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# Geochemistry, petrogenesis and tectonic significance of the basic volcanic units of the Zildat ophiolitic mélange, Indus suture zone, eastern Ladakh (India)

## *Géochimie, pétrogénèse et signification tectonique des unités volcaniques basiques du mélange ophiolitique de Zildat, Suture de l'Indus du Ladakh oriental (Inde)*

T. AHMAD, R. ISLAM, P.P. KHANNA and V.C. THAKUR

**ABSTRACT.** – Basic volcanic rocks within the Zildat ophiolitic mélange of Indus suture zone in eastern Ladakh are medium to fine grained with partially preserved primary texture and mineralogy. These rocks are predominantly alkaline basalt with high Nb/Y and enriched incompatible trace element characteristics, similar to those of the oceanic island basalt (OIB). The minor sub-alkaline basaltic rocks resemble N-type mid ocean ridge basalt (N-MORB) but with much lower abundances of incompatible trace element including REE. The alkaline rocks probably generated through variable, but low degrees of partial melting of enriched mantle source and evolved through high pressure olivine and clinopyroxene fractionation. Low pressure plagioclase and Fe- Ti oxide do not appear to be major fractionating phases. Limited data on the sub-alkaline rocks suggest that their parental melts were derived from mantle sources somewhat similar to that of N- MORB. Significant role of added cumulates of olivine, clinopyroxene and Fe- Ti oxides is also indicated in their genesis. Ophiolitic mélanges all along the Indus suture zone appear to have formed due to the accumulation of mélange material in the upper part of the subduction zone where they suffered glaucophanitic (blueschist) metamorphism and retrograded partially to greenschist grade as these were subsequently obducted to its present position probably during the Cenozoic Himalayan orogeny due to collision of Indian and Eurasian plates.

**Key-words :** Indus suture zone, Zildat ophiolitic mélange, Eastern Ladakh, Geochemistry, Petrogenesis, Neo-Tethyan ocean.

**RÉSUMÉ.** – Les volcanites basiques du mélange ophiolitique de la suture de l'Indus, au Ladakh oriental, ont parfois

préservé leur texture et leur minéralogie primaires. Ce sont essentiellement des basaltes alcalins avec un rapport Nb/Y élevé, riches en éléments en traces incompatibles et comparables aux basaltes océaniques insulaires (OIB). Quelques basaltes sub-alcalins, moins riches en éléments en trace incompatibles, y compris les Terres Rares, sont plutôt comparables aux basaltes de ride médio-océanique de type N (N-MORB). Les roches alcalines semblent être issues de la faible fusion partielle d'un manteau enrichi et ont évolué par fractionation à haute pression de l'olivine et du clinopyroxène. Du plagioclase de basse pression et les oxydes ferro-titanés ne semblent pas avoir participé à la fractionation. Les magmas parentaux des roches sub-alcalines pourraient dériver d'une source mantélique assez similaire à celle des N-MORB. Les mélanges ophiolitiques le long de la suture de l'Indus se sont donc formés dans la partie supérieure d'une zone de subduction. Ils ont subi un métamorphisme de faciès schistes bleus avant d'être partiellement rétrotransformés dans le faciès des schistes verts. Ils ont été obductés dans leur position actuelle au cours du Cénozoïque, lors de l'orogène Himalayen dû à la collision entre l'Inde et l'Eurasie.

**Mots-clés :** Suture de l'Inde, Mélange ophiolitique de Zildat, Ladakh oriental, Géochimie Pétrologie, Néo-Téthys.

The Indus suture zone marks the boundary between the Indian and Eurasian plates (Gansser, 1977), running east-west for about 2 500 km to the north of the Himalaya. It is considered to represent remnants of the Neo-Tethyan ocean, when the latter closed via northward subduction under the Eurasian plate. In Ladakh, the Indus suture zone comprises two major ophiolitic mélanges, namely the Shergol ophiolitic mélange in western Ladakh and the Nidar ophiolite complex, with Zildat ophiolitic mélange at its base in eastern Ladakh

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(Thakur & Misra, 1984). Magmatic rocks of the Sergol ophiolitic mélange and other minor mélanges of western Ladakh have been studied in some details (Honegger *et al.*, 1982, 1989; Dietrich *et al.*, 1983; Rai, 1987; Sinha & Mishra, 1992a,b). However, the ophiolitic rocks of eastern Ladakh have remained largely neglected. We present a new set of geochemical data (major and trace elements including rare earth elements) on the less known Zildat ophiolitic mélange. The data is being used to chemically characterise these magmatic rocks, evaluate the possible petrogenetic processes involved and discuss their tectonic implications with respect to the Neo-Tethyan ocean.

## GEOLOGICAL SETTING

In Ladakh, the Indus suture zone is bounded in the south by the south dipping Indus suture thrust separating it from Tethys Himalaya and in the north by the north dipping Karakoram thrust separating it from the Karakoram zone (Thakur, 1992). The Indus suture zone is characterised by ophiolitic mélange, ophiolitic complex, island arc volcanic series and a linear flyschoid belt along the southern margin of Ladakh batholith. In eastern Ladakh, Thakur and Virdi (1979) have classified the Sumdo Formation of Shankar *et al.* (1976) into two tectonostratigraphic units, viz. the Zildat ophiolitic mélange and Nidar ophiolite. The Zildat ophiolitic mélange is thrust over the Tso-Morari crystalline complex and in turn is overlain by the Nidar ophiolite (fig. 1). The contact between the Zildat ophiolitic mélange and the Nidar ophiolite is the thrusta (Thakur & Misra, 1984). The Zildat ophiolitic mélange occurs in a belt that can be traced from south of Chumathang through Sumdo, extending further south east into Hanle and western Tibet. It is best exposed along the track between Sumdo and Mahe villages in the Indus valley (fig. 1).

The Zildat ophiolitic mélange comprises chaotic blocks of schistose basic volcanics, agglomerates, amygdaloidal basalts, chlorite schist, deformed conglomerate schist, glaucophane schist, slates and large lenses of pelagic limestones dispersed in a turbiditic matrix. Lenses of serpentinite are also observed together with agglomerates. A basic volcanic unit is one of the major lithological unit of this mélange. It is amygdaloidal in nature and amygdules are filled by calcite and chloritic material. The schistose nature of the basic volcanics and conglomerates suggests strong penetrative deformation. The deformed amygdules indicate a flattening type deformation (Thakur & Misra, 1984). Pillow lavas are nevertheless preserved.

Rocks of the Zildat ophiolitic mélange have undergone high pressure glaucophanitic metamorphism giving rise to blue schist assemblages containing glaucophane, lawsonite, epidote, garnet, stilpnomelane and spinel (Virdi *et al.*, 1977). Glaucophane occurs here in the basic volcanics, interbedded pyroclastics and serpentinites. These blueschist occur near the thrust NW and SE of Sumdo village and pass into greenschist towards north.

## PETROGRAPHIC CHARACTERISTICS

Basic volcanic rocks of the Zildat ophiolitic mélange are mostly medium to fine grained, porphyritic, granular, vesicular to amygdaloidal, greyish green in colour with some dark grey varieties. These rocks are foliated at the margin and massive in central portion. Vesicles are elongated, show deformation features and are filled by calcite and chlorite.

In thin section V series samples have clinopyroxene, plagioclase and Fe-Ti oxide as the major minerals make up. These rocks are porphyritic with large phenocrysts of clinopyroxene and plagioclases. Augite and ferroaugite are the dominant clinopyroxenes, occurring as euhedral to subhedral phenocrysts, and in the groundmass often replaced by chlorite. In most cases plagioclases both in phenocrysts and groundmass are patchy with development of chlorite and clay minerals. Fe-Ti oxides (magnetite, ilmenite and leucoxene) at times occur as small euhedral phenocrysts but mostly as fine dust dispersed in the phenocrysts and groundmass. In some samples, the groundmass is cryptocrystalline to almost glassy, but in majority of the samples it is fine grained, frequently showing development of schistosity. The groundmass consists of magnetite, calcite, chlorite, leucoxene, shreds of pyroxene and epidote. Serpentine pseudomorphs after olivines are often observed.

The OT series samples show equigranular texture in the case of OT1 and porphyritic in the other two samples. Sample OT1 is a medium to coarse grained, holocrystalline rock. It consists of subhedral grains of olivine and clinopyroxene with very little interstitial matrix material. Olivine is largely replaced by serpentine. Clinopyroxene grains have been partly altered to chlorite. Both olivine and clinopyroxene crystals have inclusions of magnetite dust. The other two samples, OT3 and OT4, show clouded plagioclases as the major phenocrystic phase. Phenocrysts of pyroxene, partly replaced by chlorite, and small phenocryst of Fe-Ti oxides are common. Few olivine phenocrysts now pseudomorphed by serpentine are also observed. These rocks exhibit a sub-ophitic texture between the clinopyroxene and plagioclase phenocrysts. Matrix material consists of fine grained clinopyroxene, plagioclases and Fe-Ti oxides showing preferred orientation in many of the samples. Minor mineral consists of epidote, pumpellyite, chlorite and calcite. Clinopyroxene and plagioclase represent the relict mineralogy.

## GEOCHEMISTRY

### Analytical techniques

Major elements were analysed using standard XRF technique, analytical details remaining the same as described by Bhat and Ahmad (1990). Trace elements and rare earth elements (REE) were determined by ICP-AES at the Wadia Institute of Himalayan Geology, Dehra Dun. 100 ml of 1% rock solution was prepared by

the method given in Walsh *et al.* (1981). 75 ml of this was processed for REEs and 25 ml was used for estimating other trace elements. REEs were separated by ion chromatography following the method of Walsh *et al.* (1981). REEs except Ce, Gd and Sm were determined using multi-element salt standard. Concentrations of Ce, Gd and Sm were measured using the separated REE fraction of a rock standard of matching matrix.

Analysis of trace and rare earth elements was carried out by monochromator of ICP-AES (Jobin Yvon, Model: JY 70 plus). Instrumental parameters are the same as given in Rathi *et al.* (1991). Analysis for thirteen selected, relatively less altered samples of the Zildat ophiolitic mélangé are presented in table I. The accuracy and precision of our analysis are presented in table II.

### Elemental mobility

Primary abundances of some of the elements may be perturbed as no sample is entirely fresh: they all have undergone hydrous alteration, blueschist and retrograded greenschist grade metamorphism. Therefore, before using any of the analysed elements they are assessed for their mobility. To do this, the major elements are plotted against SiO<sub>2</sub> and CaO (fig. 2), which in turn are plotted against Zr (fig. 3a) known to be relatively immobile during post crystallization alteration and/or low grade metamorphism (Winchester & Floyd 1977; Macdonald *et al.*, 1988). SiO<sub>2</sub> shows a good magmatic correlation with Zr ( $r=0.88$ ) probably indicating that the former was not much affected by secondary processes. Other major elements show discernable to good magmatic relationships with each other e.g. Al<sub>2</sub>O<sub>3</sub> vs CaO, Al<sub>2</sub>O<sub>3</sub> vs MgO, MgO vs CaO etc. (fig. 2) and between major and trace elements that follow major elements in a given crystal structure e.g. Fe<sub>2</sub>O<sub>3</sub> vs V and TiO<sub>2</sub>, K<sub>2</sub>O vs Rb, Ba etc. (plots not shown here). Minor elements (TiO<sub>2</sub> and P<sub>2</sub>O<sub>5</sub>) and many of the analysed incompatible trace elements also show a good magmatic relationship with Zr (fig. 3). In addition to showing their less mobile nature, figure 3 depicts the incompatible trace elements enriched nature with respect to primitive mantle ratios of most of the Zildat samples (PM: Sun & McDonough, 1989). All the enriched samples have smooth and coherent normalised REEs and multi-element (spidergram) abundance patterns (fig. 4). The depleted rocks also show smooth REE patterns except for La and Eu anomalies (Fig. 4a). Hydrothermal alteration of basalt may cause La enrichment (Sun & Nesbitt, 1978) and Ce depletion (De Baar *et al.*, 1985). The kinks observed for La with respect to Ce in the rare earth patterns for the depleted samples (fig. 4a) may be due to either of the above processes or a combination of these. Positive Eu anomalies in two of

the samples which also have very low abundances for all the REEs could be related to plagioclase accumulation. Thus, the above review indicate that most of the major, trace and REEs, except for probably La and Ce in depleted samples, have undergone limited to no remobilization in the selected samples, and therefore, are likely to represent near primary abundances and ratios.

### Magma type

In total alkalis (Na<sub>2</sub>O + K<sub>2</sub>O) vs SiO<sub>2</sub> plot (fig. 2d) all enriched samples (fig. 4) classify as basaltic with clear alkaline nature, two depleted samples show their sub-alkaline nature and the third plots separately due to its very low SiO<sub>2</sub> content. Using relatively immobile, incompatible trace elements ratio (Nb/Y vs Zr/TiO<sub>2</sub>; fig. 5), which is more reliable for rocks that have undergone low grade metamorphism and alteration (Winchester & Floyd, 1977), the enriched samples depict their highly alkaline nature and the three depleted samples plot in the sub-alkaline basalt field. Based on the Ti/Y and Zr/Y ratios all the alkaline samples can be classified as high Ti basalts (Ti/Y >410 and Zr/Y >6: Erlank *et al.*, 1988). Two of the sub alkaline samples (OT3 and OT4) also have Ti/Y >410, which could be due to the added clinopyroxene and Fe-Ti oxides cumulates; their low Zr/Y ratio (<2) clearly discriminate them from the other magma type.

Normalised REEs and multi-element patterns for the Zildat ophiolitic mélangé samples are respectively shown in Fig.4a and b. In order to avoid crowding and overlapping of the patterns for alkaline samples, average of six samples with similar abundances (table I) is shown as pattern AVG and one of the two extremely enriched samples (pattern V7) is shown in fig. 4a and b. REE and multi-element patterns for the three sub-alkaline samples (OT1, OT3 and OT4) are shown in fig. 4a and b. Chondrite normalised REEs abundances (fig. 4a) for the alkaline rocks have highly fractionated patterns (Ce/Sm)<sub>N</sub> = 2.68-3.5 and (Ce/Yb)<sub>N</sub> = 19 to 34, where subscript "N" signifies normalisation of element ratios against C1 chondrite: Sun & McDonough 1989) with the light rare earth (La and Ce) having about 250-300 times and heavy rare earths (Yb and Lu) having <10 times chondritic abundances. The sub-alkaline rocks have nearly flat to depleted LREE and HREE patterns with (Ce/Sm)<sub>N</sub> = 0.62 to 0.80 and (Sm/Yb)<sub>N</sub> = 0.88 to 1.33 (fig. 4a). Mantle normalised multi-element patterns for the sub-alkaline samples show highly irregular patterns (fig. 4b). Two of these samples (OT3 and OT4) have extremely low abundance of REE, Zr, Y, high Nb, Sr, Ti, P, V, Sc and positive Eu anomalies. These charac-

Fig. 1. - Geological map of eastern Ladakh and a cross section along the line A-B, showing the contact relationships among various lithological units of the study area (after Thakur & Misra, 1984). Inset map of India showing the location of Zildat ophiolitic mélangé.

Fig. 1. - Carte et coupe (ligne A-B) géologiques simplifiées du Ladakh oriental illustrant les relations entre les unités lithologiques de la région étudiée (d'après Thakur & Misra, 1984). En encart, carte de l'Inde situant le mélangé ophiolitique de Zildat.



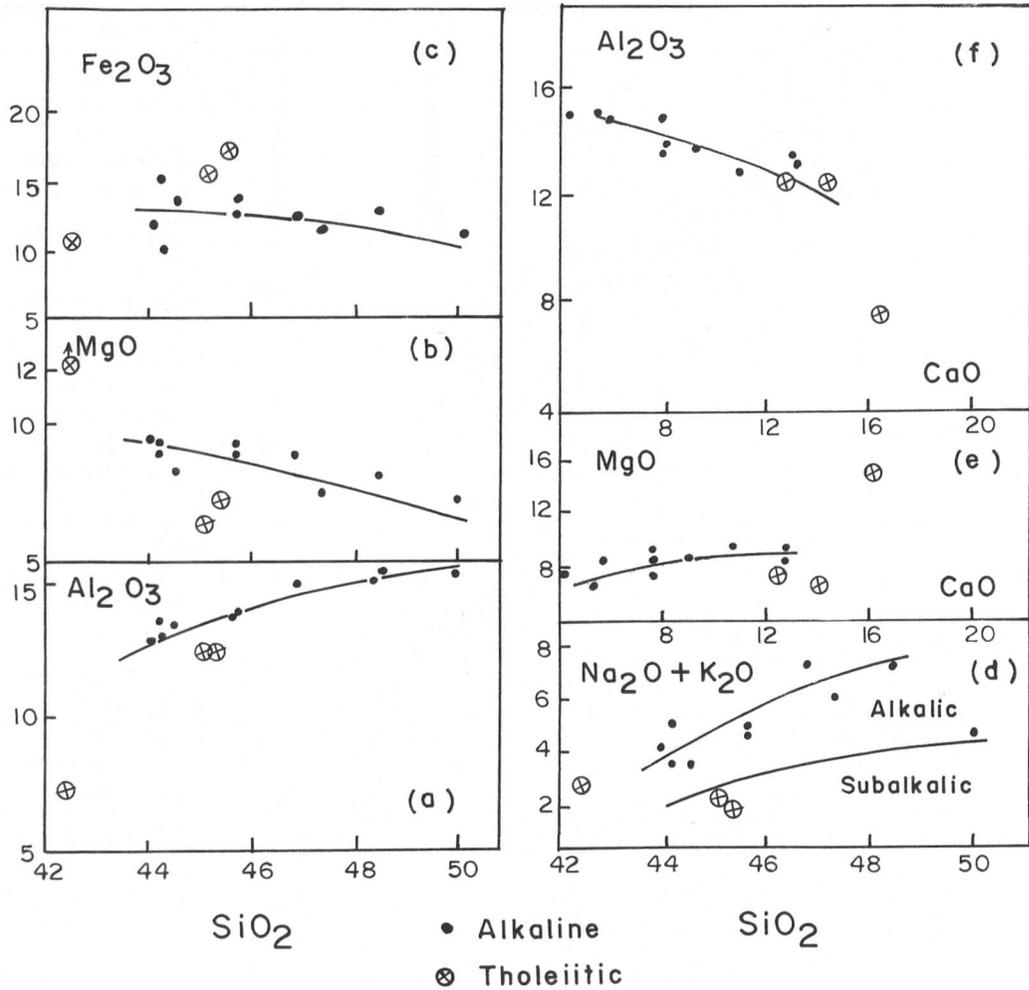


Fig. 2. - Binary plots of major elements against  $\text{SiO}_2$  and  $\text{CaO}$  showing magmatic trends. Filled circles are alkaline rocks and open circles with cross are tholeiitic basalts of Zildat ophiolitic mélange.

Fig. 2. - Diagrammes binaires d'éléments majeurs en fonction de  $\text{SiO}_2$  et  $\text{CAO}$  pour définir les suites magmatiques. Ronds pleins = roches alcalines. Croix encerclées = basaltes tholéiitiques du mélange ophiolitique de Zildat.

teristics may be related to added cumulates of plagioclase (as indicated by positive Eu anomalies), clinopyroxenes and Fe-Ti oxides, as petrography of these samples reveals that these phases are the dominant phenocrystic phases. Sample OT1 has high abundance of MgO, CaO, Ni, Cr and Sc, low abundances of  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{TiO}_2$  and incompatible trace elements including REEs. These characteristics are consistent with added cumulates of olivine and clinopyroxene, these being the major mineral phases in thin section. Considering the mineral/melt distribution coefficients of REE for olivine and clinopyroxene (Hanson, 1980) addition of these phases as cumulates may not alter the REE pattern to any significant degree, although their abundances may be diluted. Addition of plagioclase,

however, will cause a positive Eu anomalies. This would imply that the nearly flat to depleted LREE and HREE nature of the sub-alkaline samples may be primary i.e. their parental melts had similarly depleted trace element characteristics. However, the overall low abundances of all the incompatible elements including REE and high abundances of compatible elements e.g., Ni, Cr, Sc, V in the samples could be related to addition of cumulate phases to the parental melts. Mantle normalised multi-element patterns (fig. 4b) for the alkaline samples show their enriched incompatible trace element characteristics similar to those of the OIB (Sun & McDonough, 1989) and alkaline rocks of the Shergol ophiolitic mélange of western Ladakh (Sinha & Mishra, 1992a), although the latter two patterns

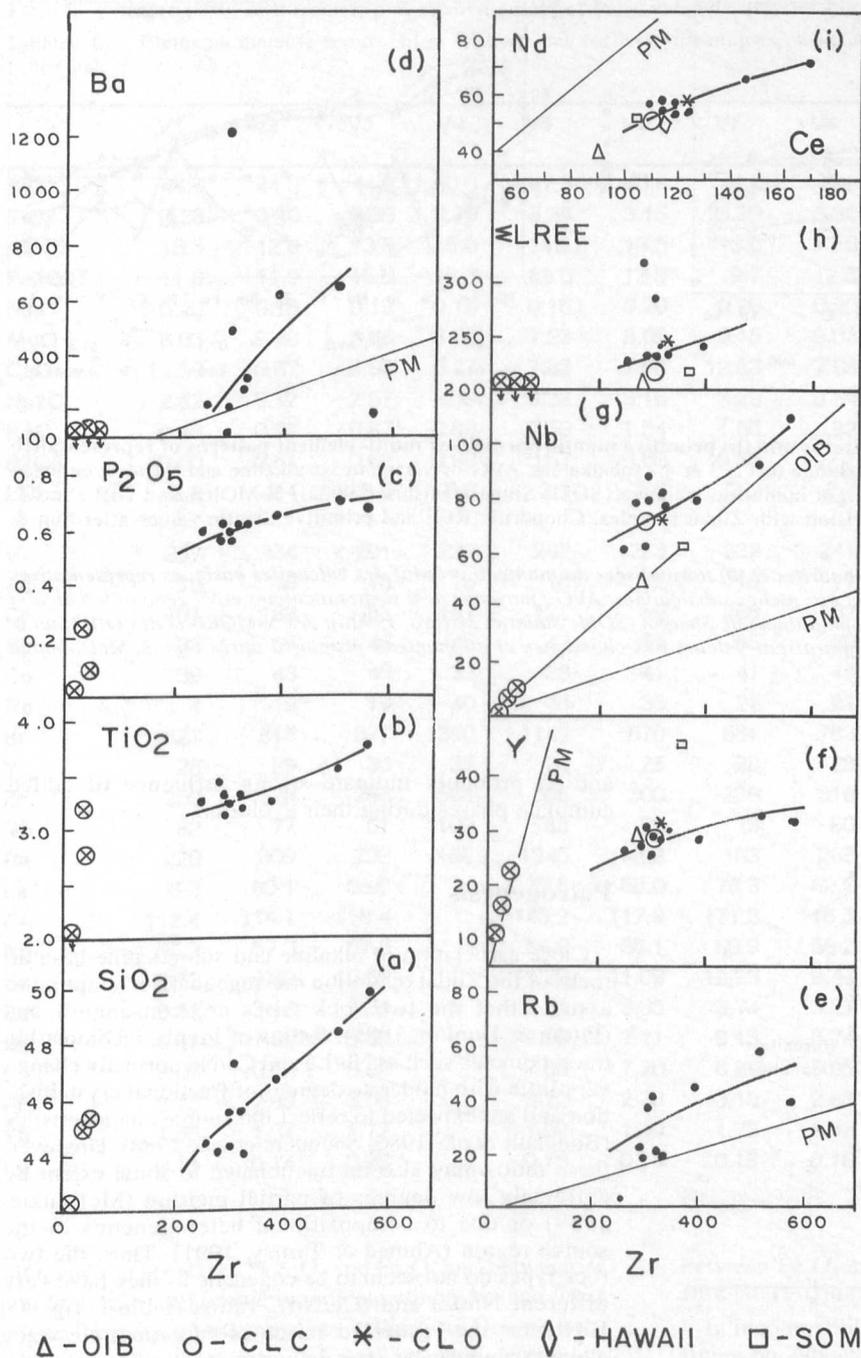


Fig. 3. - Binary plots of  $\text{SiO}_2$ , minor and trace elements plotted against Zr. Plots show magmatic trends with enriched incompatible trace elements characteristics for the alkaline rocks relative to primitive mantle (PM: Sun & McDonough, 1989). Symbols as in figure 2. Averages of oceanic island basalt (OIB-open triangle: Sun & McDonough, 1989), alkaline Cameroon line continental and oceanic (CLC-open circle and CLO- asterisk respectively: Fitton & Dunlop, 1985), alkaline Hawaii (open diamond: McKenzie & O'Nions, 1991) and Shergol ophiolitic mélange (SOM-open square: Sinha & Mishra, 1992a) are plotted for comparison with Zildat samples.

Fig. 3. - Diagrammes binaires de  $\text{SiO}_2$ , des éléments mineurs et en trace en fonction de Zr. Ces reports montrent les suites magmatiques enrichies en éléments en trace, caractéristiques des roches alcalines (PM: manteau primitif, Sun & McDonough, 1989). Mêmes symboles qu'en figure 2. Les moyennes de basaltes océaniques insulaires (OIB = triangles vides, Sun & McDonough, 1989), de la lignée continentale (CLC = rond vides) et océaniques (CLO = astérisques) du Cameroun (Fitton & Dunlop, 1985), des basaltes alcalins d'Hawaï (losanges, McKenzie & O'Nions, 1991) et du mélange ophiolitique de Shergol (SOM: carrés, Sinha & Mishra, 1992a) sont reportées pour comparaison.

show somewhat lower abundances for highly incompatible elements (Nb, La, and Ce). This may indicate that the Zildat alkaline samples are either derived from relatively lower degrees of partial melting or from more enriched mantle sources compared to those for average OIB and Shergol ophiolitic mélange.

Incompatible trace element ratios range between 2.0 and 3.13 for Nb/Y, between 650 and 749 for Ti/Y,

between 10.21 and 17.63 for Zr/Y and between 69 and 99 for Ti/V in the alkaline samples of Zildat which are similar to those of OIB with Nb/Y of 1.66, Ti/Y of 593, Zr/Y of 9.66 (Sun & McDonough, 1989). REE patterns for the sub-alkaline samples of Zildat resemble those of N-MORB (Sun & McDonough, 1989) but with considerably lower REE abundances. The highly irregular multi-element patterns with positive anomalies for Nb, Sr, P

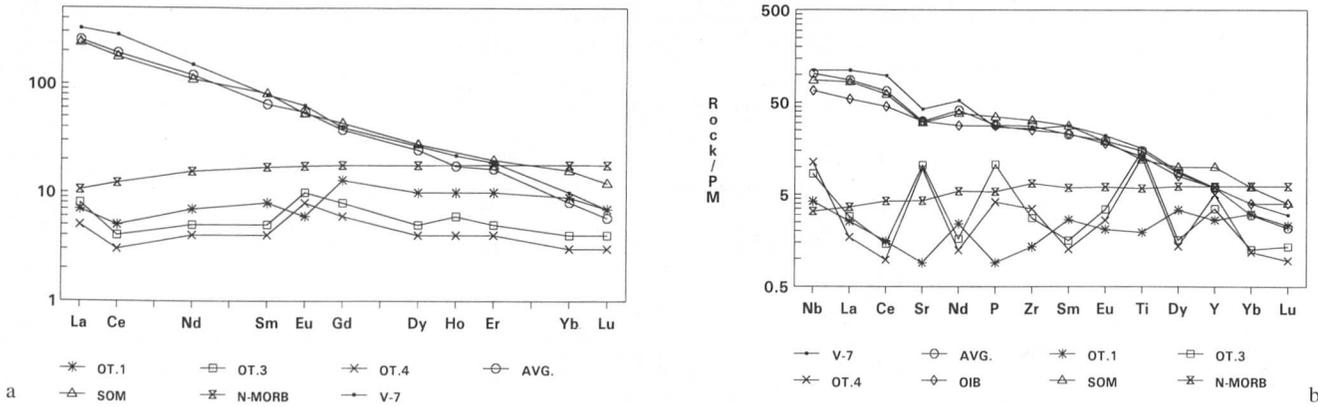


Fig. 4. – (a) Chondrite-normalised REE patterns and (b) primitive mantle normalised multi-element patterns of representative basic volcanic units of Zildat ophiolitic mélange (OT1, 3 & 4 - subalkaline; AVG - Average of six alkaline and V7 most enriched alkaline sample). Average patterns of Shergol ophiolitic mélange (SOM: Sinha & Mishra, 1992a), N-MORB and OIB (Sun & McDonough, 1989) are shown for comparison with Zildat samples. Chondritic REE and primitive mantle values after Sun & McDonough (1989).

Fig. 4. – (a) Terres rares normalisées aux chondrites et (b) normalisées au manteau primitif des volcanites basiques représentatives du mélange ophiolitique de Zildat (OT1, 3 et 4 = roches subalkalines; AVG : moyenne de 6 roches alcalines et V7 échantillon alcalin le plus enrichi). Les moyennes du mélange ophiolitique de Shergol (SOM; Sinha & Mishra, 1992a), des N-MORB et des OIB (Sun & McDonough, 1989) sont données pour comparaison. Valeurs des chondrites et du manteau primitif d'après Sun & McDonough (1989).

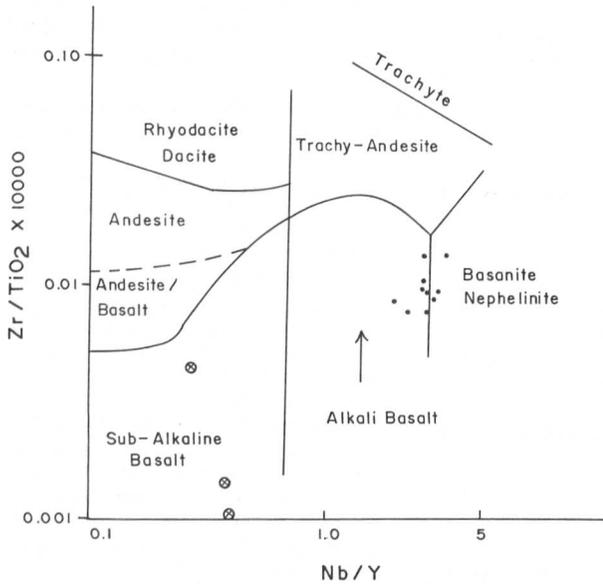


Fig. 5. – Plots of Nb/Y vs Zr/TiO<sub>2</sub>\*10000 (Winchester & Floyd, 1977) for the basic volcanic units of Zildat ophiolitic mélange. Note the predominantly alkaline nature of the enriched and sub-alkaline nature for the depleted samples. Symbols as in figure 2.

Fig. 5. – Rapports Nb/Y sur Zr/TiO<sub>2</sub>\*10000 (Winchester & Floyd), 1977) des volcanites basiques du mélange ophiolitique de Zildat. Noter la nature essentiellement alcaline des basaltes enrichis, et la nature sub-alkaline des échantillons dépliés. Mêmes symboles qu'en figure 2.

and Ti probably indicate strong influence of added cumulate phases during their evolution.

### Petrogenesis

Close association of alkaline and sub-alkaline basaltic rocks of the Zildat ophiolitic mélange make it tempting to assume that the two rock types are consanguineous (Fitton & Dunlop, 1985). Ratios of highly incompatible trace elements such as Nb/La and Ce/Nd normally change very little with moderate degrees of fractional crystallisation and are expected to reflect the source characteristics (Bougault *et al.*, 1980; Saunders *et al.*, 1988). However, these ratios may also be fractionated to some extent by extremely low degrees of partial melting (McKenzie, 1989) or due to compositional heterogeneities in the source region (Ahmad & Tarney, 1991). Thus, the two rock types do not seem to be cogenetic as they have very different Nb/La and (Ce/Nd)<sub>N</sub> ratios (table-I, fig. 4). However, the restricted range of incompatible trace element abundances (fig. 4a and b) and rock types indicate that the studied samples within individual groups are derived from same or similar sources and had common petrogenetic histories.

Since the data on the sub-alkaline rocks are limited, it is not possible to evaluate their genesis in detail. We will restrict our petrogenetic discussion to the alkaline rocks. The negative relationship between SiO<sub>2</sub> and MgO (fig. 2b), Zr and Ni and the positive relationship between MgO and Ni (not shown here) probably indicate olivine (ol) fractional crystallization. Negative relationship between

Table I. — Major (w%) and trace (ppm) elements data of basic volcanic units of Zildat ophiolitic melange, eastern Ladakh.

Tableau I. — Eléments majeurs (poids %) et en trace des rochers volcaniques basiques du mélange ophiolitique de Zildat Ladakh oriental.

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	OT1	OT3	OT4
SiO <sub>2</sub>	44.4	44.0	44.2	50.0	47.3	45.6	44.2	45.6	46.8	48.4	42.5	45.1	45.4
TiO <sub>2</sub>	3.28	3.20	3.35	3.79	3.28	3.15	3.39	3.30	3.28	3.60	0.42	3.24	2.78
Al <sub>2</sub> O <sub>3</sub>	13.3	12.8	13.5	15.0	14.8	13.5	13.0	13.6	14.7	15.0	7.3	12.4	12.2
Fe <sub>2</sub> O <sub>3</sub> T	11.8	11.9	15.0	10.3	11.0	13.3	9.7	12.5	11.8	12.4	9.7	15.3	16.9
MnO	0.20	0.18	0.19	0.18	0.15	0.20	0.20	0.20	0.21	0.17	0.17	0.24	0.18
MgO	8.03	9.40	8.66	6.66	7.23	8.65	9.15	9.03	8.54	7.73	15.66	5.97	6.91
CaO	12.69	10.57	8.96	5.27	7.63	7.58	12.83	7.66	5.68	4.03	16.07	14.09	12.47
Na <sub>2</sub> O	2.82	3.12	2.57	2.39	3.23	3.16	3.29	3.64	3.88	3.78	2.44	1.92	1.62
K <sub>2</sub> O	0.48	0.97	0.87	0.89	2.59	1.54	1.65	0.82	3.11	3.16	0.23	0.04	0.05
P <sub>2</sub> O <sub>5</sub>	0.60	0.61	0.62	0.69	0.57	0.60	0.58	0.61	0.66	0.71	0.02	0.23	0.09
LOI	2.8	2.4	3.9	2.9	2.1	2.6	3.3	2.7	2.9	2.3	5.2	3.8	3.2
V	257	234	291	229	247	253	232	241	234	277	280	584	624
Sc	19	19	18	15	18	19	18	17	18	15	97	53	55
Cr	101	183	85	121	121	89	258	132	129	166	951	166	179
Ni	33	65	43	45	42	54	85	69	38	36	121	39	41
Co	39	43	45	32	38	41	41	44	37	46	33	50	46
Rb	4	19	19	40	48	38	21	21	46	58			
Sr	627	815	677	1390	1149	570	881	783	435	495	19	218	199
Y	26	29	30	32	29	25	28	29	29	33	12	16	23
Zr	250	328	296	564	306	300	286	318	391	508	15	31	39
Nb	62	77	61	109	88	79	79	80	79	91	3	6	8
Ba	220	309	209	188	1345	492	103	263	633	668	13	31	6
La	58.3	60.1	58.0		75.8	58.0	76.3	62.6	61.8		1.75	1.98	1.17
Ce	112.4	114.1	116.4		145.2	117.9	171.3	118.3	124.3		2.73	2.58	1.73
Nd	55.7	57.0	57.8		64.9	58.1	69.9	56.2	51.6		3.24	2.22	1.67
Sm	9.72	9.89	10.59		11.29	11.09	12.23	9.44	9.31		1.18	0.70	0.56
Eu	3.31	3.18	3.34		3.61	3.38	3.74	3.27	2.91		0.35	0.58	0.44
Gd	8.41	7.59	8.80		7.99	7.11	8.13	8.74	6.44		2.71	1.70	1.23
Dy	6.07	6.58	6.69		7.00	7.20	6.81	5.85	5.66		2.52	1.18	1.01
Er	2.75	2.89	3.06		3.10	2.73	3.15	2.88	1.91		1.63	0.84	0.73
Yb	1.55	1.34	1.77		1.59	1.40	1.78	1.42	1.04		1.52	0.62	0.58
Lu	0.15	0.14	0.20		0.15	0.13	0.18	0.16	0.11		0.17	0.10	0.07

SiO<sub>2</sub> and CaO ( $r = -0.85$ ), SiO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub> and between Zr and Sc ( $r = -0.89$ ) probably indicate clinopyroxene (cpx: augite-ferroaugite) fractional crystallisation. Ol+cpx fractional crystallisation is also indicated by positive relationships between MgO, CaO and Fe<sub>2</sub>O<sub>3</sub> (fig. 2). Positive relationships between SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> (fig. 2a), absence of any negative Eu anomaly in the REE patterns of alkali basalt, negative relationships between MgO and Al<sub>2</sub>O<sub>3</sub> ( $r = -0.81$ ) and between CaO and Al<sub>2</sub>O<sub>3</sub> (fig. 2f) collectively indicate that plagioclase was not a major fractionating phase. High abundances of TiO<sub>2</sub> (3.2 to 3.79 wt%), positive relationships between Zr and TiO<sub>2</sub> (fig. 3b) and SiO<sub>2</sub> and TiO<sub>2</sub> ( $r = 0.74$ ) and a negative relationship

between Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> probably indicate that low pressure Fe-Ti oxide was also not a fractionating phase.

In incompatible element ratio / ratio plots presented in figure 6a, Nb and Ce are more incompatible than Zr and Y. Thus the rock representing the smallest degrees of partial melting or derived from more enriched sources will have the lowest Zr/Nb and highest Ce/Y. However, with increasing degrees of partial melting Zr/Nb will increase and Ce/Y will decrease. The Zildat alkaline samples plot along a curved trend with low Zr/Nb and high Ce/Y compared to alkali basalt averages of Cameroon line from continental sector (CLC), oceanic sector (CLO), Shergol ophiolitic mélange (SOM) and average OIB. Zildat alkaline samples thus appear to

Table II. – **Accuracy and Precision Test.** Concentration (ppm) of trace and rare earth elements as determined in 5 rock standards by ICP-AES and their mean % deviation. Values in paranthesis are concensus values from Govindaraju (1994).

Tableau II. – Test de précision : concentration (en ppm) des éléments en traces et des Terns Raves des 5 roches standards par ICP-AES et leur déviation moyenne en %. Les valeurs entre parenthèses sont des valeurs consensuelles de Govindaraju (1994).

	Andesite USGS:AGV-1 (1)	Basalt USGS:BHVO-1 (1)	Basalt CRPG:BR (1)	Metabasic WIHG:MB-H (2)	Granite USGS:G-2 (1)	Mean % Dev.	RSD (A)	(%) (B)
Ba	1175 (1226)	129 (1369)	1163 (1050)	490 (482)	1960 (1882)	5.6	5.6	3.7
Co	17 (15.3)	51 (45)	53 (52)	42 (37)	5 (4.6)	7.9	8.1	4.9
Cr	8 (10.1)	244 (289)	336 (380)	72 (65)	10 (8.7)	13.0	0.84	11.4
Nb	13 (15)	18 (19)	92 (98)	19 (17.9)	11.5 (12)	7.8	2.7	9.4
Ni	14 (16)	113 (121)	274 (260)	19 (17.9)	ND (5)	8.1	1.1	9.5
Sc	14 (12.2)	30 (31.8)	22 (25)	43 (45.9)	4 (3.5)	10.7	1.6	7.8
Sr	678 (662)	387 (403)	1484 (1320)	142 (147)	489 (478)	4.9	0.8	5.6
V	144 (121)	284 (317)	245 (235)	313 (300)	38 (36)	8.7	1.0	7.2
Y	19 (20)	29 (27.6)	29 (30)	55 (52.5)	12 (11)	4.4	1.6	8.5
Zr	209 (227)	168 (179)	249 (260)	223 (233)	ND (309)	5.7	3.2	9.4
La	45 (38)	17 (15.8)	99 (82)	40 (36)	95 (89)	10.5	4.8	6.4
Ce	65.5 (67)	42 (39)	160 (151)	73 (73.6)	166 (160)	4.1	5.1	7.2
Nd	31 (33)	29 (25.2)	73 (65)	41.5 (39.4)	54 (55)	8.0	7.4	7.7
Sm	6.8 (5.9)	6.2 (6.2)	13 (12)	9.8 (9.69)	7.6 (7.2)	5.7	2.6	7.7
Eu	1.64 (1.64)	2.29 (2.06)	3.8 (3.7)	2.74 (2.77)	1.4 (1.4)	3.4	4.8	6.7
Gd	4.8 (5)	6.9 (6.4)	10.3 (9.5)	9.6 (9.28)	4.2 (4.3)	4.8	2.4	8.5
Dy	3.3 (3.6)	5.5 (5.2)	7.2 (6.2)	9.1 (9.35)	2.3 (2.4)	7.7	3.9	6.7
Er	1.8 (1.7)	3.1 (2.4)	2.35 (2.4)	5.2 (5.23)	0.95 (0.92)	8.6	9.5	7.4
Yb	1.69 (1.72)	2.1 (2.02)	1.85 (1.9)	5 (5.02)	0.76 (0.8)	2.7	3.9	6.6
Lu	0.23 (0.24)	0.26 (0.29)	0.28 (0.25)	0.67 (0.67)	0.08 (0.11)	13.4	12.6	5.4

(1) Average of 3-4 analyses carried over a short period of time.

(2) Average of 11-16 analyses carried over a period of &gt;2 years.

RSD = Relative standard deviation (standard deviation/mean analysis) × 10.

(A) : Short term precision calculated for BHVO-1.

(B) : Long term precision calculated for MB-H.

represent varying but lower degrees of partial melting (Smedley 1988) or derived from more enriched sources compared to those for rocks from the other areas shown in fig. 6a. In figure 6b, Zr and La are much more incompatible with respect to Y and Yb. Thus, following the same logic as in figure 6a, the expected positive trend is observed, confirming the above inferences. Since Zildat rocks tend towards basanitic-nephelinitic compositions

(fig. 5), their overall enrichment in highly incompatible trace elements abundances and higher ratios of e.g. Nb/Zr, La/Yb (fig. 6) compared to average OIB is not surprising.

In summary, major and trace elements (including both compatible and incompatible) data indicate that the alkaline rocks of Zildat have been generated either by varying but lower degrees of partial melting or from

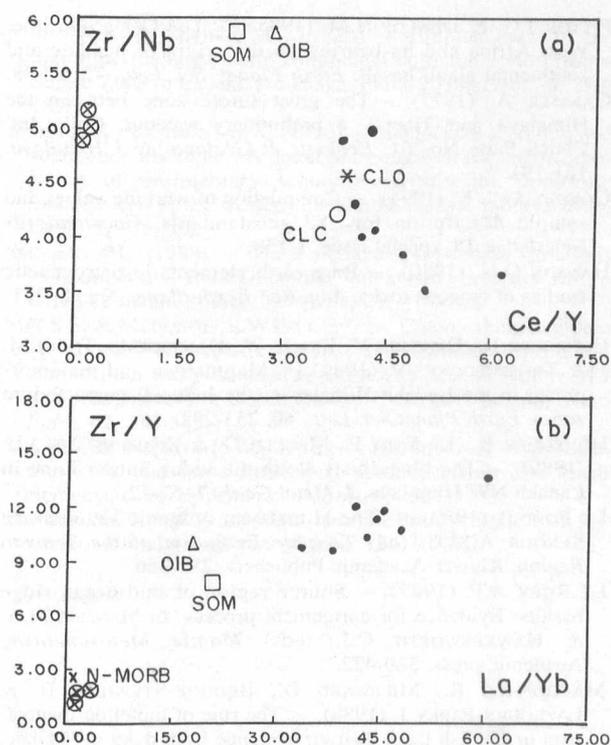


Fig. 6. — Plots of Ce/Y vs Zr/Nb (a) and La/Yb vs Zr/Y (b) for the basic volcanic units of Zildat ophiolitic mélangé. Symbols as in figures 2 and 3.

Fig. 6. — *Rapports (a) Ce/Y versus Zr/Nb et (b) La/Yb versus Zr/Y des volcanites basiques du mélangé ophiolitique de Zildat. Mêmes symboles que pour les figures 2 et 3.*

more enriched mantle sources compared to those for the rocks of Shergol ophiolitic mélangé, Cameroon line and average OIB. The melts appear to have evolved through high pressure ol+cpx fractional crystallisation. Low pressure plagioclase and Fe-Ti oxide do not appear to have been major fractionating phases. Limited data on the sub-alkaline rocks indicate that their parental melts generated from nearly flat to depleted mantle sources somewhat similar to those of typical N-MORB (Le Roex, 1987).

## TECTONIC IMPLICATIONS

Analytical data on the basic volcanic rocks of the Zildat ophiolitic mélangé indicate the presence of basaltic rocks similar to both N-MORB and OIB. Honegger *et al.* (1982) studied the volcanic rocks of ophiolitic mélanges occurring south of Dras, north of Sankoo in Suru valley, south of Pashkyum and from the Spongant klippe in western Ladakh. Interestingly, the four samples selected by them for analysis have N-MORB chemistry. However, in a subsequent study of blueschist from the Shergol- Baltikar section of western

Ladakh, Honegger *et al.* (1989) reported primary alkaline nature of the metabasalt, suggesting OIB or a transitional MORB type primary geotectonic setting. Rai (1987) has reported presence of both N-MORB and OIB type volcanic rocks from the Khangral-Chiktan section of western Ladakh. Recently, Sinha and Mishra (1992a) have also reported the presence of OIB volcanic rocks within the Shergol ophiolitic mélangé, western Ladakh.

Presence of N-MORB in ophiolitic mélanges of Ladakh may imply that the Neo-Tethys was a fully developed ocean with eruption of N-MORB probably derived from nearly flat to depleted mantle sources. The ocean floor appears to have also received OIB type magma from enriched sources. Transitional MORB reported by Honegger *et al.* (1989) probably generated through mixing of depleted and enriched sources and / or melts (Zindler & Hart, 1986). Studies of basaltic rocks by Honegger *et al.* (1982) and Rai (1987) have suggested that N-MORB and OIB type basalt in the ophiolitic mélanges of western Ladakh erupted during opening of the Neo-Tethyan ocean rather than during its subduction in an island arc environment. Intercalation of bedded chert with alkaline basalts probably also indicate that the latter erupted on deep ocean floor.

In addition to the presence of mafic-ultramafic rocks, the ophiolitic mélanges of the Indus suture zone includes disrupted deep ocean sediments such as terrigenous turbidites, bedded chert and radiolarites. Blocks of shallow water limestone and metamorphic rocks such as slate, glaucophane schist and amphibolites are also commonly observed in these mélanges. These rocks of diverse origins are intimately intermingled in a turbiditic (trench fill) matrix, giving rise to block-in matrix fabric (Sinha & Mishra 1992b). Above observations indicate that ophiolitic mélanges in the Indus suture zone probably originated due to the subduction of the Tethyan ocean floor, its sedimentary cover (from shallow marine to deeper pelagic sediments) and metamorphic rocks, under the Eurasian plate. Tectonic skimming and partial offscraping of these material and their accumulation probably in the upper part of the subduction zone (Beukel & Wortel, 1992) within the trench as indicated by the turbiditic matrix (Scholl *et al.*, 1980; Sinha & Upadhyay, 1990) produced the observed large scale structural mixing and deformation of rocks from diverse origins.

Honegger *et al.* (1989) have estimated a temperature and pressure ranges of 350-420 °C and 9-11 kb for the blueschist rocks of the Shergol ophiolitic mélangé. K-Ar age of around 100 Ma have been estimated for the crystallization of blue amphiboles during the blueschist metamorphism by these authors. This would imply that the mélangé zone material were subducted and lay at depths in the pressure range of 9-11 kb about 100 Ma earlier. When these materials were obducted and brought to their present positions is controversial. While Brookfield and Reynolds (1981), Searle (1983) and Searle *et al.* (1988) have demonstrated that the ophiolitic mélanges were thrust on the late Cretaceous shelf sediments and opine that the obduction was completed by Maestrichtian. Baud *et al.* (1984) and Thakur (1987)

have shown that Spongtag ophiolite in western Ladakh rests on the fossiliferous Early Eocene sediments and therefore, the obduction must have been at least post Early Eocene. Le Fort (1989) has further constrained the timings of obduction between Eocene and Oligocene. The restricted time span suggested for the obduction of ophiolitic mélanges in Ladakh indicate that it was probably not a continuous process. It is suggested that ophiolitic material subducted earlier were abruptly incorporated and brought to its present position through Himalayan orogenic processes (Beukel & Wortel, 1992) due to collision of Indian and Eurasian plates (Searle *et al.*, 1988).

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