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# GEOCHEMISTRY AND TECTONIC ENVIRONMENTS OF BABUSAR AMPHIBOLITES IN SOUTHEAST KOHISTAN, PAKISTAN.

BY

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**Abstract:-** *The Kohistan terrane is a good example of young arc crust, sandwiched between the Indian and Karakoram plates. The base is occupied by a major stratiform Sapat ultramafic-gabbroic complex which overrides the crust of the Indian plate along the Indus suture (i.e., the Main Mantle Thrust; MMT). It was intruded into the base of a thick pile of metavolcanics of the Kamila belt, which comprise MORB-type tholeiitic basalts, island-arc tholeiites and calc-alkaline. The Chilas complex comprising ultramafic and gabbronorite rocks, is also intrusive into the Kamila belt, it is emplaced onto the top of the Kamila belt. The Kamila Amphibolite rocks are intruded by granitoids of different composition. The Kamila belt is a composite mass dominated by amphibolite facies. KAU does not occur as a single, extensive body, field relation show that it is divisible into three linear belts in addition to small patches and screenswithin or between plutons. These belts are named from south to north as Babusar, Niat and Jal and within the Niat belt, a thin slice named Sumal amphibolites. units. Present article deals with the brief study of Babusar amphibolites. Babusar amphibolites are generally medium grained, and hypidioblastic to xenoblastic with hornblendic composition ranging from 20 to 70%. Eight samples were selected for geochemical studies. All the samples show low TiO2 (mean 0.8 wt%) and MgO (Mean 5.6 wt%).All the trace elements are also depleted as Nb (0.8 ppm), Y (15.3 ppm), Zr (8.6 ppm) and Ni (18.7 ppm). Babusar amphibolites are tholeiitic and depleted in LIL elements which show normalized trace element patterns consistent with the subduction related component.*

## INTRODUCTION

Amphibolites are widespread in the Kohistan sequence and form a prominent belt that extends from Afghanistan in the west, through Bajaur, Dir, Swat, and Indus valley, up to Nanga Parbat in the east. The belt has a maximum width of about 50 km and a length of 300 km. Preliminary studies were performed by Martin et al. (1962) and Davies (1965) in the Swat area and they included the Kohistan amphibolites in their “Upper Swat Hornblendic Group” and interpreted them to be a product of metamorphism rather than igneous processes. In contrast, part of the amphibolite belt exposed in the Thak valley was assigned an igneous parentage by Shams (1975), who called them “veined metadiorites”. Jan and Kempe (1974) introduced the name "the Kohistan Basic Complex" for the basic rocks of southern Kohistan and recognized the presence of an extensive suite of amphibolites. Jan (1979) classified the amphibolites into two varieties: (a) massive and homogeneous, and (b) banded and sheared. Tahirkheli and Jan, 1979; Coward et al., 1986 referred these amphibolites as the Kamila amphibolite belt and Jan, 1979, 1988; Bard et al., 1980; Bard, 1983 a, b as the southern amphibolites.

The true thickness of the Kamila amphibolites is still uncertain due to an abundance of intrusive plutonic bodies and intense ductile-brittle shearing. However, the stratigraphic position of the Kamila amphibolites in the Kohistan sequence has become clearer with the delineation of its lower stratigraphic contact in the presently studied area and the upper contact in the Dir-Swat area (Sullivan et al., 1993). Therefore the name “Kamila Amphibolite Unit (KAU)” is used in this paper, which carries a stratigraphic connotation. KAU has a vast distribution in southern Kohistan (Fig.1). It was considered that the unit occupies

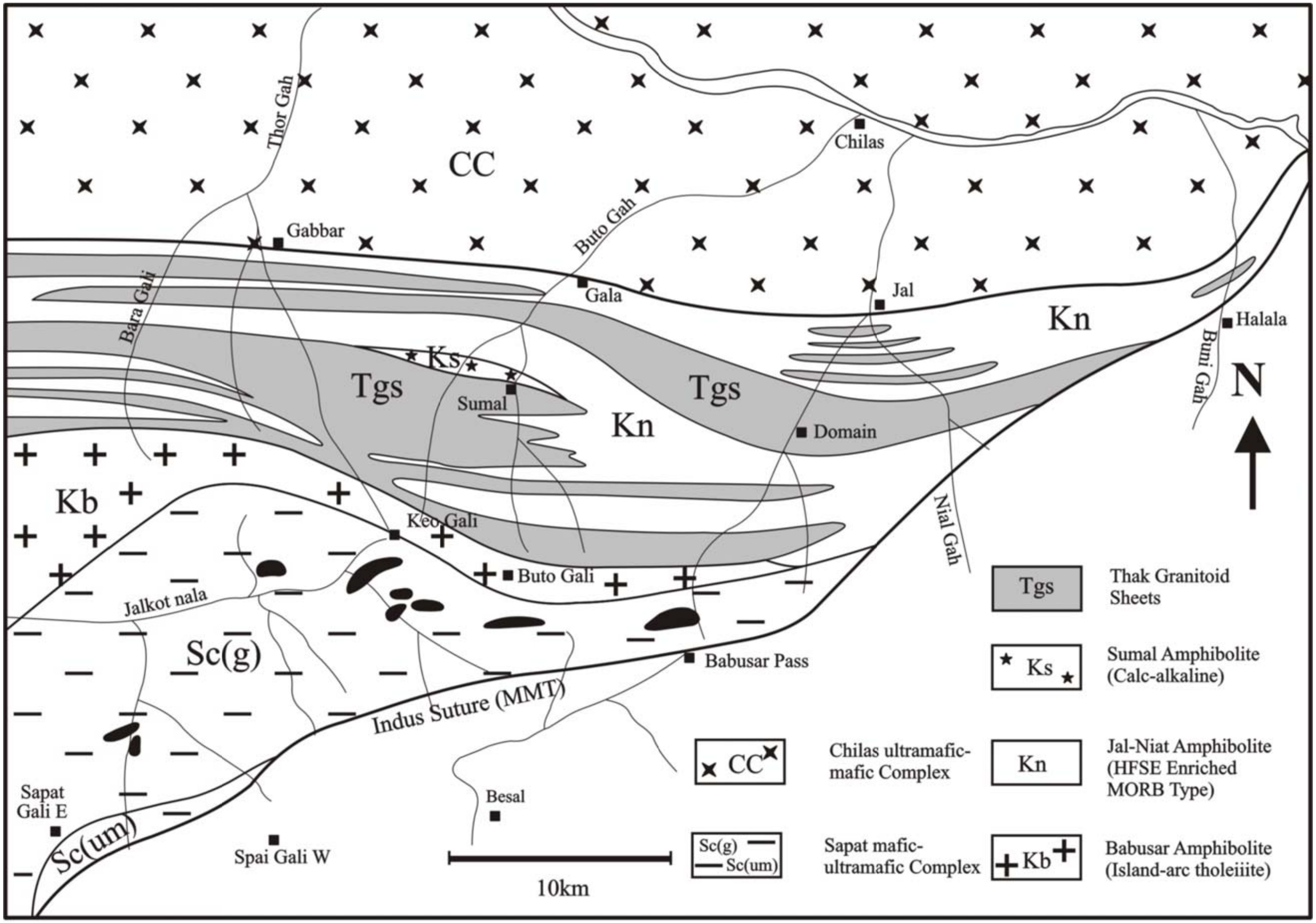


**Fig.1.** Geological map of SE Kohistan showing detailed lithological subdivisions, the Sapat complex, the Kamila amphibolite belt and the Thak granitoid sheets (Khan, 1997)

the entire southern part of the Kohistan terrane between the Main Mantle Thrust (MMT) in the south and the Chilas Complex in the north (Tahirkheli and Jan, 1979; Bard et al., 1980). In the Indus valley, the unit is overlying the Jijal Complex which occupies the hanging wall of the MMT. This study has revealed that it is in direct contact with the MMT only in the extreme eastern (i.e., Bunar valley) and western parts of the Kohistan terrane. In the area between the Babusar Pass in the east and the Indus Valley in the west, the unit is separated from the MMT by a basal mafic-ultramafic layered complex in the hanging wall of the MMT, termed the Sapat Complex (Jan et al., 1993). To the north, the unit is bounded by the Chilas Complex, which occupies an axial position in the Kohistan terrane. KAU does not occur as a single, extensive body, field relations show that it is in three main linear belts, in addition to small patches and screens within or between plutons. These belts are named from south to north as Babusar, Niat, and Jal. Within the Niat belt, a thin slice of amphibolites with distinctly different characteristics is named as Sumal amphibolites. Diorites, granodiorites, trondhjemites and granites intrude all these amphibolites.

## LITHOLOGY AND PETROGRAPHY OF BABUSAR AMPHIBOLITES

The amphibolites are best exposed in the southern part of the study area as east-west belt stretching between the drainage divide of Jalkot Nala and the tributaries of the Indus River at high reaches of Katai gali, Butogah gali, Keo gali, Makheli gali, Shikaro gali and Sherman gali. The width of the belt in the eastern part of the area in the Thak valley is 1.5 km while in the western part near Sherman Gali it is 5 km. The belt has a gradational contact with the basal ultrmafic-mafic rocks of Sapat-Babusar Complex to the south. To the north the contact is sharp with intrusive diorites. To the east of Babusar Pass in the Charal gah the belt occurs directly in the hanging wall of the Indus suture. On the fresh surface the rocks are dark grey to dark greenish grey. On weathered surface, they look dark greenish brown. The rocks are strongly foliated, sheared and commonly banded. Foliation is mostly parallel to the banding. The banded aspect of these rocks is due to variations in the proportions of amphibole, epidote and plagioclase ±quartz in alternate layers. The bands range from centimeter to over half a meter in thickness. Most of them are less than two centimeters thick and usually have sharp contacts.

The amphibolites are generally medium-grained, and hypidioblastic to xenoblastic. Locally they contain poikiloblasts and porphyroblasts with minor inclusions. Foliation and gneissose banding are common; in some rocks alternating bands of quartz and plagioclase with fine-grained aggregates of amphibole and epidote are present. In foliated varieties flaky minerals are oriented in one direction; elongation is also seen in quartz and epidote crystals. The banded varieties are mostly finer grained than the homogeneous types some of which are coarse-grained. Variations in texture and mineral proportion are common in both the varieties. They contain hornblende, epidote and plagioclase as the dominant constituents. Chlorite, quartz, sphene, rutile and opaque minerals occur as accessories, while some samples contain biotite, white mica and garnet and a few have clinopyroxene.

The amphibole is mostly hornblendic in composition and shows a wide range from 20% to 70% (Table-1), subhedral to anhedral, fresh but some of the large are uralitized at boundaries. Inclusions of quartz and opaque minerals, suggesting post magmatic growth but in some cases these minerals occur only in the central parts. Small inclusions of hornblende within large hornblende crystals are also observed. Hornblende encloses or is enclosed by epidote and it is partly replaced by chlorite, less commonly by epidote, sphene and minor chlorite. It is light green to brownish green and bluish green and displays zoning with bluish green cores and greenish blue margins. Actinolite occurs as long prismatic crystals and in columnar to fibrous aggregates. It is colourless to light green.

The plagioclase ranges from 4% to 23% and is cloudy. It is in the range of andesine ($An_{40-46}$) but in rare cases it is sodic labradorite. Untwinned and anhedral plagioclase are enclosed by quartz and show myrmakitic intergrowth. Inclusions of sericite are common with some apatite; it is replaced by epidote and albite. Epidote is from 8% to 40%, elongated, subhedral as well as anhedral, and has likely formed subsequent to the growth of amphibole. Inclusions of epidote are present in hornblende. It is zoned and displays anomalous blue colour in cores and greenish or brownish in margins. Quartz from 3% to 20%, anhedral and shows strong strain effects. It is in the form of aggregates elongated parallel to the well-developed schistosity of the rocks. Its segregation and straining boundaries suggest that the recrystallization occurred during metamorphism. Sphene, biotite, magnetite or ilmenite are common accessories. Sphene is developed along the fractures, cleavages and along grain boundaries of hornblende. Calcite occurs is minor with a good zoning, bluish green to light green flakes along the margins and within fractures of the hornblende. Opaque minerals occur in the cores and along boundaries of hornblende. Rutile is associated with magnetite, and both may be derived from ilmenite.

## GEOCHEMISTRY

Eight selected samples from the Babusar amphibolites are used for the evaluation of the geochemical characteristics of these rocks (Table-2). All the samples

**Table.1**
Modal composition of Babusar Amphibolite

| **Sample No** | **A-243** | **A-241** | **BS-10** | **A-31** | **BS-18** | **A-56** | **A-58** | **A-59** |
|---|---|---|---|---|---|---|---|---|
| Amphibole (%) | 30.0 | 40.0 | 55.0 | 39.0 | 7.0 | 55.0 | 58.0 | 70.0 |
| Plagioclase (%) | 4.0 | 23.0 | 0.0 | 22.0 | 4.0 | 20.0 | 14.0 | 6.0 |
| Epidot (%) | 8.0 | 22.0 | 24.0 | 24.0 | 40.0 | 8.0 | 11.0 | 9.0 |
| Quartz (%) | 20.0 | 6.0 | 10.0 | 5.0 | 3.0 | 7.0 | 9.0 | 6.0 |
| Chorite (%) | 4.0 | 9.0 | 8.0 | 6.0 | 43.0 | 2.0 | 3.0 | 0.0 |
| Magnetite (%) | 1.0 | 1.0 | 1.0 | 1.0 | 0.0 | 4.0 | 5.0 | 3.0 |
| Sphene (%) | 3.0 | 2.0 | 2.0 | 1.0 | 3.0 | 4.0 | 6.0 | 6.0 |
| Biotite (%) | 0.0 | 1.0 | 0.0 | tr | 0.0 | 0.0 | 0.0 | 0.0 |
| Calcite (%) | 30.0 | 0.0 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Mucovite (%) | tr | 2.0 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Apatite (%) | 0.0 | 0.0 | tr | 0.0 | tr | 0.0 | 0.0 | tr |

**Table.2**
Major and trace element composition of Babusar Amphibolites.

| **Sample No** | **BS-3** | **BS-7** | **BS-8** | **BS-9** | **BS-10** | **BS-11** | **BS-18** | **BS-19** |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 49.43 | 47.86 | 56.09 | 54.34 | 43.21 | 46.54 | 49.32 | 45.13 |
| $TiO_2$ | 1.25 | 0.86 | 0.85 | 0.63 | 0.72 | 1.00 | 0.79 | 0.68 |
| $Al_2O_3$ | 15.80 | 20.36 | 15.83 | 17.70 | 19.05 | 17.82 | 18.21 | 18.76 |
| $Fe_2O_3$ | 13.98 | 11.95 | 10.89 | 9.67 | 13.47 | 14.75 | 12.50 | 14.25 |
| MgO | 5.72 | 4.25 | 4.26 | 4.20 | 7.88 | 6.19 | 4.93 | 7.06 |
| CaO | 12.38 | 10.81 | 8.88 | 9.98 | 15.37 | 11.81 | 11.48 | 12.93 |
| $Na_2O$ | 0.87 | 3.28 | 2.76 | 3.00 | 0.04 | 1.50 | 2.45 | 0.95 |
| $K_2O$ | 0.21 | 0.12 | 0.15 | 0.18 | 0.02 | 0.04 | 0.04 | 0.01 |
| MnO | 0.24 | 0.26 | 0.19 | 0.19 | 0.23 | 0.28 | 0.21 | 0.22 |
| $P_2O_5$ | 0.11 | 0.24 | 0.10 | 0.10 | 0.02 | 0.06 | 0.07 | 0.01 |
| | | | | | | | | |
| Nb | 0.70 | 1.70 | 1.00 | 0.50 | 0.60 | 0.20 | 0.90 | 0.20 |
| Zr | 15.40 | 25.10 | 8.70 | 11.90 | 1.00 | 5.00 | 5.50 | 3.60 |
| Y | 23.10 | 28.90 | 16.80 | 17.30 | 6.30 | 12.50 | 14.80 | 10.80 |
| Sr | 252.00 | 296.50 | 154.70 | 167.40 | 148.60 | 167.40 | 200.30 | 141.60 |
| Rb | 1.20 | 0.50 | 1.10 | 1.50 | 1.50 | 1.00 | 0.90 | 0.40 |
| Th | 0.40 | 0.20 | -0.50 | 0.30 | -0.10 | 0.10 | -0.10 | -0.50 |
| Pb | 4.20 | 2.10 | 1.70 | 2.40 | 1.10 | 1.50 | 1.00 | 0.90 |
| Ga | 17.90 | 19.00 | 14.50 | 15.40 | 14.80 | 17.20 | 18.00 | 15.80 |
| Zn | 115.30 | 110.10 | 92.40 | 85.00 | 88.80 | 126.40 | 100.00 | 99.50 |
| Cu | 96.50 | 17.00 | 38.80 | 35.30 | 49.70 | 103.40 | 123.20 | 67.50 |
| Ni | 21.80 | 6.30 | 14.00 | 16.60 | 36.40 | 17.90 | 16.60 | 23.00 |
| Cr | 28.60 | 4.70 | 34.70 | 36.20 | 82.30 | 41.70 | 36.80 | 88.40 |
| V | 498.10 | 148.70 | 299.70 | 247.10 | 464.50 | 414.10 | 395.80 | 439.00 |
| Sc | 51.40 | 26.10 | 39.10 | 41.50 | 60.10 | 59.90 | 49.00 | 65.10 |
| Ba | 29.50 | 31.50 | 55.30 | 67.60 | 17.60 | 21.60 | 28.50 | 16.90 |
| La | 0.60 | 2.90 | 1.50 | 1.30 | -1.40 | 0.10 | -0.20 | -1.30 |
| Ce | 6.10 | 10.20 | 3.60 | 4.30 | 1.40 | 2.60 | 2.90 | 3.50 |
| Nd | 5.50 | 10.40 | 3.60 | 3.90 | 0.60 | 0.60 | 2.70 | 1.10 |

have low $TiO_2$ (mean 0.8 wt%) and MgO (mean 5.6 wt%). All the trace elements also are depleted in these rocks, but the elements like Nb (0.7ppm), Y (15.3ppm), Zr (8.6 ppm) and Ni (18.7ppm) are particularly depleted.

**Classification**

The amphibolites classify as basalts and basaltic andesites (BS-8 and BS-9) on the $SiO_2$–($Na_2O$+$K_2O$) plot of Le Maitre et al. (1989) and one sample (BS-10) plot in the field of picrobasalt (Fig.2). On the classification scheme of De La Roche et al. (1980) the analyses range from olivine basalt through tholeiite to andesite basalt. One sample (BS-8) plots in the field of andesite (Fig.3). The Jensen cation plot (Jensen, 1976) supports the above classification of the studied amphibolite rocks (Fig.4). Four samples BS7, 8, 9 and 18) plot in the field of andesite and the rest of the four samples show an affinity with high-Fe tholeiite basalt. On AFM diagram of Irvine and Barager (1971), the amphibolites classify as tholeiites but they display an alkali-enrichment trend (Fig.5). The $K_2O$ content in all the analyses is low (< 0.2 wt%) and the rocks classify on this basis as low-K tholeiites on K2O versus SiO2 diagram (Fig.8) after Le Maitre et al.,(1989).

**Fractionation Assemblage**

To evaluate the crystallization sequence of Babusar amphibolites, variation diagrams using $SiO_2$ as a fractionation index are plotted (Fig.5, Fig.6a & Fig.6b). Depletion of MgO and Ni with advancing fractionation in the studied rocks is indicative of early crystallization of olivine. The depletion of these two elements together with that of Cr, increasing degree of fractionation suggests the igneous parentage of these rocks. The low $TiO_2$ and low $Zr/TiO_2$ ratios also confirm the igneous past of these amphibolites. The depletion of iron and CaO increasing fractionation warrants the crystallization of an iron oxide and clinopyroxene. $Na_2O$ and Sr variation trend supports this sequence of fractionation. $Na_2O$, $K_2O$ and $P_2O_5$ show enrichment with increasing proportions of $SiO_2$. Depletion in $Al_2O_3$ suggests plagioclase crystallization started early in the sequence. Sr is highly compatible with plagioclase and shows enrichment in early fractionation and at ~ 50 wt%, Sr trend becomes negative. It is likely that the plagioclase crystallizing earlier was calcic to accomodate much Sr, but at ~50 wt% of $SiO_2$, it probably changed its composition. $TiO_2$ shows some enrichment in early fractionation and then, because of probable crystallization of ilmanite, shows a decline. On the basis of major and trace element variations it is considered that olivine, clinopyroxene and iron oxide were the earliest crystallizing minerals and joined subsequently by plagioclase. This sequence of crystallizing minerals is mainly responsible for the compositional diversity in the Babusar amphibolites. The crystallization of plagioclase after clinopyroxene in the crystallizing sequence is a characteristic of subduction-related settings than that of mid-ocean ridges (Perfit et al., 1980).

## TRACE-ELEMENT VARIATIONS

The Babusar amphibolites are generally depleted in large-ion lithophile elements like Rb, Pb, Th and K (Table-2). The contents of these elements show an increase with fractionation. Amongst the high-field strength elements (HFSE) Ti concentration is controlled by tholeiitic trend of the studied suite. The amounts of Zr and Y are about eight times higher than those in the chondrites. In some samples the Zr concentration is equal or less than chondrites.

**Ferromagnesian Elements**

Ni ranges from 6 ppm to 36 ppm and Cr from 5 ppm to 88 ppm in the studied rocks (Table-2). When plotted against $SiO_2$, the elements like Ni, V, Sc and Cr display decrease in concentration with increasing contents of $SiO_2$ (Fig.5). Decrease in Ni with increasing $SiO_2$ may be attributed to olivine fractionation and that in Cr to clinopyroxene and Cr-spinel seperation.

**Trace-element Patterns as Spidergrams**

The Babusar amphibolites have highly spiked trace element pattern characterized by positive peaks for Ba, K, Sr, Ti, and negative anomalies for Rb, Nb and Zr. The patterns have a peculiar shape which resembles the alphabet "W" (Fig.9). These patterns are different from that of the ocean-floor tholeiites and are matching with the island arc tholeiites (Fig.7). The peaks and troughs of arc tholeiites are, in general, corresponding with the amphibolites of this group.

**Tectonic Environment**

The Babusar amphibolites are tholeiitic and are depleted in large ion lithofile (LIL) elements, which is a characteristic feature of tholeiitic rocks from mid-ocean ridge and subduction-related environments (island arcs and Andean-type continental margins). Tholeiitic basalts can occur in all the major tectonic settings of magma generation. The depleted contents of LIL elements in the Babusar amphibolites clearly indicate their affinity with within-plate oceanic or continental settings, so the Babusar amphibolites are may be related to either oceanic– or island arc/continental margin environments. The tholeiite series is considered to be the earliest and in some cases dominating phase of magmatism in island arc /continental margin environments. The island arc basalts are characterized by selective enrichment of elements of low ionic potential (Sr, K, Rb, and Th) and low abundances of elements of high ionic potential (Nb, P, Zr, Ti, and Y) compared to N-type MORB (Fig.9). The enrichment in low ionic potential elements has been attributed to metasomatism of the mantle source of arc basalts by fluids released from the subducted

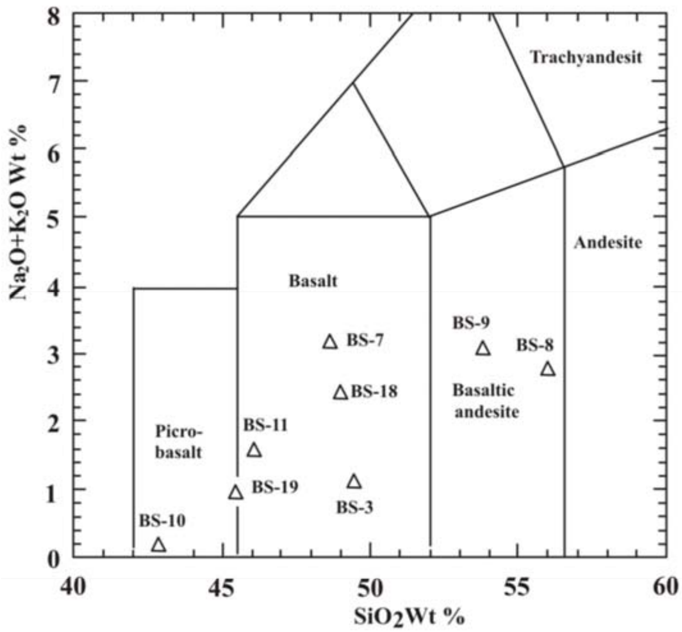


**Fig.2.** Chemical classification and nomenclature of Babusar amphibolites using total alkalies versus $SiO_2$ (TAS) plot after Le Maitre et al., (1989).

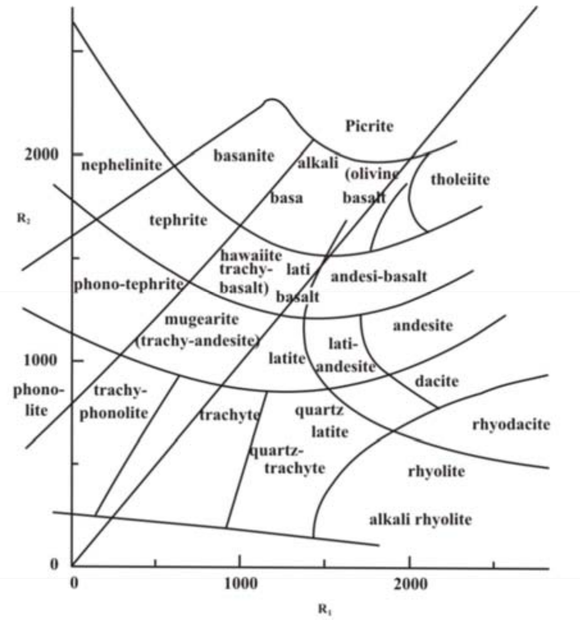


**Fig.3.** R1-R2 diagram of Babusar amphibolites after De La Roche et al., (1980).
R1 = 4Si - 11(Na + K) - 2(Fe + Ti),
R2 = 6Ca + 2Mg + Al.

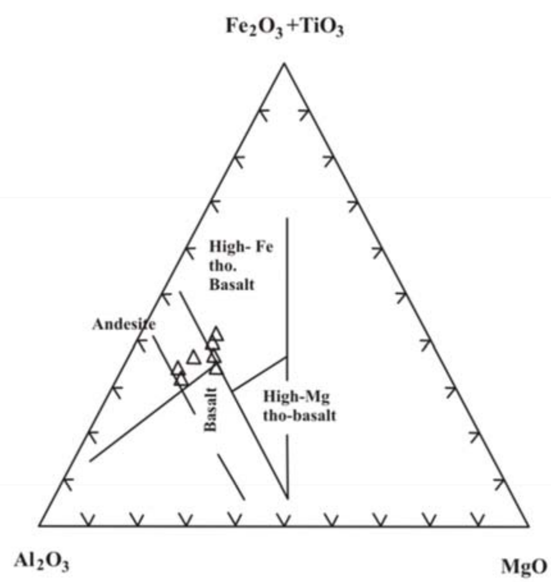


**Fig. 4.** Ternary plot of classification according to cation percentage of Al, (Fetotal +Ti) and Mg after Jensen, (1976).

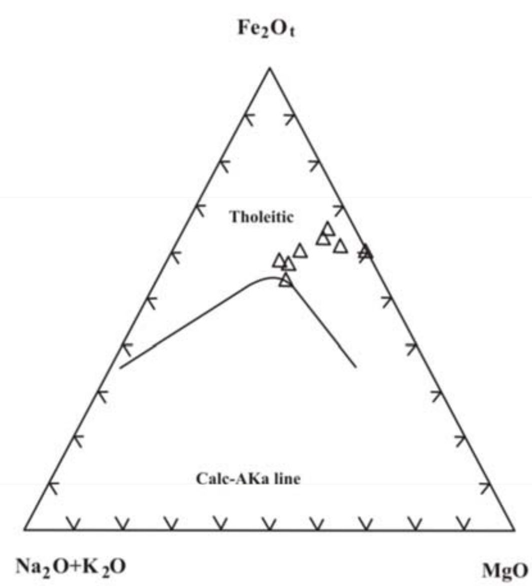


**Fig. 5.** AFM digram of studied rocks after Irvine and Barager, (1971)

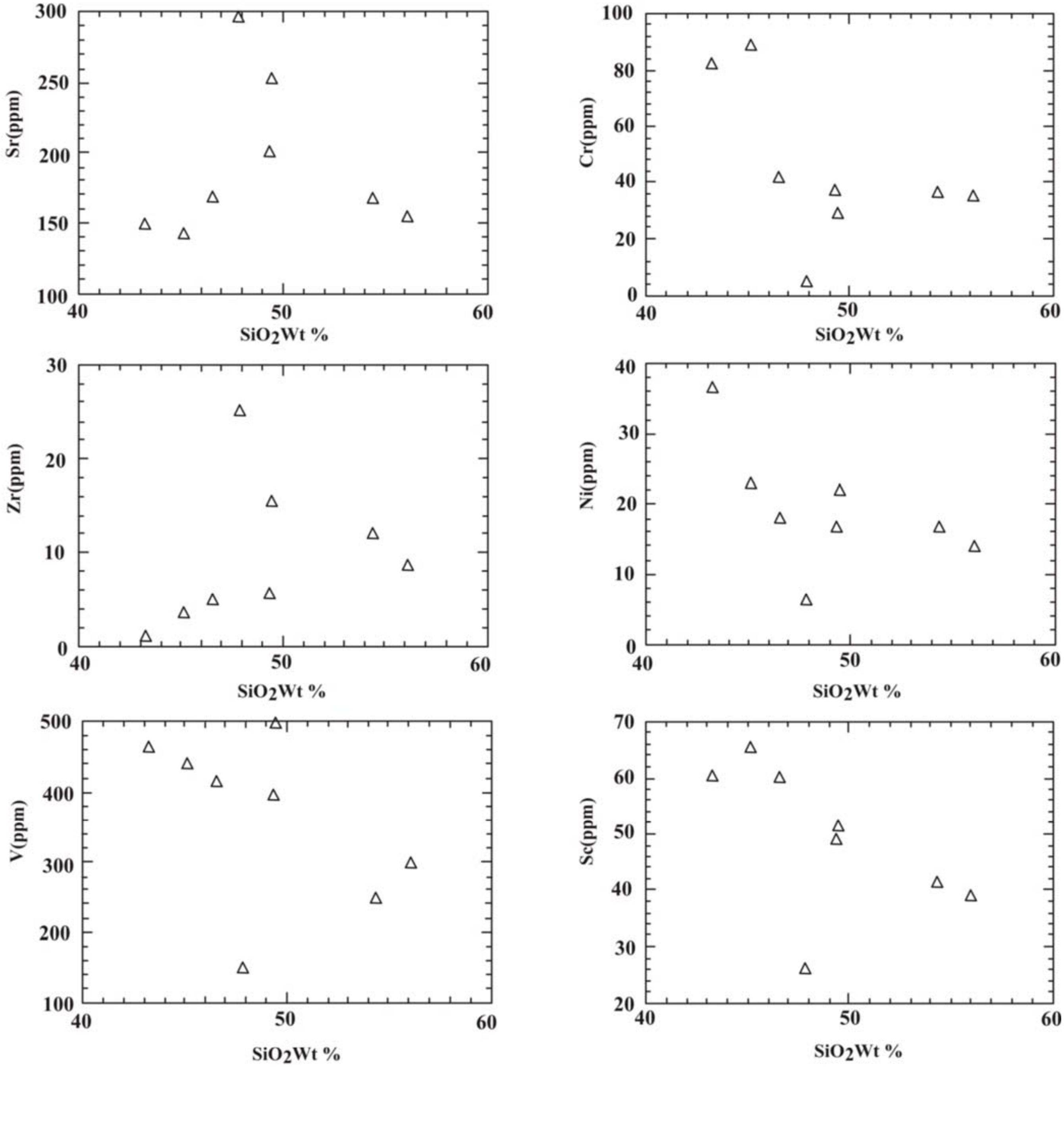


**Fig. 5.** Binary plots of trace elements versus $SiO_2$ wt % for Babusar

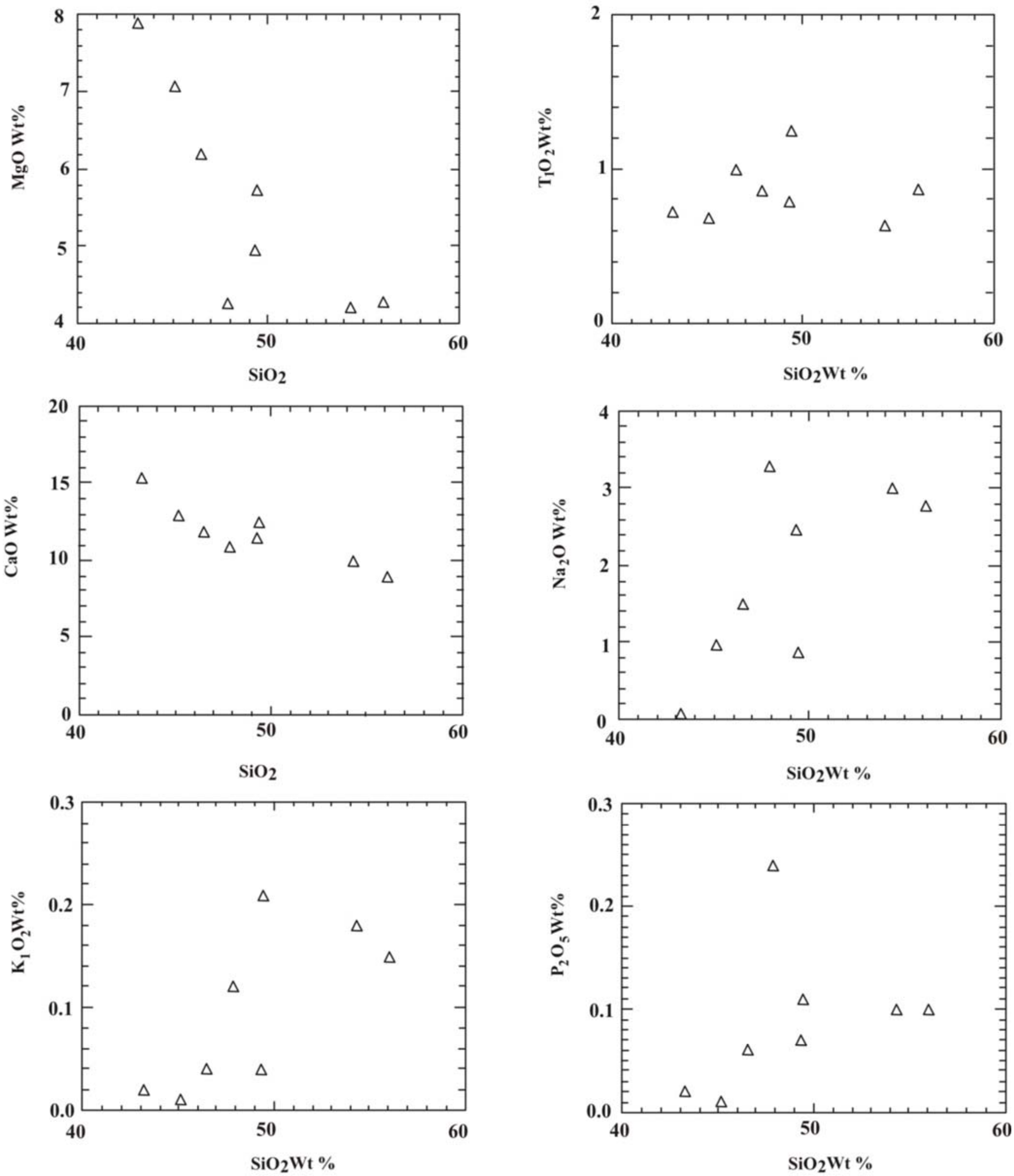


**Fig. 6a.** Binary Plot of Major oxides versus SiO2 wt %

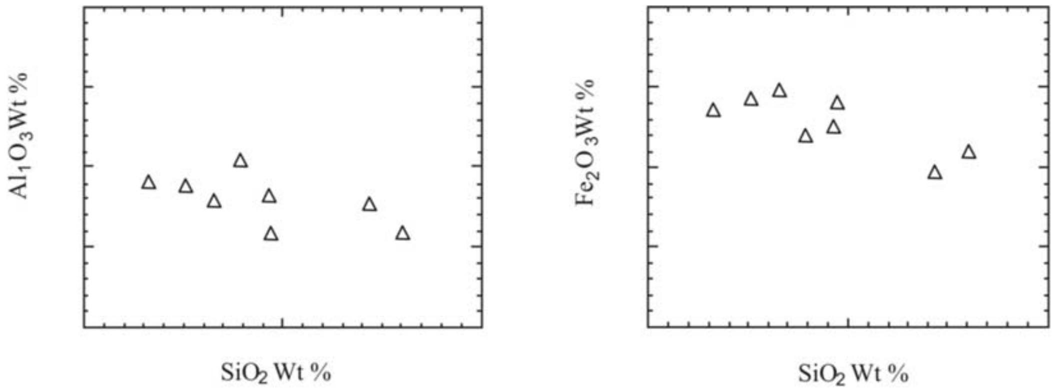


**Fig.6b** Binary Plot of Major oxides versus SiO2 wt %

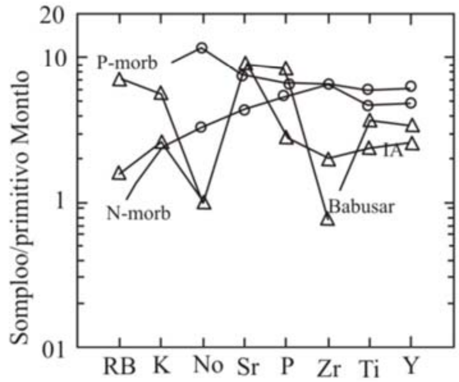


**Fig.7** Primordial mantle normalized diagram of Babusar amphibolites showing the spike trace elements pattern and also compared with various tectonic setting after Sun and

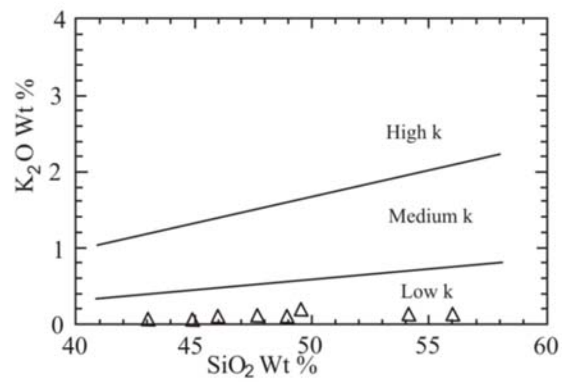


**Fig.8** Subdivision of Babusar amphibolites on $K_2O$ versus $SiO_2$ wt % diagram after Le Maitre et al (1989).

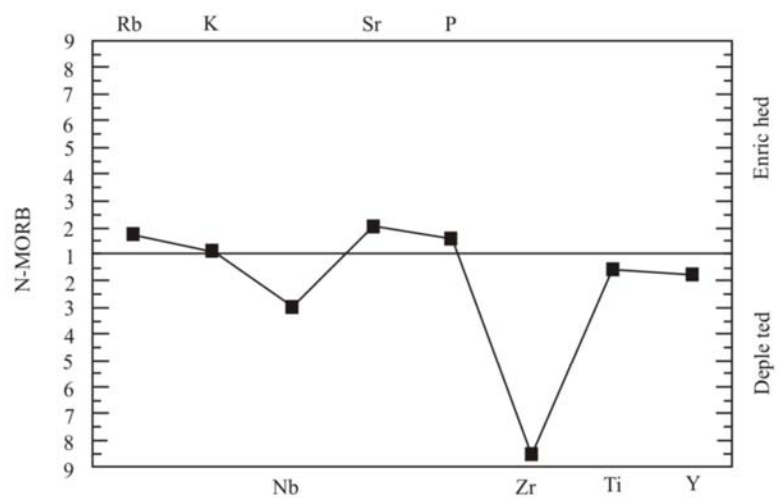


**Fig. 9.** Diagram showing enrichment of low ionic potential elements (Sr, K, P and Rb) and depletion of high ionic potential elements (Nb, Zr, Ti and Y) in island arc tholeiite and Babusar amphibolites

slab. In contrast, the relative depletion in high ionic potential elements has been variably attributed to higher degrees of partial melting and to the stability of residual mantle phases (Pearce, 1982). N-Morb normalized values of the Babusar amphibolites and oceanic island arc basalts clearly show enrichment in elements of low ionic potential (Rb, K, Sr and P) and depletion in high ionic potential (Nb, Zr, Ti and Y) (Fig.7 & Fig.9). The only difference in the studied rocks and the island arc rocks is that the Babusar amphibolites are highly depleted in Zr and Rb, and show some enrichment in P, but the patterns are broadly the same.

The Babusar amphibolites show the distinctive spiked pattern with peaks at Th, Sr and Y, and negative anomalies for Rb, Nb and Zr. These patterns are a characteristic of all subduction related magmas, attesting to the involvement in their petrogenesis of subduction zone fluids enriched in Sr and Th. The peaks and troughs in the Babusar amphibolites show a general resemblance with the low-K island arc tholeiites.

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