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BABUSAR AMPHIBOLITES: ARC THOLEIITES FROM THE SOUTHERN KOHISTAN ARC, N. PAKISTAN

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ABSTRACT

An imbricate sequence of amphibolites, apparently in the form of a linear belt, occurs in the hanging wall of the Indus Suture at Babusar Pass (SE Kohistan). Major–, trace– and a limited rare-earth element data classifies them to be arc tholeiite in composition, in contrast to the bulk of the Kohistan arc which is predominantly calc-alkaline. Models are discussed about their position with respect to the rest of the Kohistan magmatic sequence. Whereas there is a possibility that they represent early tholeiite phases of arc magmatism, a model is presented which considers them (together with a conformable basal ultramafic unit) as crust of a tholeiitic island arc, formed as a separate entity from a predominantly calc alkaline Kohistan arc to the north.

INTRODUCTION

The Kohistan sequence in N. Pakistan is world-wide unique for its exposure of a more or less complete island arc crust, which has been obducted in its entirety onto the Indian plate along the Indus Suture (the Main Mantle Thrust of Tahirkheli et al., 1979, 1983). Since the recognition of island arc character of this sequence (Tahirkheli et al., 1977), several studies have been completed on detailed aspects of various lithologies in terms of field disposition, mineralogy, petrology, metamorphism, structure and radiometric dating (Jan and Howie, 1981; Petterson and Windley, 1985; Coward et al., 1986, 1987; Khan et al., 1989; Jan and Windley, 1990). One of the relatively less explored units includes the amphibolites occurring at the basal to intermediate crustal levels of the Kohistan arc. Jan (1979, 1988) and recently Treloar et al. (1990) have described amphibolites from the Swat and Indus valleys in the west-central Kohistan in terms of petrography, geochemistry and structure. Ahmed and Chaudhry (1976) reported occurrences of amphibolites from the south-eastern Kohistan near Babusar Pass. This paper concerns these latter amphibolites, in terms of their geochemistry, petrogenesis, and their role in the crustal evolution of the Kohistan arc.

REGIONAL TECTONIC SETTING

The Kohistan sequence in N. Pakistan is considered to have formed in two stages of arc growth, separated by a major deformation event (Coward et al., 1986). An early intraoceanic phase resulted in the formation of an arc crust which in its basal parts comprised ultramafic-mafic plutons, while the middle and upper crustal levels contained variably metamorphosed basalt-andesite volcanics with minor acidic magmatic activity (e.g., 102 Ma old granites of Petterson and Windley, 1985). The second phase of arc growth in Kohistan was mainly in an Andean-type continental margin environment resulting from the late Cretaceous accretion of the Kohistan arc with the Karakoram plate. The subduction-related magmatism at this stage was mainly acidic resulting in the formation of the Kohistan batholith and acidic volcanics in Swat, Dir and Shandur Pass areas.

Amphibolites are the most voluminous lithology in the early phase magmatic sequence in the Kohistan arc. Although a considerable proportion of the volcanics occurring in the upper arc crust (e.g., Chalt and Shamran volcanics, and their equivalents in the Jaglot area and to the north of the Chilas Complex; Petterson et al., 1990; Pudsey et al., 1985; M.A. Khan, personal observations) are metamorphosed in amphibolite facies, the principal occurrence of amphibolites in the Kohistan sequence is in the form of a linear belt intervening between the Indus Suture and the Chilas Complex, with a type section in the Indus valley to the south of the village Kamila in the Kohistan district. These amphibolites are recognised by several names such as the Kamila amphibolite belt (Jan, 1979, 1988; Tahirkheli and Jan, 1979), the southern amphibolites (Bard et al., 1980; Bard, 1983a,b) or the Kamila shear zone (Treloar et al., 1990). A characteristic feature of these amphibolites is their predominantly calc-alkaline character (Jan, 1988; J. Tarney, personal communication). It is generally assumed that this amphibolite belt is continuous both to the west and east of the Indus valley forming the southern margin of the arc, with local occurrences of ultramafic rocks (e.g., the Jijal Complex; Jan and Howie, 1981; Jan and Windley, 1990; the Babusar ultramafics; Ahmed and Chaudhry, 1976; Sapat Gali ultramafics: Khan et al., in preparation) where the thrust has cut deeper down through the arc crust. The work of Shams (1975), Ahmed and Chaudhry (1976), and Khan (1988), however, showed that in the valleys to the south of Chilas in SE Kohistan, there are two amphibolite belts between the Indus Suture and the Chilas Complex (Fig. 1). The northern of these amphibolite belts lies directly at the southern contact of the Chilas Complex in the footwall of a 100 m wide south-verging shear zone termed as the Jal Shear Zone (Coward et al., 1987; Khan, 1988), which is probably an equivalent of the Kamila Shear Zone of Treloar et al. (1990). Although, apparently, this amphibolite is in continuity with the Kamila amphibolites, the recently acquired geochemical data negates this possibility (Khan and Thirlwall, in preparation). The second amphibolite occurrence in the Thak-Babusar valley in SE Kohistan, is in the hanging wall of the Indus Suture where it encloses tectonically a lensoid mass of ultramafic rocks. The two amphibolite belts in this part of Kohistan are intervened by alternating sheets of granites and greenschist-facies metavolcanics, a situation which is different from the Indus and Swat valley sections, where the amphibolites are more or less continuous throughout between ultramafic rocks at the Indus Suture and the Chilas Complex in the north. Coward et al. (1987) and Khan and Coward (in press) discussed the possibility that the part of the Kohistan arc to the south of the Chilas Complex may represent a separate island arc now accreted to the northern Kohistan arc at the site of the Jal-Kamila shear zone. Alternatively the ultramafics and amphibolites in the north-eastern Kohistan may represent remnants of earliest island arc magmatic phases. Geochemistry of the amphibolites occurring at the Babusar Pass in the Thak valley is used in this paper to constrain these models.

FIELD RELATIONS

A simplified map of the Babusar Pass area is presented in Fig. 1. The Babusar amphibolites occur in the form of a 1.5 to 3 km wide east-west striking belt resting tectonically over the metasediments of the Indian plate. Apparently the belt is imbricated by more than one shear

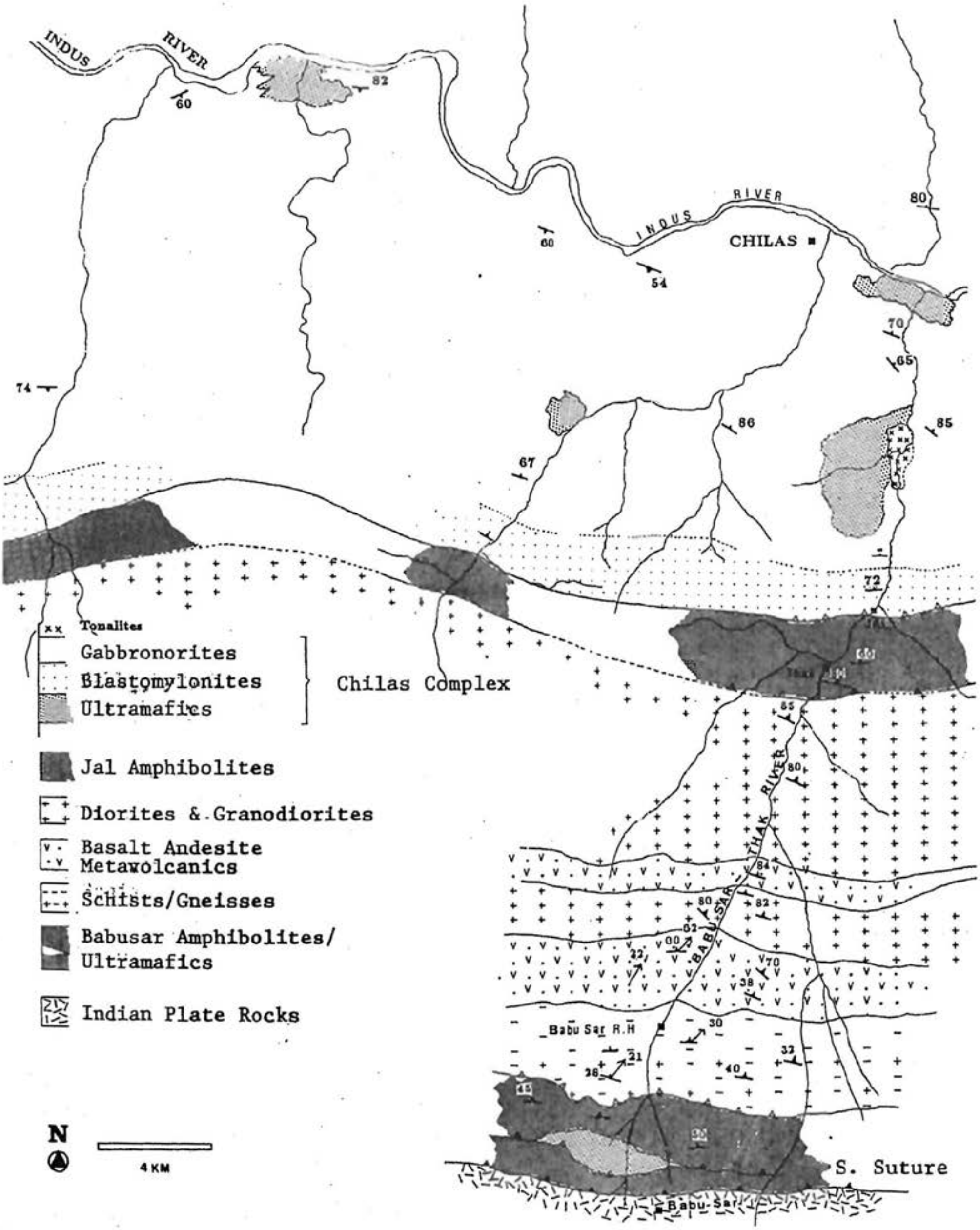

Fig. 1. Simplified geological map of the Babusar-Thak valley, SE Kohistan (after Ahmed and Chaudhry, 1976; Shams, 1975; Khan, 1988).

zones with a south verging reverse slip (thrust) sense of movement. One such shear zone brings a slice of ultramafic rocks, together with stratigraphically overlying amphibolites, on top of the amphibolites in the immediate hanging wall of the Indus Suture.

As noted by Ahmed and Chaudhry (1976), the amphibolites at Babusar include both banded and homogeneous varieties. The banded amphibolites are particularly common in a narrow (200 m wide) zone at the northern margin of the belt, where they are also garnetiferous. The rest of the amphibolites are generally massive and homogeneous except in the shear zones where they are transformed into gneisses probably due to solid state metamorphic differentiation accompanying deformation. Apparently the homogeneous amphibolites represent basaltic lavas (or equivalent shallow level plutonic rocks), while the banded amphibolites in the northern, stratigraphically upper, part of the amphibolite sequence represent volcanic flows with a considerable volcanoclastic component. In general appearance the amphibolites in the Babusar Pass area resemble closely those of the Kamila amphibolite belt in the Indus Kohistan (Jan, 1979, 1988).

Petrography and modal composition data have been presented in detail by Ahmed and Chaudhry (1976). The amphibolites dominantly comprise plagioclase, amphibole and epidote, but localised zones in the northern banded part contain up to 18% garnet. Minor mineral phases include biotite, chlorite, magnetite and sphene.

GEOCHEMISTRY

Geochemical data for seven selected samples from the Babusar amphibolites are presented in Table 1. Three representative major-element analyses published by Ahmed and Chaudhry (1976) are also included in this table for comparison. Our analyses were obtained using X–ray Fluorescence technique at the Royal Holloway and Bedford New College (RHBNC), Egham, U.K. Rare earth elements (REEs) for the two samples, included in this study, were determined using an Inductively Coupled Plasma (ICP) Spectrometer at RHBNC, Egham, U.K. (see Khan et al., 1989 for further details on analytical techniques).

General Geochemical Characteristics

The Babusar amphibolites are predominantly orthoamphibolites, i.e., they are metamorphosed from originally igneous rocks. This is reflected in their regular depletion in MgO, Ni, and Cr contents (Fig. 2) with increasing degree of fractionation (cf. Leake, 1963; Van de Kamp, 1969). All the samples analysed during this work have low TiO_2 (< 1.00 wt%), and low Zr/TiO_2 ratios which confirm their igneous past. TiO_2, however, is typically high in all the analyses listed by Ahmed and Chaudhry (1976), in two samples being > 4.00 wt%. We believe that TiO_2 is highly overestimated in these analyses.

An idea about the equivalent igneous composition of the Babusar amphibolites is obtained using the classification scheme of De La Roche et al. (1980). On their diagram (Fig. 3), majority of the Babusar amphibolites plot in the field of basalts (ranging from olivine–, through tholeiite–, to andesi-basalts). Two samples with higher SiO_2 contents plot in the field of dacite, while the samples with R2 > 2000 are apparently cumulates with originally abnormal plagioclase (but now amphibole) enrichment.

Despite discrepancies for certain major elements (TiO_2, MnO, K_2O, and Na_2O) between our data and those of Ahmed and Chaudhry (1976), fairly regular variations are observed in the

TABLE 1. WHOLE-ROCK GEOCHEMICAL ANALYSES OF THE BABUSAR AMPHIBOLITES, S.E. KOHISTAN

	BS7	BS8	BS9	BS10	BS11	BS18	BS19	11918Z	11916A	11916B
	1	2	3	4	5	6	7	8	9	10
SiO_2	48.44	56.71	54.87	43.80	47.24	49.94	45.47	46.60	50.46	58.76
TiO_2	0.87	0.86	0.64	0.73	1.02	0.80	0.68	4.54	1.46	3.60
Al_2O_3	20.61	16.00	17.87	19.31	18.09	18.45	18.90	14.90	26.19	14.24
Fe_2O_3*	10.90	9.92	8.80	12.30	13.49	11.40	12.94	10.40	7.35	6.18
MnO	0.26	0.19	0.19	0.23	0.28	0.21	0.22	0.29	0.31	0.61
MgO	4.30	4.30	4.24	7.98	6.28	4.99	7.12	7.13	3.91	1.36
CaO	10.94	8.97	10.08	15.58	11.99	11.62	13.02	12.92	7.63	11.57
Na_2O	3.32	2.79	3.03	0.04	1.52	2.48	0.96	2.67	2.27	2.95
K_2O	0.13	0.15	0.18	0.02	0.04	0.04	0.01	0.26	0.24	0.51
P_2O_5	0.24	0.10	0.10	0.02	0.06	0.07	0.68	0.30	0.21	0.22
Ni	6	14	17	36	18	17	23	—	—	—
Cr	5	35	36	82	42	37	88	—	—	—
V	149	300	247	465	414	396	439	—	—	—
Sc	26	39	42	60	60	49	65	—	—	—
Cu	17	39	35	50	103	123	68	—	—	—
Zn	110	92	85	89	126	100	100	—	—	—
Cl	< 50	< 50	< 50	< 50	< 50	< 50	132	—	—	—
Ga	19	15	15	15	17	18	16	—	—	—
Pb	2.1	1.7	2.4	1.1	1.5	1.0	< 1	—	—	—
Sr	296.5	154.7	167.4	148.6	167.4	200.3	141.6	—	—	—
Rb	0.5	1.1	1.5	1.5	1.0	0.9	0.4	—	—	—
Ba	32	55	68	18	22	29	17	—	—	—
Zr	25.1	8.7	11.9	1.0	5.0	5.5	3.6	—	—	—
Nb	1.7	1.0	0.5	0.6	< 0.4	0.9	< 0.4	—	—	—
Th	< 0.8	< 0.8	< 0.8	< 0.8	< 0.8	< 0.8	< 0.8	—	—	—
Y	28.9	16.8	17.3	6.3	12.5	14.8	10.8	—	—	—
La	2.9	1.5	1.3	< 1	< 1	< 1	< 1	—	—	—
Ce	10.2	3.6	4.3	1.4	2.6	2.9	3.5	—	—	—
Nd	10.4	3.6	3.9	0.6	0.6	2.7	1.1	—	—	—

* Total iron as Fe_2O_3. All the analyses are normalised to 100% on anhydrous basis. Analyses 8, 9, 10 from Ahmed & Chaudhry (1976).

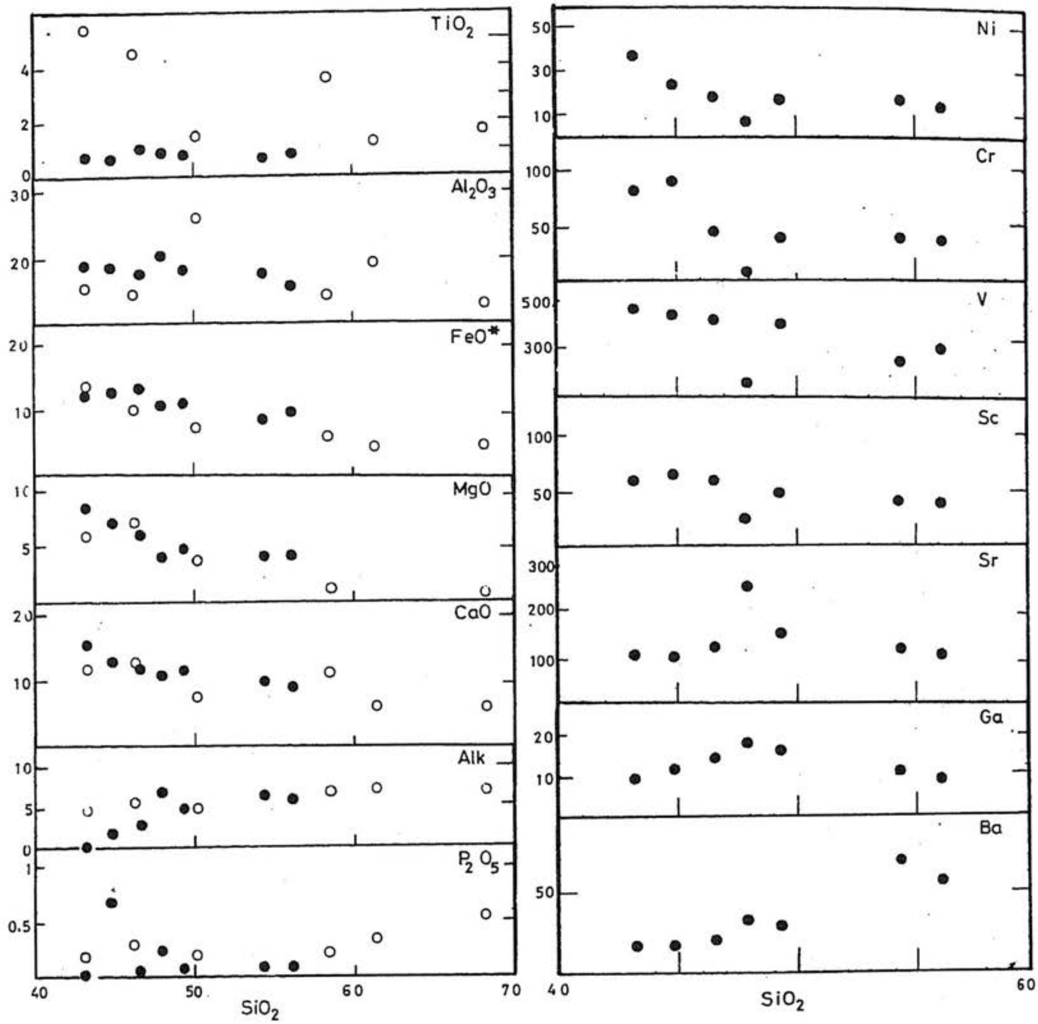

Fig. 2. Geochemical variations in the Babusar amphibolites (filled circles = data from this study; open circles = data from Ahmed and Chaudhry, 1976).

amphibolite analyses when plotted on Harker-type variation diagrams (Fig. 2). There is a marked decrease in the concentration of major oxides such as iron (total as FeO), MgO and CaO, while there is a corresponding enrichment in SiO_2, $Na_2O + K_2O$, and P_2O_5. The intermediate to low Mg#s (molecular MgO/MgO+FeO calculated on the basis of $Fe_2O_3/FeO=0.2$) suggest that none of the analysed amphibolites represent initial melt composition, and that there must be a role of fractional crystallisation in the compositional variations observed. Olivine fractionation is clearly reflected in regular depletion of MgO and Ni with increase in SiO_2. The depletion of FeO with increasing fractionation warrants the crystallisation of an iron oxide. An interesting variation is observed in Al_2O_3, which shows an inversion in its trend at SiO_2 ~50 wt%. Both Na_2O and Al_2O_3 increase rather abruptly with increasing fractionation, but while the Al_2O_3 variation becomes –ve with further fractionation, the Na_2O trend remains +ve but becomes less steep. These variations are interpreted to be due to a relatively earlier crystallisation

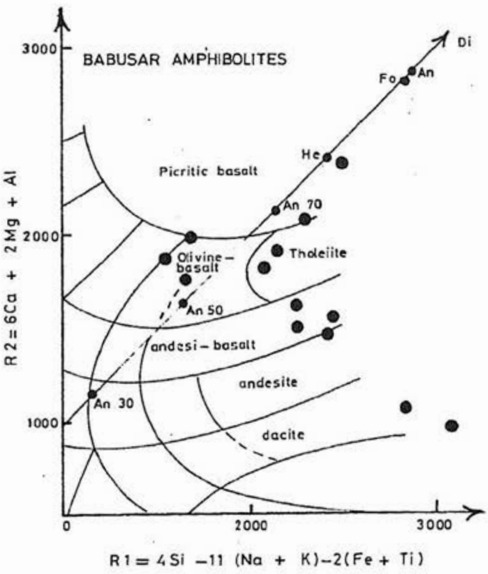

Fig. 3. Characterisation of the equivalent igneous composition of the Babusar amphibolites in terms of De La Roche et al. (1980) classification.

of clinopyroxene (probably accompanying that of olivine and an iron oxide) which caused earlier enrichment of both Al_2O_3 and Na_2O, and a rather rapid decrease in CaO. A later introduction of a calcic plagioclase in the crystallisation sequence caused an inversion in the Al_2O_3 variation trend and also decreased the rate of Na_2O enrichment. It is to be noted that Ga and Sr which are highly compatible with plagioclase (plagioclase/melt partition coefficient being 1 and 1.8, respectively; Henderson, 1982) show variations which are identical to those of Al_2O_3. In summary, on the basis of major and trace element variations, it is possible to deduce a sequence of crystallising minerals which caused the compositional diversity in the Babusar amphibolites. It is interpreted that olivine, clinopyroxene and and iron oxide phase (or ?chrome spinal) were the earliest crystallising minerals, which were later joined up by plagioclase. It is to be noted that a relatively later crystallisation of plagioclase in the crystallisation sequence is more a characteristic of subduction-related settings than that of mid oceanic ridges (Perfit et al., 1980).

Tectonic Setting of Origin

The Babusar amphibolites are plotted on the conventional AFM diagram (Irvine and Baragar, 1971) in Fig. 4. Inspite of a lack of a pronounced iron-enrichment, the samples plot in the field of tholeiites (except for one sample of Ahmed and Chaudhry, 1976). Further confirmation of the tholeiitic character of the Babusar amphibolites is obtained from chondrite-normalised rare earth and mantle-normalised traced element patterns (Fig. 5a,b). In both these diagrams, the Babusar amphibolites are relatively depleted in large ion lithophile (LIL) and light rare earth elements which is a characteristic feature of tholeiitic rocks from mid-ocean ridge and subduction-related environments (island arcs and Andean-type continental margins) rather than those of calc-alkaline and alkaline rocks.

Almost all the major tectonic settings of magma generation contain tholeiitic basalts in their magmatic products. The pronounced depletion of LIL and LRE elements in the Babusar

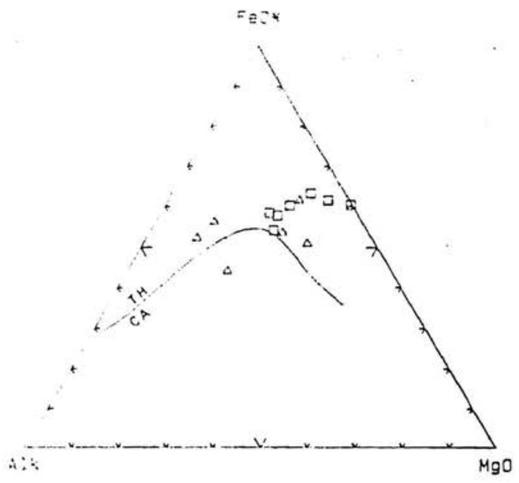

Fig. 4. Babusar amphibolites plotted in the Alk-FeO(total)–MgO diagram. The line separating tholeiites and calc-alkaline rocks is after Irvine and Baragar (1971). (Squares = data from this study; Triangles = data from Ahmed and Chaudhry, 1976).

amphibolites readily precludes their affinity with within-plate oceanic (e.g., ocean islands) or continental settings. This leaves the possibility of their affinity with either ocean environments (which are invariably characterised by tholeiitic basalt magmatism) or with island arc/continental margin environments in which tholeiitic series is considered to be the earliest and in some cases the dominating phase of magmatism (e.g., Table 2.1 in Wilson, 1989). In Fig. 6, we have compared the mantle-normalised trace element patterns of the Babusar amphibolites with those of type tholeiites from island arc and ocean floor settings. The Babusar amphibolites have highly spiked trace element pattern characterised by positive peaks for Ba, K, Sr, P and Ti, and negative anomalies for elements Rb, Th, Nb, Nd, and Zr. The pattern have a peculiar shape roughly resembling the alphabet "v", the lower end of which is pivoted at Nb (Fig. 6a). This patterns is closely matched with that of the low-K island arc tholeiites (Fig. 6b) but differs substantially from that of the ocean-floor tholeiites (Fig. 6c), which are characterised by a nearly flat Nb–Rb segments. Moreover, whereas the peaks and negative anomalies in the low-K arc tholeiites are in general correspondence with those of the Babusar amphibolites, they are mostly opposite in the case of the ocean floor tholeiites.

DISCUSSION

An intriguing aspect of the Kohistan-arc stratigraphy has been a general absence of tholeiites, either of ocean-floor or even of island arc origin. The ultramafic rocks at Jijal and the associated garnet granulites may be of tholeiitic lineage (Jan and Windley, 1990), which is difficult to ascertain because of their cumulus nature and subsequent metamorphism. However, the Kamila amphibolites, and the Chilas Complex are certainly calc alkaline in character (Ian Luff, unpublished data; Jan, 1988; Khan et al., 1989). A large part of the volcanic belt in the upper parts of the Kohistan sequence (including Chalt, Shamran, and Kalam-Dir volcanics) is also calc-alkaline in chemistry. Recently, however, Petterson et al. (1990) have presented data on some high–Mg tholeiite volcanics from the Chalt area. When compared with the Babusar

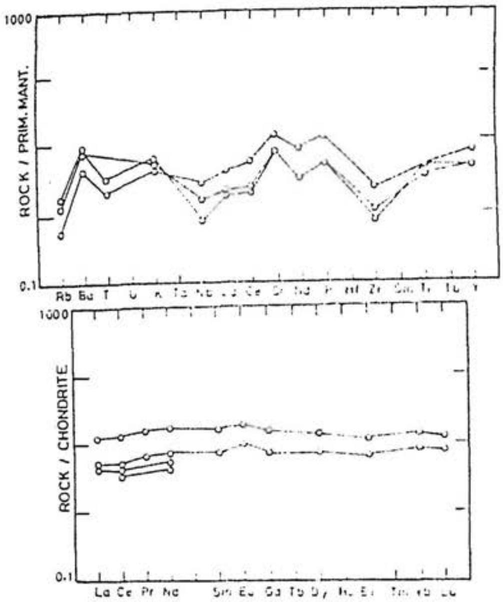

Fig. 5. Mantle-normalised trace element (a) and chondrite-normalised rare-earth (b) patterns of the amphibolites from Babusar.

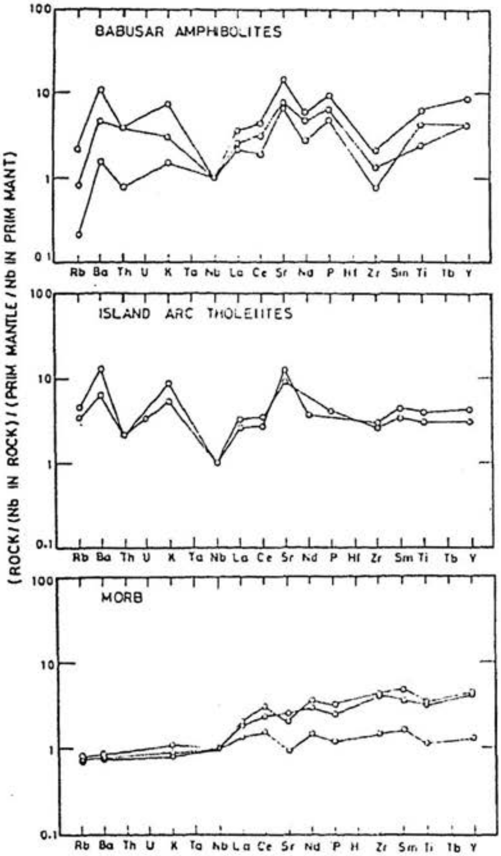

Fig. 6. Mantle-normalised ratio-spidergrams (i.e., (element in sample/Nb in sample)/(element in Primordial Mantle/Nb in Primordial Mantle)) of the Babusar amphibolites (a) compared with those of the type island arc tholeiites (b) and average mid-ocean ridge basalts (c).

tholeiites, the Chalt tholeiitic volcanics show several dissimilarities reflected in contrasting mantle normalised trace element patterns.

Thus the Babusar amphibolites are amongst the first ever reported tholeiitic basalts of their kind from the Kohistan arc. Obviously an immediate concern is their tectonic position with respect to the Kohistan sequence which is predominantly calc alkaline in composition. The simplest models would explain these arc tholeiites as a magmatic phase related with early arc development in Kohistan. Their tectonic position in the hanging wall of the thrust fault marking the Indus Suture, and hence near to the now obliterated subduction zone, lends a sound support to this explanation (cf. Baker, 1973; Wilson, 1989). Alternatively, the Babusar amphibolites might have been a part of a southern tholeiitic island arc, distinct from a calc-alkaline main Kohistan arc in the north. We are currently exploring this possibility.

The existence of more than one island arcs within the Kohistan sequence has already been pointed out. Coward et al. (1987) realised that when the isoclinally folded and imbricated Kohistan arc sequence is restored back to its original dimensions, it is abnormally large for an island arc. Khan (1988) mapped a 100 m thick greenschist to lower amphibolite-facies mylonite zone at the southern contact of the Chilas Complex in the valleys to the south of Chilas. And above all, our recently acquired geochemical data from the southern Kohistan arc point to the existence of an ocean-floor basement intervening between the Babusar amphibolites and the Chilas Complex (Khan and Thirlwall, in prep.). All this leads us to suggest that the Kohistan is a composite island arc system. The ultramafic complexes, such as those of Jijal, Allai, Sapat Gali and Babusar in the hangingwall of the Indus Suture together with the stratigraphically overlying metamorphosed gabbros/basalts (the Babusar amphibolites and their equivalents in southern Kohistan), in our model represent crust of a relatively smaller tholeiitic island arc. This island arc formed in the Tetheys probably earlier than the northern calc-alkaline main Kohistan arc (which would include the Chilas Complex, the Kamila amphibolites, and the volcanics and sediments in the northern Kohistan), and the two accreted together probably at the same time when the marginal basin between Kohistan and the Karakoram plate closed to form the northern suture (Pudsey et al., 1985; Coward et al., 1986). The Jal Shear Zone at the southern contact of the Chilas Complex, which has in its footwall metamorphosed amphibolites of ocean-floor affinity (Khan and Thirlwall, in prep.) is probably the site of accretion between the two island arcs suggested in this model.

Our model about the composite nature of the Kohistan island arc is still in infancy. More field work, detailed geochemistry and radiometric dating is obviously required to further refine this model. Nevertheless, the island arc tholeiites such as those from the Babusar area, described in this paper, certainly add new dimensions to the stratigraphic set up of the Kohistan arc.

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