterparts and its relationships with the opening of Neotethys. Lavas show features of tholeiitic low-Ti (< 1.6%) continental flood basalts with LREE, Th enrichments and Nb-Ta negative anomalies. Trace element ratios combined with ϵNd_i values (-3.6 to +0.9) and high Pb isotopic ratios suggest that these tholeiitic basalts were derived from an OIB-like mantle contaminated at various degrees by a continental crust component. Previous geochemical features are broadly similar to those of the coeval Panjal volcanic sequences identified westwards (Ladakh, Kashmir and Pakistan). Present geochemical constraints obtained for the Panjal Traps basalts suggest they originated from rapid effusion of tholeiitic melts during opening of the Neotethys Ocean. Similar magmatism implying an OIB-type reservoir is contemporaneously recognized on and along the adjacent Arabian platform. Both Indian and Arabian Permian volcanics were emplaced during coeval syn-rift to post rift transition. These Lower to Middle Permian south Neotethyan continental flood magmatism are regarded as associated to a passive rifting. In this scheme, OIB-type isotopic signature would be related either to a melting episode of syn-rift upwelling mantle plumes or to a melting of a regional abnormally hot and enriched mantle.

Géochimie des basaltes des trapps de Panjal (NW Himalaya) : un enregistrement de la fragmentation de la Pangée au Permien

Mots-clés. – Trapps de Panjal, Basaltes continentaux, Géochimie, Néotéthys, Rifting.

Résumé. – Les trapps de Panjal (fin Permien inférieur – Permien supérieur, NW Himalaya) représentent la plus grande province magmatique mise en place sur la plate-forme nord indienne pendant l'ouverture de la Néotéthys. De nouvelles analyses géochimiques et isotopiques ont été réalisées sur les coulées basaltiques de la bordure Est des trapps, dans la région du SE Zaskar-NW Spiti. Le but est de caractériser ce volcanisme et de le comparer avec les équivalents connus des trapps de Panjal, afin de discuter des variations géochimiques existantes et de mieux comprendre ses relations avec l'ouverture de la Néotéthys. Les laves analysées ont des compositions de basaltes tholéiitiques pauvres en Ti (< 1.6%), montrant un enrichissement en terres rares légères et en Th, ainsi que des anomalies négatives en Nb et Ta. Ces signatures géochimiques sont typiques de basaltes tholéiitiques continentaux. Les rapports en éléments traces, les valeurs de ϵNd_i (-3.6 to +0.9) et les rapports isotopiques élevés du Pb suggèrent que ces tholéiites dérivent de la fusion d'un manteau de type OIB, contaminé à des degrés variés par un composant enrichi de type croûte continentale. La signature géochimique des coulées étudiées est très similaire à celle des séquences volcaniques équivalentes qui sont reconnues plus à l'Ouest (Ladakh, Kashmir et Pakistan). Les compositions géochimiques de l'ensemble des basaltes de Panjal suggèrent qu'ils proviennent de l'effusion rapide de liquides tholéiitiques associés à l'ouverture de l'océan Néotéthys. Un magmatisme similaire et impliquant également un réservoir de type OIB caractérise à la même période la formation de la marge adjacente nord arabe. Le volcanisme des marges indienne et arabe s'épanche au cours de la transition des périodes syn-rift à post-rift. La mise en place de ce magmatisme continental sud néotéthysien au cours du Permien inférieur à moyen est interprétée comme associée à un rifting de type passif. Dans ce contexte, les signatures isotopiques de type OIB peuvent être reliées à la fusion de panaches mantelliques syn-rift, ou bien à la fusion d'un manteau régional enrichi et anormalement chaud.

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INTRODUCTION

Opening of the Neotethys Ocean produced the fragmentation of Pangea and resulted in the separation of numerous Peri-Gondwana continental blocks from the northeast of Gondwana. Southern margins of this ocean comprised the northern rim of African, Arabian, Indian and Australian plates [Stampfli *et al.*, 1991; Dercourt *et al.*, 1993]. These new continental plate boundaries evolved as passive margins during the Mesozoic. Since closure of the oceanic realm during the Cretaceous and Tertiary, major parts of the southern Neotethyan margins were inverted and incorporated within the Alpine chains. Today, preserved fragments of those margins carry traces of the different within-plate magmatic episodes, which accompanied their formation. The latter are dispersed along the Tethyan orogenic belt (fig. 1a), from Australia, Himalaya, Oman, to Zagros and eastern Mediterranean chains (Syria, Turkey, Cyprus, Maury *et al.*, [2008]). This paper is focused on the NW Himalayan volcanics, which accompanied the break-up of the northern Indian plate rift during the Permian (fig. 1b).

Voluminous volcanic flows were emitted on the NW Indian rifted platform, during the late Lower to Middle Permian. They represent the greatest volume of melts emplaced during the Neotethyan opening and are called the Panjal Traps (fig. 1b). Whereas this name was used to describe the 2500 m-thick volcanic succession from the Kashmir mountains [Pareek, 1976], now it includes all the coeval flows found from Pakistan to the west, to Ladakh and Zaskar suite to the east [fig. 1c; Honegger *et al.*, 1982; Papritz and Rey, 1989; Gaetani *et al.*, 1990; Spencer *et al.*, 1995]. The different Panjal lavas occurrences have been unevenly studied or their geochemical characteristics and often only in order to establish correlations between the various Permian Traps outcrops.

In the present work, we determined Sr-Nd-Pb isotopic data and major and trace element analyses on representative samples (sixteen lavas) of Panjal Traps basalts of the Zaskar-Spiti area. The main aims were to determine the geochemical affinities and source characteristics of this Permian volcanism. These data are compared with the coeval Panjal magmatic flows of the Pakistan, Kashmir and Ladakh and with worldwide continental flood basalts geochemical features. This paper yields the first complete geochemical study of the Lower to Middle Permian magmatic remnants from the NW Indian plate break-up.

GEOLOGICAL SETTING

Analyzed samples of volcanic rocks were sampled in the SE Zaskar-NW Spiti area (NW Himalaya, SE Ladakh, fig. 1c), which is the easternmost Panjal Traps flows outcrop. They belong to the Tethyan zone sedimentary belt of the higher Himalaya, which includes the Late Paleozoic to Mesozoic northern Indian platform sequence (fig. 1c). The latter corresponds to the northern Indian passive margin successions, preserved in thrust sheets or nappes. This Tethyan zone faces the northern Indus-Yarlung suture zone (IYSZ, fig. 1c) units, including the Indian margin slope and basin sequences, and the Tethyan oceanic units of the Spontang and Nidar ophiolites [Masclé, 1985].

The Carboniferous to early Permian sedimentary deposits of the Tethyan zone mainly consist of successive terrigenous detrital accumulations, separated by local unconformities, and associated with scarce magmatism mainly of alkaline affinity [Garzanti *et al.*, 1992, 1994, 1996a,b; Vannay, 1993; Spring *et al.*, 1993]. These sedimentary successions are considered as the products of rift-shoulder erosion taking place during differential uplift of the Indian margin rifted zones [Bassoulet *et al.*, 1980; Vannay and Spring, 1993; Garzanti *et al.*, 1999]. The late Paleozoic rifting phase and its associated magmatic remnants are documented in Pakistan [Pogue *et al.*, 1992], Zaskar [Vannay and Spring, 1993; Spring *et al.*, 1993] and in the central part of the chain [Central Nepal, Garzanti *et al.*, 1992; 1994; Sciuinnach and Garzanti, 1996]. More voluminous volcanic extrusions are identified in the eastern and central parts of the Himalaya (fig. 1b). They consist of the late Carboniferous-Early Permian Abor volcanics (~1500 m of basaltic to andesitic flows and tuffs, Arunachal Pradesh, NE Syntaxis) [Bhat, 1984], and the late Lower Permian 300 m-thick tholeiitic Nar-Tsum spilites and Bhote Kosi basalts (Sakmarian-Roadian), which lie on top of the late Palaeozoic syn-rift successions [South Tibet, Garzanti and Sciuinnach, 1997; Garzanti *et al.*, 1999]. These tholeiitic affinity sequences erupted during a subsidence stage of the Indian margin and are interpreted as the remainders of the continental break-up and opening of the Neotethys [Garzanti *et al.*, 1999].

The slightly younger Panjal Traps magmatic event [Artinskian-Kazanian, Nakazawa *et al.*, 1975; Gaetani *et al.*, 1990] led to the emplacement of the greatest magmatic province in the NW Indian margin rifted platform (fig. 1c). Remnants of the Panjal Traps magmatism are found in more than 10⁵ km² from the easternmost Zaskar-Spiti to NE Pakistan in the west [Honegger *et al.*, 1982; Papritz and Rey, 1989].

In the Zaskar-Spiti-Lahul studied area (SE Ladakh), Panjal volcanic flows belong to the Kuling detrital terrigenous group of Garzanti *et al.* [1996a, b], which exhibits a major basal unconformity observed in Spiti [Fuchs, 1982] and Zaskar [Vannay, 1993; Garzanti, 1993; Garzanti *et al.*, 1996a]. In this area, Panjal continental flood basalts [Honegger *et al.*, 1982; Vannay and Spring, 1993] are regarded as traps, which filled a rifted valley recognized as the Zaskar-Spiti synclinorium [Fuchs, 1982; Gaetani and Garzanti, 1991; Garzanti *et al.*, 1996a].

Panjal Traps are also described throughout all Ladakh [fig. 1c, N Zaskar in Singh *et al.*, 1976; Suru area in Honegger *et al.*, 1982] and in the Kashmir basin [fig. 1c; Pareek, 1976; Bhat and Zainuddin, 1978, 1979] where they reach a 2500 m maximum thickness. Here they consist in a basal unit made of intermediate to acid pyroclastic rocks [Pareek, 1976] overlain by massive aphyric basaltic flows with tholeiitic to slightly alkaline affinities [Singh *et al.*, 1976; Honegger *et al.*, 1982; Gupta *et al.*, 1983; Vannay and Spring, 1993]. The intermediate and acid differentiated rocks constitute a minor part of the total volume of the extruded rock [Pareek, 1976]. They were also recognized in the western syntaxis of NE Pakistan [fig. 1c; Papritz and Rey, 1989; Spencer *et al.*, 1995]. In this zone, remnants of this magmatism have been identified within the lesser and higher Himalaya series [respectively, Panjal and Salkhala tectonic units, Papritz and Rey, 1989; and Upper Kaghan area, Spencer *et al.*, 1995]. They are exposed as feeder

dykes crosscutting the crystalline basement and Lower Palaeozoic cover and as magmatic flows interlayered in the Upper Palaeozoic/Lower Mesozoic cover [Tethyan Zone,

Spencer *et al.*, 1995]. They are widespread (up to 2 km-thick) and metamorphosed under eclogites and amphibolites metamorphic facies conditions.

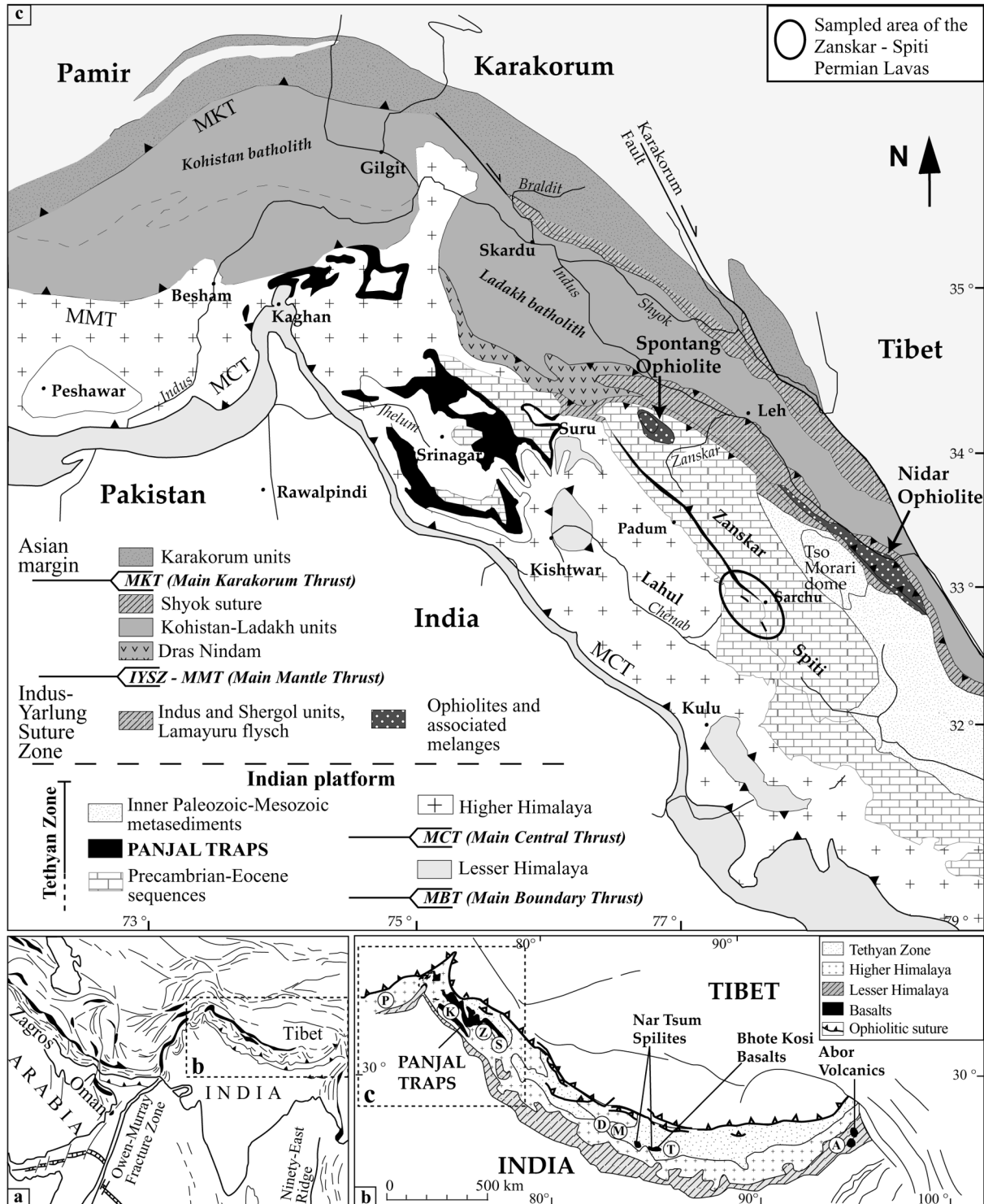


FIG. 1. – (a) Tethyan Suture (ophiolites and associated mélanges) after Coleman [1981]. (b) Main geologic features of the Himalayan Range showing the various occurrences of Permian basalts. P=North Pakistan; K=Kashmir; Z=Zaskar; S=Spiti; D=Dolpo; M=Manang; T=South Tibet; A=Arunachal Pradesh [Garzanti *et al.*, 1999]. (c) Geological map of the northwestern Himalaya modified after Guillot *et al.* [2003]; Spencer *et al.* [1995]; Pogue *et al.* [1992]; Vannay and Spring [1993].
 FIG. 1. – (a) Suture téthysienne (ophiolites et mélanges associés) d'après Coleman [1981]. (b) Carte géologique simplifiée des principales unités de la chaîne himalayenne et montrant les différentes séquences basaltiques permiennees. (c) Carte géologique du NW de l'Himalaya, modifiée d'après Guillot *et al.* [2003]; Spencer *et al.* [1995]; Pogue *et al.* [1992]; Vannay et Spring [1993].

procedures of Cotten *et al.* [1995] and using international standards for calibration tests (ACE, BEN, JB-2, PM-S, WS-E). Rb was measured by flame atomic emission spectroscopy. Relative standard deviations are ca. 1% for SiO₂ and 2% for other major elements except P₂O₅ and MnO (0.01%). All rocks were pulverised in an agate mill.

Trace elements including the REE were analyzed by ICP-MS at the Université Joseph Fourier in Grenoble, after acid dissolution of 100 mg sample, using the procedures of Barrat *et al.* [1996]. Standards used for the analyses were BHVO and BIR-1. Analytical errors are less than 5% for trace elements.

Sr (static acquisition) and Nd (semi-dynamic acquisition) isotopic ratios were measured at the LMTG de l'Université Paul Sabatier de Toulouse on a Finnigan MAT 261 multicollector mass spectrometer using the analytical procedures of Lapierre *et al.* [1997]. Results on standards yielded ¹⁴³Nd/¹⁴⁴Nd = 0.511961 ± 9 (n=4) and ⁸⁷Sr/⁸⁶Sr = 0.710252 ± 9 (n=4) for neodymium rennes standard [Chauvel and Blichert-Toft, 2001] and NBS 987, respectively. ¹⁴³Nd/¹⁴⁴Nd and ⁸⁷Sr/⁸⁶Sr were normalized for mass fractionation relative to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219 and ⁸⁸Sr/⁸⁶Sr = 8.3752, respectively. Two leaching steps (HCl acid during 20 minutes at 100°C) were done before acid digestion of samples.

Nine basalts were selected for lead separation. Selection was conducted after trace element measurements and neodymium isotopic analyses, in order to choose the greatest chemical and isotopic diversity of the sample set. A leaching

step with 6N HCl during 30 minutes at 65°C was done before acid digestion (36-48 hours on a hotplate in ultrapure HF and HNO₃ concentrate acids). After complete evaporation, 0.5 ml of concentrated HBr was added to the sample and kept at 70°C for 2-3 hours before complete evaporation. The chemical separation of lead was done using 50 µl of anion exchange resin (AG1X8, 200-400 mesh) with 0.5N HBr and HCl acids as reagents. Pb blanks were less than 40 pg. Lead isotope measurements were made on a VG model Plasma 54 multi-collection magnetic sector-inductively coupled plasma-mass spectrometer (MC-ICP-MS) at the Ecole Normale Supérieure in Lyon. Lead isotope compositions were measured using the TI normalization method described by White *et al.* [2000]. For Pb isotope analyses, samples were bracketed between NBS 981 standards and calculated with respect to the value reported for this standard by Todt *et al.* [1996]. This technique yields internal precision of ca. 50 ppm (2s) and an external reproducibility of ca. 250 ppm (2s) for ²⁰⁶Pb/²⁰⁴Pb ratios (n=15). Initial isotopic ratios have been calculated assuming an age of 275 Ma.

RESULTS

Petrography

Most of the samples (collected by Spring and Vannay in 1993) were already powdered before being analyzed. In the three available rock samples, magmatic minerals have been modified by the Himalayan metamorphism and weathering processes. Two out of the sixteen Panjal basalts (793-13 and 293-12), have preserved aphyric, spherulitic and vesicular textures of pillow rims. The plagioclase microlites organized in spherulites are albitized. The groundmass is mainly constituted by the following assemblage albite + oxydes + chlorite + epidote + actinolite + calcite, which characterizes a greenschist facies previously recognized by Vannay and Spring [1993]. Sample 293-11 shows a porphyritic texture with numerous pseudomorphs of olivine phenocrysts, replaced by serpentine and surrounded by an assemblage made of chlorite, epidote and actinolite. The latter likely derives from destabilisation of clinopyroxene. The high Cr (2440 ppm) and Ni (920 ppm) contents of the whole rock suggest initial accumulation of olivine and clinopyroxene (table I).

Major and trace elements

The loss of ignition (LOI) of analysed samples ranges between 3.5 and 8% (table I). These high contents suggest significant modification of the Zanskar-Spiti Permian lavas primary composition. This is also evidenced with the erratic behaviours that are observed plotting the mobile major elements Na₂O, CaO, and K₂O against SiO₂ contents variations (figs. 2a-b). In the MacDonal and Katsura [1964] discriminating diagram (fig. 2a), analyzed lavas mainly fall in the tholeiites basic field, between the picritic SiO₂ content of the 293-11 cumulate and the basaltic andesite compositions for the most evolved melts. In this diagram, the scattering of data suggests that K₂O and Na₂O contents have been remobilized during secondary processes. The zirconium content has therefore been reported against major (figs. 2c-d), lithophile (fig. 2e) and incompatible high field strength elements (fig. 2f) in view to check the mobility of elements during

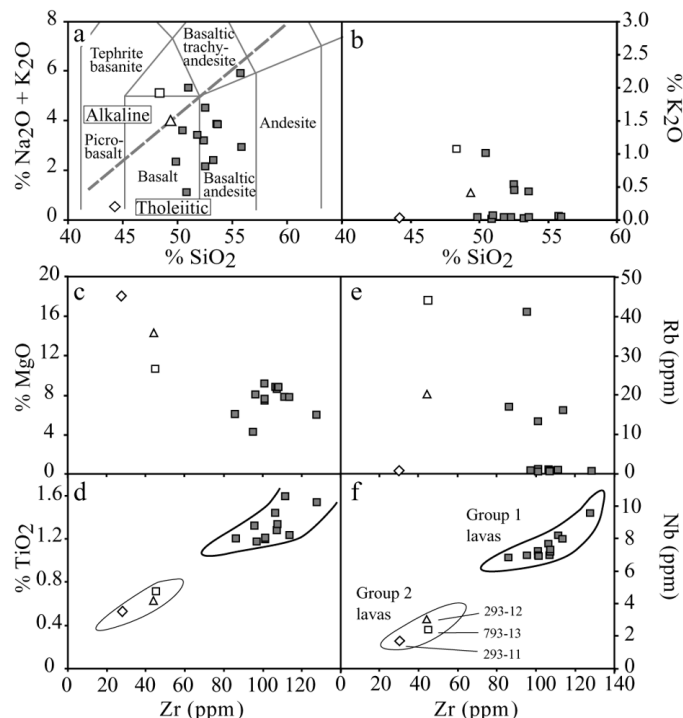


FIG. 2. – (a) Na₂O + K₂O (%) vs SiO₂ (%) [MacDonal and Katsura, 1964], (b) K₂O (%) vs Zr (ppm), (c) MgO (%) vs Zr (ppm), (d) TiO₂ (%) vs Zr (ppm), (e) Rb (ppm) vs Zr (ppm), (f) Nb (ppm) vs Zr (ppm) plots for the Zanskar-Spiti samples of the Panjal Traps. Legend is reported in the fig. 2f.
 FIG. 2. – Diagrammes de corrélation : (a) Na₂O + K₂O (%) vs SiO₂ (%) [MacDonal et Katsura, 1964], (b) K₂O (%) vs Zr (ppm), (c) MgO (%) vs Zr (ppm), (d) TiO₂ (%) vs Zr (ppm), (e) Rb (ppm) vs Zr (ppm), (f) Nb (ppm) vs Zr (ppm) pour les échantillons des trapps de Panjal du Zanskar-Spiti. La légende est indiquée sur la fig. 2f.

secondary processes. TiO_2 and Nb versus Zr contents exhibit good correlations and thus are considered as representative of initial magmatic characters. In contrast, no satisfactory alignment is obtained in Na_2O , K_2O (not shown), MgO, Sr and Rb versus Zr diagrams (figs. 2b-e) suggesting significant mobility of these elements during secondary processes and that they can not be used to characterize the magmatic affinities of the studied Panjal Traps lavas.

Analyzed basalts can be subdivided into two main groups based on their TiO_2 , Zr, Nb and REE contents (figs. 2-3). Group 1, which encompasses the large majority of Zanskar-Spiti samples (13 samples), is characterized by homogeneous Zr contents ($86 < \text{Zr}_{\text{ppm}} < 128$ with an average of 105 ± 20 ppm), significantly higher than those measured for Group 2 samples (793-13, 293-12 and 293-11; $31 < \text{Zr}_{\text{ppm}} < 45$) (table I). The Panjal volcanics show basaltic contents in MgO ($\text{MgO} > 6\%$, excepted for sample 04/08 B) with low TiO_2 ($< 1.6\%$) and P_2O_5 ($0.06 < \text{P}_2\text{O}_5\% < 0.16$) contents. Overall, Group 2 rocks have, compared to Group 1, significantly lower SiO_2 , TiO_2 and P_2O_5 contents and higher concentrations in MgO (10.6 to 18%, table I). Thus, Group 2 presents geochemical affinities with more primitive liquids than Group 1.

Group 1 chondrite-normalized REE patterns show homogeneous distributions with significant LREE enrichment relative to MREE ($1.7 < (\text{La}/\text{Gd})_{\text{N}} < 2.8$) and HREE ($2.5 < (\text{La}/\text{Yb})_{\text{N}} < 4.7$) and slight Eu negative anomalies ($0.78 < \text{Eu}/\text{Eu}^* < 0.99$) (fig. 3a, table I). Group 1 primitive mantle-normalized multi-elements spectra are characterized by significant Th and LREE enrichment and by marked Nb negative anomalies ($1.0 < \text{La}/\text{Nb} < 1.8$) (fig. 3b, tables Ia-b). No significant depletion of the less incompatible elements is observed. Samples 793-13 and 293-12 (Group 2) show rather flat chondrite-normalized REE-patterns ($(\text{La}/\text{Yb})_{\text{N}} \sim 1.2$) with small LREE enrichment while sample 293-11 has a slight LREE depleted pattern ($(\text{La}/\text{Yb})_{\text{N}} = 0.8$). Group 2 is

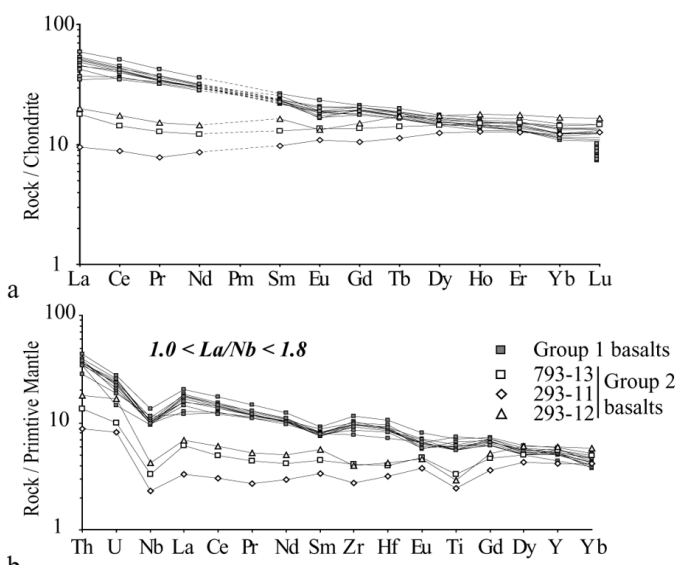


FIG. 3. – (a) Chondrite- and (b) primitive mantle-normalized [Sun and McDonough, 1989] patterns of the Panjal Traps basalts.

FIG. 3. – *Composition en éléments traces des basaltes de Panjal : (a) Spectres de terres rares normalisés aux chondrites et (b) spectres multi-éléments normalisés au manteau primitif [d'après Sun et McDonough, 1989].*

also enriched in Th but displays highest negative anomalies in Nb ($\text{La}/\text{Nb} \sim 1.8$) and Ti.

Comparison with the western Panjal Traps counterparts

Pioneer major element geochemical analyses from Kashmir and Zanskar basalts have shown that Panjal Traps flows have mainly tholeiitic affinities [Pareek, 1976; Singh *et al.*, 1976]. Major and trace elements works on coeval Permian volcanic rocks (basaltic flows and feeder intrusive bodies) outcropping in Pakistan and Ladakh have been plotted together with our data in view to establish geochemical composition variations through the Panjal Traps lavas from the Zanskar-Spiti to the Pakistan (figs. 4-5a)

$\text{Mg}\#$ [$\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$], TiO_2 (wt%) and Y (ppm) show relatively good correlations with Zr (fig. 4). This indicates that the variation in element contents of the Panjal volcanics is more probably related to igneous fractionation processes rather than to metamorphic events. Group 1 $\text{Mg}\#$ values and Zr contents indicate basaltic compositions ($51.2 < \text{Mg}\# < 62.1$), excepted for basalt 04/08B ($\text{Mg}\#=32.6$) showing no SiO_2 content correlation (table I). Group 2 exhibits significantly higher $\text{Mg}\#$ values ($66.8 < \text{Mg}\# < 73.4$) correlated with lower SiO_2 amount, this is assigned to a more primitive character of these lavas. The highly magnesian 293-11 sample, ($\text{MgO} = 18\%$, $\text{Ni} = 850$ ppm, $\text{Cr} = 2440$ ppm), should represent the remnant of an ultramafic cumulate (olivine, clinopyroxene).

Most of the samples collected in Kashmir, Zanskar and Spiti show low TiO_2 , Zr (fig. 4), and P_2O_5 (fig. 5a) contents. The greatest chemical variability is observed in the western syntaxis lavas (NE Pakistan) which display features of tholeiitic to slightly alkaline affinities, characterized by larger scale Zr and TiO_2 variations for broadly similar $\text{Mg}\#$ [Pogue *et al.*, 1992; Spencer *et al.*, 1995]. Despite a

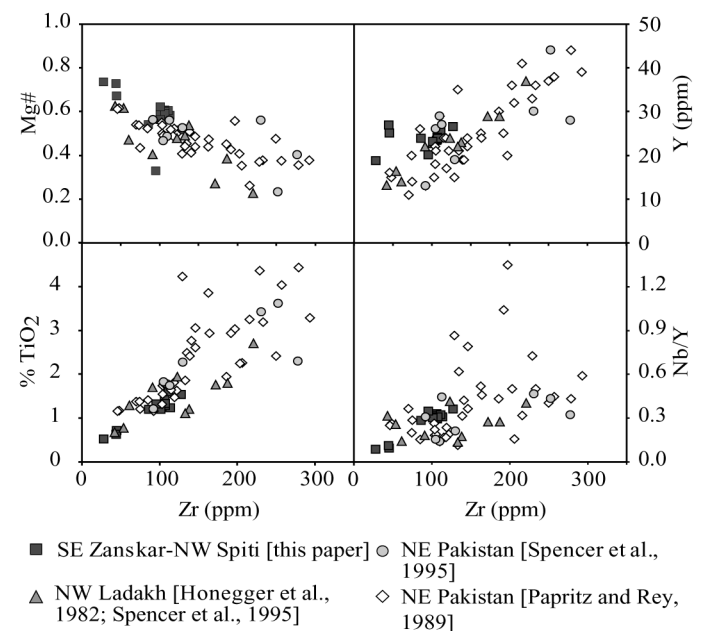


FIG. 4. – Geochemical composition of the Panjal Traps lavas plots in $\text{Mg}\#$, TiO_2 , Y and Nb/Y vs Zr diagrams.

FIG. 4. – *Composition géochimique des laves des trapps de Panjal représentée dans les diagrammes de corrélation $\text{Mg}\#$, TiO_2 , Y et Nb/Y en fonction de Zr.*

probable erratic behaviour of alkali major elements during secondary processes (fig. 5b), the discriminating diagram of MacDonald and Katsura [1964] also illustrates that most of the available Panjal lavas analyses are characterized by mainly basaltic compositions which plot within the tholeiitic melts field (fig. 5b).

Isotopic compositions of Zanskar-Spiti tholeiites

Zanskar-Spiti tholeiites (Groups 1 and 2) show very high and anomalous initial Sr isotopic ratios ranging from 0.7083 to 0.7144 (tables IIa-b). Such high and anomalous values can be assigned to an insufficient "in situ" decay correction due to mobility of lithophile elements during late alteration processes and especially the leaching of Rb. The extremely low Rb contents shown by some of the studied lavas ($Rb_{ppm} < 1$, fig. 2e, tables IIa-b) substantiate this hypothesis. ϵNd_i values range between +0.9 and -3.6 with six out of nine samples which have negative values. Such isotopic

signatures ruled out the depleted mantle (DMM) as the major component involved in the source of the studied volcanic rocks.

In the Pb-Pb correlation diagrams (figs. 6a-b), Zanskar-Spiti tholeiitic basalts plot significantly above the North Hemisphere reference line [Zindler and Hart, 1986]. For a given $(^{206}Pb/^{204}Pb)$ ratio, the two Zanskar-Spiti tholeiitic groups show more radiogenic $(^{207}Pb/^{204}Pb)$ and $(^{208}Pb/^{204}Pb)$ values than both Indian and Atlantic MORBs (figs. 6a-b). In the $(^{208}Pb/^{204}Pb)_i$ vs $(^{206}Pb/^{204}Pb)_i$ plot, tholeiites report in the OIB field whereas in the $(^{207}Pb/^{204}Pb)_i$ versus $(^{206}Pb/^{204}Pb)_i$ diagram (fig. 6a), a significant shift of the data is observed towards a ^{207}Pb -rich component close to the Enriched Mantle II-type component [EM II; Zindler and Hart, 1986]. Reported in the ϵNd_i - $(^{206}Pb/^{204}Pb)_i$ diagram (fig. 6c), Group 1 and 2 basalts plot again between the OIB-type mantle and EM II-type enriched component (table II) with the exception of sample 293-11. The Group 2 basalts show higher initial Pb isotopic ratios than Group 1 (tables IIa-b). Samples from Group 1 show very homogeneous isotopic compositions for both the Nd and Pb isotopes.

DISCUSSION

Source origin for the Zanskar-Spiti Permian basalts

Pb and Nd isotopic ratios show that the studied easternmost Panjal Traps flows derived from the melting of an OIB-like mantle source. High Pb initial ratios and negative ϵNd_i values also strongly suggest involvement of an enriched component. Plotted in the $^{147}Sm/^{144}Nd$ ratios versus ϵNd_i diagram, the two groups of Panjal Traps tholeiites define two separated fields with significantly higher $^{147}Sm/^{144}Nd$ ratios for group 2 (fig. 7a). These latter basalts are probably generated by a higher degree of partial melting than group 1 and from a mantle reservoir defined by an ϵNd_i value close to +1 (i.e. higher ϵNd_i values for the group 2 basalts). This assumption is consistent with the lower $(La/Yb)_N$ and $(La/Gd)_N$ ratios shown by group 2 compared to group 1 (tables I). Moreover, the isotopic compositions of the two groups of samples suggest that some contamination process, at variable degree, occurred between an OIB-type mantle source and an enriched reservoir (i.e. enriched lithospheric mantle, continental crust, terrigenous recycled sediments...). This contamination induces an increase of the Pb/Pb isotopic ratios simultaneously with a decrease of $^{143}Nd/^{144}Nd$ values (fig. 6c). Such an evolution is consistent with participation of an EM II-type contaminant, which is characterized in particular by high $^{207}Pb/^{204}Pb$ and moderate $^{206}Pb/^{204}Pb$ ratios and relatively low Nd isotopic ratios (fig. 6).

Plotted in the ϵNd_i versus Zr content diagram (fig. 7b), again the two previous groups are individualized and group 1 provides a more homogeneous domain than group 2. Both groups are characterized by relatively homogeneous Zr contents (table I). Two out of the three samples belonging to group 2 yield the lowest Zr contents coupled to the lowest ϵNd_i values of the present study. Therefore, the group 1 scattered field does not characterize any correlation between ϵNd_i and Zr contents. Thus, the contribution of an enriched component in the genesis of the studied lavas probably did not occur during fractional crystallisation into

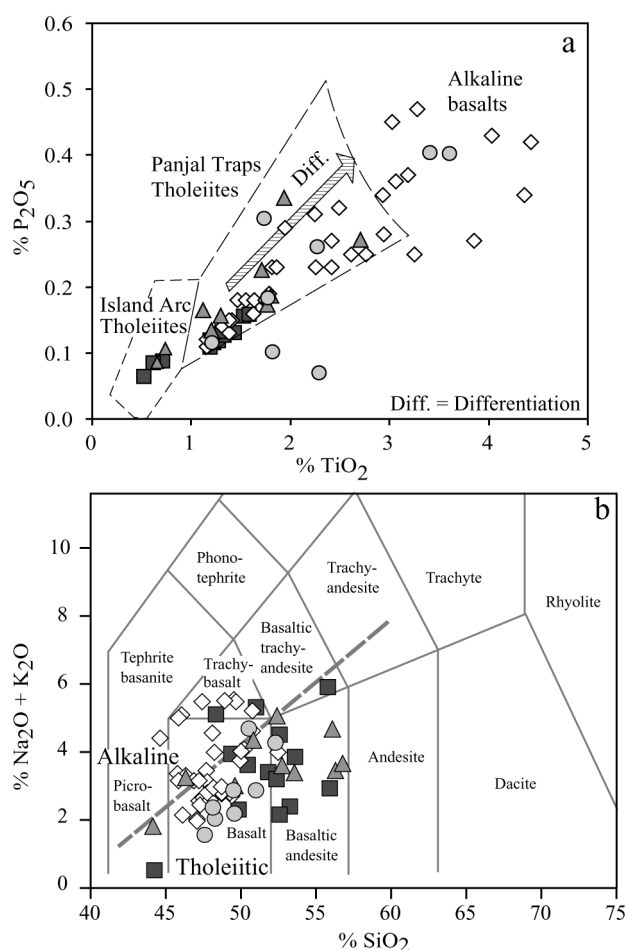


FIG. 5. – Discriminating diagrams (a) P_2O_5 vs TiO_2 from Honegger *et al.* [1982] and (b) $[Na_2O+K_2O]$ vs SiO_2 diagram from MacDonald and Katsura [1964] for the Panjal Traps lavas. See legend in figure 4. In the figure 5a, Panjal tholeiitic field is from Honegger *et al.* [1982]; alkaline basalts and island arc tholeiites fields are from Hawkins [1980]. In the figure 5b, the stippled line distinguishes tholeiitic from alkaline basalts.

FIG. 5. – Diagrammes discriminants (a) P_2O_5 vs TiO_2 d'après Honegger *et al.* [1982] et (b) $[Na_2O+K_2O]$ vs SiO_2 d'après MacDonald et Katsura [1964] pour les laves des trapps de Panjal. Légende identique à la figure 4. Sur la figure 5a, le champ des tholéïites de Panjal est défini par Honegger *et al.* [1982]; et les champs discriminants des basaltes alcalins et des tholéïites d'arc insulaire sont d'après Hawkins [1980]. Sur la figure 5b, la ligne pointillée distingue les basaltes tholéïitiques des basaltes alcalins.

TABLE IIa. – Nd, Sr and Pb isotopic compositions of the Zanskar-Spiti Panjal Traps samples.

TABL. IIa. – Compositions isotopiques du Nd, du Sr et du Pb, des échantillons des trapps de Panjal du Zanskar-Spiti.

Sample	- Group 1 -					
	Y101	Y103	Y104	Y105	Y117	Y118
Rb (ppm)	0.35	0.78	0.95	0.59	13.34	1.15
Sr (ppm)	235.41	166.73	389.88	213.21	99.96	365.36
⁸⁷ Sr/ ⁸⁶ Sr	0.714037 ± 10	0.712762 ± 10	0.710771 ± 9	0.710907 ± 7	0.715115 ± 7	0.714455 ± 9
⁸⁷ Rb/ ⁸⁶ Sr	0.004	0.014	0.007	0.008	0.386	0.009
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.71402	0.71271	0.71074	0.71088	0.71360	0.71442
εSr _i	139.8	121.2	93.3	95.1	133.9	145.5
Sm (ppm)	3.35	3.87	3.57	3.62	3.58	3.37
Nd (ppm)	13.66	14.04	13.79	14.72	14.89	13.80
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512504 ± 5	0.512628 ± 5	0.512588 ± 4	0.512512 ± 5	0.512517 ± 6	0.512496 ± 5
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.148	0.167	0.157	0.149	0.145	0.148
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.51224	0.51233	0.51231	0.51224	0.51226	0.51223
εNd	-0.91	0.86	0.43	-0.77	-0.56	-1.05
²⁰⁶ Pb/ ²⁰⁴ Pb	18.530	18.509	18.497	18.486	18.433	18.457
²⁰⁷ Pb/ ²⁰⁴ Pb	15.690	15.684	15.684	15.672	15.673	15.672
²⁰⁸ Pb/ ²⁰⁴ Pb	39.324	39.148	39.166	39.121	39.119	39.093
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.20	18.10	18.13	18.16	18.23	18.19
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.67	15.66	15.66	15.65	15.66	15.66
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.62	38.32	38.42	38.47	38.68	38.57

shallow level magma chambers. This process can occur either in the early stages of magma evolution (i.e. mantle source) or later, during magma ascent to the surface.

Melts derived from primitive mantle are expected to have a Th/Ta ratio of ~ 2.1 [Sun and McDonough, 1989]. In the Th versus Ta diagram (fig. 7c), the group 1 and group 2 defined for the Panjal basalts plot along two distinct correlation lines defined by Th/Ta ratios of ~ 5.7 and ~ 8.2, respectively. All basalts from group 2 are located on the Th/Ta line equal to ~ 8.2 suggesting that they derive from a same parental magma. Group 1 basalts show a rather large range of Ta values coupled with homogeneous Th abundance. However, three samples (Y100, Y102 and Y103, fig. 7c, table I) are more homogeneous and are located on the single Th/Ta = 3.2 correlation line. Such behaviour indicates the absence of any significant fractionation process and should reflect variable contamination degrees by an enriched

component. This is also suggested by the broadly reverse correlation existing between εNd_i values and La/Nb ratios (fig. 7d). The latter indicates a relationship between the extent of the Nb negative anomaly and the amount of the enriched component added to the OIB-like mantle. Moreover, the average Th/Ta value of the upper continental crust is as high as 10.7 [McLennan, 2001]. Taking into account isotopic and trace elements features of the studied basalts, it should be envisaged that parental magmas of both Groups 1 and 2 have been contaminated at some stages of their evolution by upper continental crust.

Spencer *et al.* [1995] published a set of Sr and Nd isotopic analyses from Pakistan Panjal Traps. The corresponding isotopic field is plotted against the Ti/Y ratio (fig. 8). In the absence of Fe-Ti oxide fractionation, the Ti/Y ratio is not affected by low-pressure fractionation processes [Brewer *et al.*, 1992] and so, variations of this ratio can be attributed either to a variable degree of partial melting or to a mixing between various components. The latter process will be characterized by significantly different Ti/Y values. In the εNd_i vs Ti/Y diagram (fig. 8), Panjal Traps lavas of Zanskar-Spiti and Pakistan plot between a crust-derived end-member and an OIB-like mantle component. The broad tendency of our data (excepted for the group 2) suggests that the mantle component initially involved in the Panjal basalts was characterized by higher Ti/Y values than normal melts generate in mid-oceanic ridge. The scattering of data can be tentatively related to drastic change in melting conditions, especially the group 2 Panjal basalts characterized by lower Ti/Y ratios are related to a higher degree of partial melting. Moreover, the lowest εNd_i values occur in the least metamorphosed and fractionated rocks of the NW Zanskar and Zanskar-Spiti Panjal tholeiites [Spencer *et al.*, 1995]. This demonstrates that the crustal contamination process is more efficient in the more primitive high-temperature tholeiites (with exception of the 293-11 cumulate).

Crustal contamination processes have been often mentioned for the more primitive, higher temperature, magmas of continental flood basalts [Saunders *et al.*, 1992]. This is the case, for example, of the Poladpur and Bushe

TABLE IIb. – Nd, Sr and Pb isotopic compositions of the Zanskar-Spiti Panjal Traps samples.

TABL. IIb. – Compositions isotopiques du Nd, du Sr et du Pb, des échantillons des trapps de Panjal du Zanskar-Spiti.

Sample	- Group 2 -			
	793 - 13	293-11	293-11dup.	293-12
Rb (ppm)	43.96	0.40	0.40	19.97
Sr (ppm)	122.15	317.47	317.47	179.74
⁸⁷ Sr/ ⁸⁶ Sr	0.712374 ± 8	0.712149 ± 10	0.712116 ± 8	0.712197 ± 8
⁸⁷ Rb/ ⁸⁶ Sr	1.042	0.004	0.004	0.322
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.70830	0.71213	0.71210	0.71094
εSr _i	58.5	113.0	112.5	96.0
Sm (ppm)	1.98	1.49		2.48
Nd (ppm)	5.64	3.99		6.71
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512588 ± 6	0.512722 ± 9		0.512504 ± 11
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.212	0.226		0.223
(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	0.51221	0.51232		0.51210
εNd	-1.51	0.62		-3.56
²⁰⁶ Pb/ ²⁰⁴ Pb	19.000	19.086		19.023
²⁰⁷ Pb/ ²⁰⁴ Pb	15.784	15.767		15.745
²⁰⁸ Pb/ ²⁰⁴ Pb	39.563	39.438		39.441
(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	18.58	18.79		18.52
(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	15.76	15.75		15.72
(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	38.81	39.02		38.73

formations from the Deccan Traps, which are characterized by high LILE (K, Rb, Ba...), Th and Pb-Sr isotopic ratios, and low Zr, Nb, Y contents and Nd isotopic ratios [Lightfoot *et al.*, 1990; Lightfoot and Hawkesworth, 1988]. Similar features have been described for low-Ti basalts from various provinces such as the East Coast of Madagascar [Saunders *et al.*, 1992], the Paraná province [i.e. Gramado basalts; Peate and Hawkesworth, 1996], the Guinean tholeiites [i.e. tholeiites from the Central Atlantic Magmatic Province; Deckart *et al.*, 2005], and the Siberian traps basalts [i.e. Wooden *et al.*, 1993; Sharma, 1997]. Alternatively, very low to intermediate $^{206}\text{Pb}/^{204}\text{Pb}_i$ values are often attributed to contribution of an enriched sub-continental lithospheric mantle component in the genesis of the basalts [e.g. Saunders *et al.*, 1992; Kieffer *et al.*, 2004].

The differences in the Nd and Pb isotopic compositions of the studied Panjal Traps basalts are not clearly linked to AFC process (fig. 7a) but more probably reflect contamination of an OIB-like mantle by an enriched component (figs. 7a-c-d). Some arguments allow us to propose that the

enriched component is the upper continental crust. They are (i) high Th/Ta and La/Nb ratios, (ii) negative correlation between ϵNd_i and Th/Ta ratios, and (iii) the geological context of Panjal Traps basalts emplacement, which is favourable to this process with an emplacement of these volcanics into the Indian continental crust.

Geodynamic implications

The chemical compositions of the Panjal Traps lavas suggest that effusions were largely dominated by basaltic melts of tholeiitic affinity (figs. 5a-b). Their low TiO_2 , Zr, and P_2O_5 contents and Nb/Y ratios (mostly lower than 0.6) but also the Th and LREE enrichments combined with Nb negative anomalies are typical features of continental flood tholeiitic basalts [Boillot and Coulon, 1998]. The minor proportion of high-fractionated melts [Pareek, 1976; Honnegger *et al.*, 1982; Papritz and Rey, 1989] and absence of Eu anomalies in Panjal lavas suggest a rapid effusion of magmas. This is commonly observed in many continental flood volcanic provinces where there is a striking contrast between the compositions of tholeiitic basalts and the petrographic and chemical diversity of other volcanic types [Arndt *et al.*, 1998; Wilson, 1989; Iacumin *et al.*, 2003]. This feature combined with the mainly tholeiitic affinities observed in the wide geographic extent of the traps

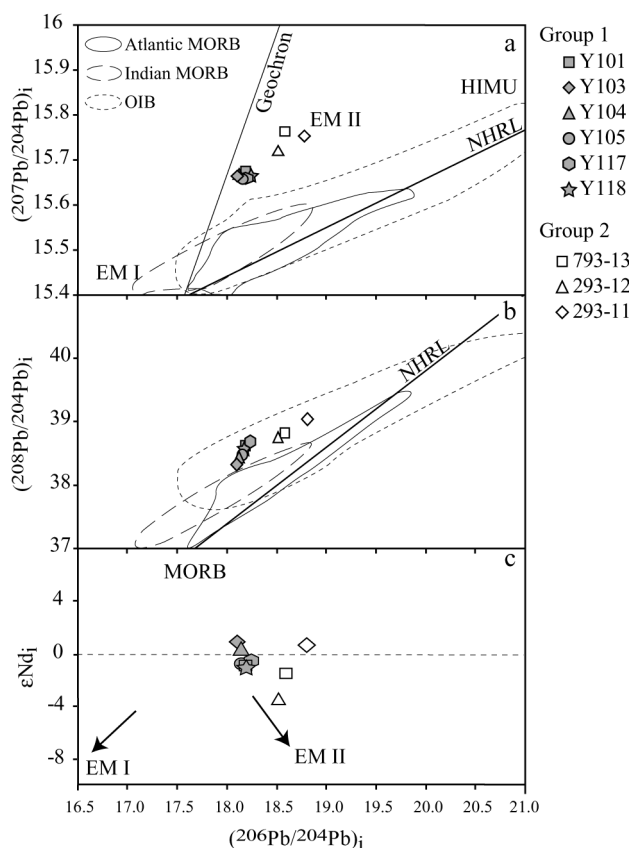


FIG. 6. – Isotopic compositions of the Panjal Traps basalts: (a) $(^{207}\text{Pb}/^{204}\text{Pb})_i$ vs $(^{206}\text{Pb}/^{204}\text{Pb})_i$ diagram. (b) $(^{208}\text{Pb}/^{204}\text{Pb})_i$ vs $(^{206}\text{Pb}/^{204}\text{Pb})_i$ diagram. (c) ϵNd_i vs $(^{206}\text{Pb}/^{204}\text{Pb})_i$ diagram. Fields of MORBs are from pre-compiled isotopic compositions in the PETDB (spreading axis tholeiitic basalts); Oceanic Islands Basalts (OIB) field, mantle components HIMU, Enriched Mantle EM-I and -II and the North Hemisphere Reference Line (NHRL) are from Zindler and Hart [1986].

FIG. 6. – Compositions isotopiques des basaltes des trapps de Panjal : Diagrammes (a) $(^{207}\text{Pb}/^{204}\text{Pb})_i$ vs $(^{206}\text{Pb}/^{204}\text{Pb})_i$, (b) $(^{208}\text{Pb}/^{204}\text{Pb})_i$ vs $(^{206}\text{Pb}/^{204}\text{Pb})_i$ et (c) ϵNd_i vs $(^{206}\text{Pb}/^{204}\text{Pb})_i$. Les champs de composition des MORBs correspondent aux compositions isotopiques pré-compilées des basaltes tholeiitiques échantillonnés à l'axe d'accrétion, sur le site de PETDB. Le champ de composition des basaltes des îles océaniques (OIB), des composants mantelliques HIMU, EM-I et EM-II et la NHRL sont d'après Zindler et Hart [1986].

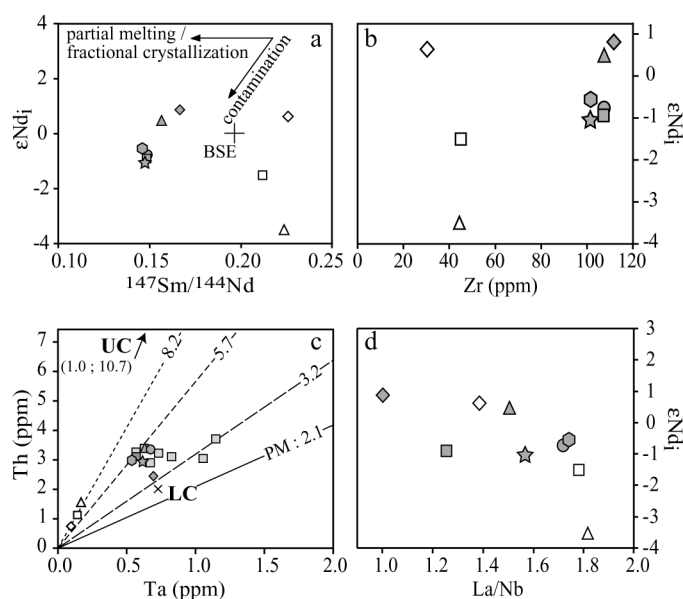


FIG. 7. – (a) ϵNd_i vs $(^{147}\text{Sm}/^{144}\text{Nd})$ diagram. (b) ϵNd_i vs Zr (ppm) diagram. (c) Th (ppm) vs Ta (ppm) diagram. Primitive mantle (PM) Th/Ta ratio (2.1) after Sun and McDonough [1989]; upper and lower continental crust (UC and LC) average contents after McLennan [2001]. Th/Ta ratio of each correlation line are plotted. (d) ϵNd_i vs (La/Nb) diagram. Samples are the same as those of the figure 6 and additional light grey squares in figure 7c correspond to the other analysed Zanskar-Spiti Panjal tholeiites.

FIG. 7. – (a) Diagramme de corrélation ϵNd_i en fonction de $(^{147}\text{Sm}/^{144}\text{Nd})$. (b) Diagramme de corrélation ϵNd_i en fonction de Zr (ppm). (c) Diagramme de corrélation des teneurs en Th (ppm) en fonction des teneurs en Ta (ppm) pour les tholéiites de Panjal. Le rapport Th/Ta (2.1) du manteau primitif (PM) est d'après Sun et McDonough [1989]; les compositions moyennes de la croûte continentale supérieure et inférieure (UC et LC) sont d'après McLennan [2001]. Les rapports Th/Ta de chaque droite de corrélation sont reportés. (d) Diagramme de corrélation ϵNd_i en fonction du rapport (La/Nb). La légende des échantillons est la même que pour la figure 6 et les carrés gris clairs supplémentaires de la figure 7c correspondent aux autres tholéiites analysées du Zanskar-Spiti.

(~ 400 km) suggests a rapid and voluminous effusion of magmatic melts derived from a high degree of partial melting. Such a scenario was already proposed for other Permian tholeiitic series [e.g. Arunachal Pradesh, Bhat, 1984; Bhat and Ahmad, 1990; Central Nepal, Garzanti *et al.*, 1999; fig. 1b], where melt ascent was more efficient through a rifted and strongly thinned lithosphere [e.g. Bhat, 1984; Garzanti *et al.*, 1999].

Compared to the Carboniferous-Early Permian climax of the continental rifting and the associated punctual mainly alkaline magmatism [Pogue *et al.*, 1992; Vannay, 1993; Garzanti *et al.*, 1996a, 1996b; Garzanti *et al.*, 1999], the Panjal Traps extrusion represents a huge magmatic episode characterized by a higher degree of partial melting. Moreover, their rapid effusion could be associated to the drastic lithospheric thinning during continental break-up.

Throughout the Arabian and Indian contiguous continental margins, the available lithostratigraphic informations reported on the southern Neotethyan platforms document that the Neotethyan rifting derived from a long term and probably polyphased tectonic process. In the Himalayan zone, rifting began as early as the Early Carboniferous [Vannay, 1993; Garzanti *et al.*, 1996a; Garzanti and Sciunach, 1997]. The Lower to Middle Permian Panjal traps extrusion would be one of the largest remnants of the final rifting stage, which accompanied the Neotethyan opening. This huge magmatism belongs to a set of Permian within plate volcanic sequences [fig. 1b], which are systematically regarded as the testimony of an advanced stage of the lithospheric stretching [Bhat and Ahmad, 1990; Stampfli *et al.*, 1991; Veevers and Tewari, 1995; Garzanti *et al.*, 1999; this paper]. Syn-rift volcanic successions were also found along the preserved fragment of the neighbouring Arabian continental margin in Oman [Béchénnec *et al.*, 1991; Maury *et al.*, 2003; Lapierre *et al.*, 2004]. In Oman, tholeiitic and alkaline melts erupted both on the rifted platform (Saihat area, Oman mountains) and in the Hawasina pelagic basin. An OIB-type mantle reservoir has been evidenced, on the basis of Nd and Pb isotopes, beneath the Arabian rifted margin during Middle Permian [Lapierre *et al.*, 2004]. Arabian Middle Permian volcanics yield isotopic compositions, which encompass the signature of the present Panjal basalts

data. So the Arabian margin can be tentatively compared to a volcanic-type margin considered as related to the melting of a mantle plume, which would have impinged the Arabian lithosphere during or after the oceanic opening [Maury *et al.*, 2003; Lapierre *et al.*, 2004].

Taking into account the discontinuous and diachronic volcanic provinces erupted along the rifted Indian (fig. 1b) and Arabian margins (between Lower Permian to Middle Permian), the model proposing emission of a huge volume of melt in a very short time does not appear satisfactory for the South Neotethyan margin formation. The lack of pre-rift traps is in favour of the active rifting model, as in the North Atlantic magmatic province and the associated Iceland plume [Saunders *et al.*, 1992; Menzies *et al.*, 2002]. Nevertheless, the emission of voluminous within plate volcanic sequence synchronously to Neotethys opening strongly suggests the presence of an abnormally hot asthenospheric reservoir, which should have produced significant volume of tholeiitic melts in relation with overlying lithosphere thinning.

Therefore, the more or less wide volcanic outcrops or traps associated to the southern Neotethyan margins rifting could be regarded either as the remnant of independent geodynamic processes suggesting upwelling of several hot spots along the rift [as in Oman, Lapierre *et al.*, 2004; Maury *et al.*, 2003], or as a common geodynamic process related to a passive-type oceanic opening. In this scheme, the triple-point device of the Indian-Arabian-Madagascar Neotethyan rift arms [Stampfli *et al.*, 1991; Veevers and Tewari, 1995; Vai, 2003] could have played a significant role for the localization of melting zones between Indian and Arabian margins.

In the Central Atlantic magmatic province, alternative mechanisms to the mantle plume are actually largely debated. The CAMP represents the wider discontinuous volcanic province related to Pangea fragmentation. It is mainly considered as a passive rifting associated volcanism and not a plume magmatic province [Mc Hone, 2000; Salters *et al.*, 2003; DeMin *et al.*, 2003; Puffer *et al.*, 2003]. An alternative model indicates that wide volumes of basaltic melts can be associated to craton edge-driven convection developed in an abnormally hot upper mantle [Mc Hone, 2000; De Min *et al.*, 2003]. Global warming of the mantle should be itself related to the Pangea supercontinent agglomeration, according to the model proposed by Coltice *et al.* [2007].

Such mechanisms should allow to fit the different Neotethyan continental flood magmatism with a passive rifting model and yield, in particular, an alternative model to the weakly constrained upwelling of a mantle plume set along the same margin. Nevertheless, the geochemical features of Arabian and Indian volcanics discussed in this paper and in Lapierre *et al.* [2004] do not reflect participation of a continental lithospheric mantle component as it is globally accepted for the CAMP related magmas.

Isotopic analyses performed on the entire Panjal Traps and on the Lower Permian tholeiitic sequences along the Indian margin [Garzanti *et al.*, 1999] should allow to better constrain the global geodynamic mechanisms associated to the South Neotethyan margin volcanism. This particularly should highlight a potential participation of the lithospheric mantle, which could represent an alternative OIB-type isotopic reservoir relatively to the mantle plume.

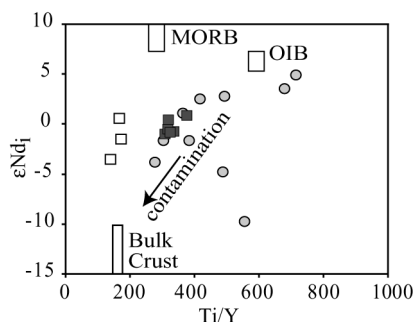


FIG. 8. – ϵNd_j vs (Ti/Y) plots of the Panjal Traps from Zaskar-Spiti (Group 1: black squares, Group 2: white squares) and Pakistan (grey circles) [Spencer *et al.*, 1995]. MORB and OIB values are from Sun and McDonough [1989] and Bulk Crust value is from McLennan [2001].

FIG. 8. – Variation des valeurs ϵNd_j en fonction de (Ti/Y) des trapps de Panjal du Zaskar-Spiti (Groupe 1 : carrés noirs, Groupe 2 : carrés blancs) et du Pakistan (ronds gris) [Spencer *et al.*, 1995]. Les valeurs des MORB et OIB sont d'après Sun et McDonough [1989] et celles de la croûte continentale, d'après McLennan [2001].

CONCLUSION

This study highlights the geochemical and isotopic characterization of the greatest volcanic episode associated to the formation of the southern Neotethyan margin. This episode led to the eruption of the Panjal Traps on the NW Indian rifted platform. The SE Zaskar-NW Spiti remnants of the Panjal lavas show features of tholeiitic low-Ti (<1.6%) continental flood basalts with LREE, Th enrichments and Nb-Ta negative anomalies ($1.0 < La/Nb < 1.8$). The low ϵNd_i values (-3.6 to +0.9), and high Pb-isotopic ratios indicate that the Panjal Traps derived from an OIB-like mantle, which was contaminated by an EM II-type component.

– The high La/Nb and Th/Ta ratios combined with the negative ϵNd_i values suggest this enriched component should be the upper continental crust. The crustal contamination process did not occur during an AFC-type process but more probably in the most primitive high-temperature tholeiites.

– Trace elements and isotopic ratios also suggest that the Panjal lavas derived from high partial melting degrees of an OIB-like mantle source. The absence of marked Eu anomalies combined with the low proportion of highly fractionated melts supports that Panjal lavas underwent no important differentiation process in shallow magmatic chambers.

– The geochemical features of the Zaskar-Spiti basaltic flows appear largely similar to the coeval Panjal volcanic sequences (Ladakh, Kashmir and Pakistan).

These features allow us to consider the Lower to Middle Permian magmatic event as a melting episode of huge magmatic volumes, generated by a high amount of partial melting in a within-plate setting. Relatively to the Carboniferous to early Permian rifting stages and associated scarce and mainly alkaline magmatism, these Lower to Middle Permian tholeiitic melts are regarded as the remnants of the late stages of lithospheric thinning and probably as the record of continental break-up. All these features support geological evidences that the Panjal Traps were extruded during the final step of the Neotethyan rifting episode. In such a scheme, the Panjal Traps were more probably formed in a passive-type rifting environment.

Despite a slight diachronism, similar conclusions are emphasized for the tholeiitic series of the central and eastern segments of the Indian margin, and in the adjacent Arabian margin. Whereas mantle plume upwelling is proposed for the Arabian margin volcanism, such a geodynamic model is not applicable to the entire volcanic sequences of the southern Neotethyan margin.

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