Geochemistry of amphibolites from the southern part of the Kohistan arc, N. Pakistan

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Abstract

The southern part of the Cretaceous Kohistan island arc is occupied by an extensive belt dominantly comprised of amphibolites. These include banded amphibolites of partly meta-volcanic parentage, and non-banded amphibolites derived from intrusive rock. In addition to being relict, banding has also been produced by shear deformation, metamorphic/metasomatic segregation and, possibly, by lit-par-lit injection of plagiogranitic material. Non-banded amphibolites also occur as retrograde products of noritic granulites forming the lopolithic Chilas complex. The chemistry of 37 rocks has been compared with those of known tectonic environments. The amphibolites have chemical characteristics similar to volcanic rocks found in island arcs and most of the analyses apparently support affinity with the calc–alkaline series. The amphibolites consist essentially of hornblende, plagioclase and/or epidote. Garnet and clinopyroxene have developed locally in rocks of appropriate bulk composition. Metamorphism may have taken place during the mid-Cretaceous under conditions of 550 to 680 °C and 4.5 to 6.5 kbar P_{H_2O}. The metamorphic grade appears to increase from the centre of the southern belt toward the Chilas complex to the north and Indus–Zangbo suture (IZS) to the south. In the vicinity of the IZS, garnet–clinopyroxene ± amphibole assemblage developed locally in response to high *P–T*.

KEYWORDS: amphibolites, geochemistry, Kohistan arc, Pakistan

Introduction

THE Indus Zangbo Suture (IZS) in Ladakh and Kohistan bifurcates into the Main Karakoram Thrust (MKT) in the north, and the Main Mantle Thrust (MMT) in the south. Both are characterized by the association of ophiolitic mélanges and, in the case of MMT, blueschists and high-*P* garnet granulites. The MKT and MMT extend E–W as northerly convex arcs that are terminated in eastern Afghanistan by the N–S Bela–Zhob–Waziristan suture. They enclose the dominantly Cretaceous Kohistan–Ladakh island arc, to the north of which occurs the Karakoram plate and to the south, Indian plate. Several lithologies common to Kohistan and Ladakh are separated by the N–S elongated Nanga Parbat–Haramosh dome. The Kohistan part appears to represent a deeper and the Ladakh part a shallower section of the arc that became an Andean-type margin during the Late Cretaceous (for further details, see Tahirkheli and Jan, 1979; Tahirkheli *et al.*, 1979; Klootwijk *et al.*, 1979; Andrews-Speed and Brookfield, 1982; Coward *et al.*, 1982, 1986; Honegger *et al.*, 1982; Bard, 1983*a*,*b*; Thakur and Sharma, 1983; Windley *et al.*, in press).

The ~36 000 km^2 Kohistan island arc is tilted so that a complete sequence can be observed in the Middle Indus valley (Fig. 1). A N–S section across the arc between MKT and MMT shows the following major lithologies, each stretching for several hundred kilometers.

(1) Yasin Group: Mid Cretaceous, mainly detrital sediments of deep-water origin, probably deposited in intra-arc basin. These consist of slates, turbidites, volcaniclastics, limestone and basal conglomerate (Ivanac *et al.*, 1956; Coward *et al.*, 1986).

(2) Chalt Volcanics: Cretaceous and possibly Late Jurassic lava flows (some pillowed), tuffs, pyroclastics and minor calcareous rocks underlying the Yasin group. These represent a basalt–andesite–rhyolite series island-arc volcanics metamorphosed to the greenschist facies (Ivanac *et al.*, 1956).

(3) Kohistan–Ladakh Plutonic Belt: Mid Cretaceous–Tertiary calc–alkaline (mafic to silicic) plutons with associated detrital and

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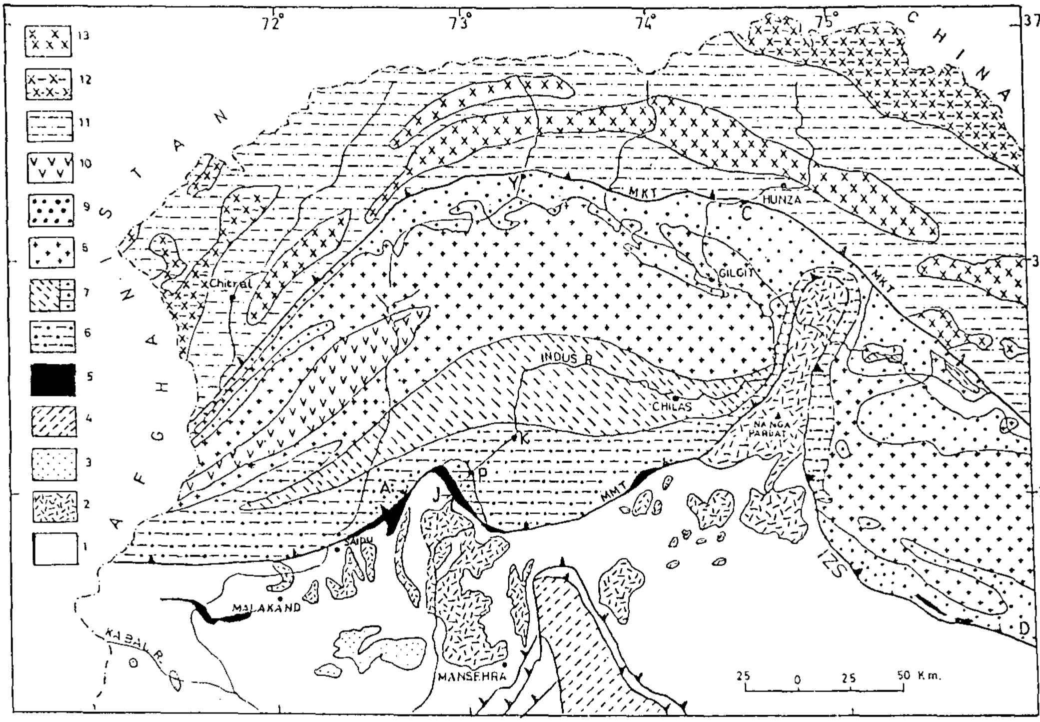

FIG. 1. Simplified geological map of northern Pakistan (after Jan *et al.*, 1984). (1) Precambrian to Mesozoic sedimentary rocks of the Indian Plate; (2) Cambrian granitic rocks; (3) Late Palaeozoic alkaline to subalkaline igneous rocks; (4) Middle Tertiary clastic sediments; (5) Ultramafic ophiolites; (6) The southern (Kamila) amphibolite belt; (7) Chilas–Jijal mafic complexes; (8) Kohistan–Ladakh granitic belt; (9) Chalt volcanics and Yasin sediments; (10) Kalam sediments and volcanics; (11) (meta)sediments of the Karakoram plate; (12) Khunjerab–Wakhan–Tirichmir granites (Mesozoic); (13) Creto–Tertiary Karakoram granitic belt. A, Alpurai; C, Chalt; D, Dras; IZS, Indus–Zangbo suture; J, Jijal; K, Kamila; MKT, Main Karakoram Thrust; MMT, Main Mantle Thrust; P, Patan; Y, Yasin.

calcareous metasediments and metavolcanics (amphibolites). The Tertiary plutons are generally undeformed but the Cretaceous ones are metamorphosed and therefore deformed (Jan and Asif, 1983; Petterson and Windley, 1985).

(4) The Chilas Complex: Early to Middle Cretaceous, over 300 km long and up to 40 km wide, a lopolithic body of granulite facies metamorphosed gabbro–norites, with some hypersthene–quartz diorites, gabbros, troctolites, anorthosites, pyroxenites, chromite-layered dunites and peridotites, and retrograde amphibolites (Jan *et al.*, 1984).

(5) Southern (Kamila) Amphibolite Belt: These, the subject of this paper, form an extensive belt of possibly Late Jurassic–Cretaceous metavolcanics with a variety of plutonic rocks (ultramafics, gabbros, diorites, tonalites, granites, trondhjemites), and rare siliceous and calcareous metasediments (Jan, 1979).

(6) The Jijal–Patan Complex: A ~150 km^2 tectonic wedge of ultramafic rocks, and mafic–ultramafic garnet–granulites possibly related to the Chilas complex. The granulites have a Sm–Nd mineral isochron age of 104 Ma (Coward *et al.*, 1986). It has been suggested that they were equilibrated during a subduction-related metamorphism at deep crustal level (>40 km, Jan and Howie, 1981; Bard, 1983*b*).

(7) In west–central Kohistan in Swat and Dir occur andesite–dacite–rhyolite–ignimbrite flows, tuffs and agglomerates of Eocene–Oligocene age (Majid and Paracha, 1980). These overlie earlier Kohistan–Ladakh plutons and Cretaceous detrital sediments of the Kalam group and are cut by younger granitic intrusions.

This paper uses the chemistry of 37 rocks to explore the parentage of banded amphibolites and associated amphibole gneisses from the Southern (Kamila) Amphibolite Belt, and to elicit the tectonic environments of these amphibolites from southern Kohistan. Details of petrography have been presented by Jan (1979) and only a summary is included here.

Petrography

Amphibolites (Jan, 1979) not only form the bulk of the southern belt but are also widespread in the Chilas complex, where they are a retrograde product of noritic granulites and generally consist of amphibole, plagioclase, minor oxide ± quartz, with local chlorite, epidote and, very rarely, garnet. The southern ones range from mela-amphibolites to leucocratic hornblende gneisses and can be classified into (1) medium- to fine-grained banded, and (2) medium- to coarse-grained non-banded types. These consist essentially of hornblende, plagioclase and/or epidote, with increasing quartz in the gneisses. Opaque minerals, apatite, rutile and/or sphene are the common accessory minerals. Micas, garnet, clinopyroxene, cummingtonite, actinolite, zoisite, chlorite, calcite, K-feldspar, kyanite, tourmaline, and green spinel are locally present (Chaudhry *et al.*, 1974; Jan, 1979; Bard, 1983*b*). Corundum/staurolite amphibolites containing alumino-tschermakite and secondary margarite have been described from southern Dir (Jan *et al.*, 1971; Van de Kamp and Leake, 1975).

The southern amphibolite belt is structurally complex with at least three phases of deformation; isoclinal folding and shearing are common. The banded rocks, forming over a quarter of the exposures, are characterized by the concentration of hornblende and plagioclase ± quartz in alternate bands; however, garnet-, epidote- and quartz-rich bands also occur locally. Some bands are plagiogranite in composition and locally they may be sufficiently more abundant than the associated amphibolites to be called hornblende gneisses. Intercalations in a few places are metasedimentary lithologies, e.g. quartzites, marbles, micaceous bands and patches, calc-silicates, clinozoisite–corundum rocks. These, coupled with banding, led previous workers to conclude that the banded amphibolites are themselves metasedimentary. The non-banded amphibolites, generally, are medium- to coarse-grained and display intrusive relationships with their host rocks.

The plagioclase in the amphibolites is principally andesine and in the gneisses it is oligoclase in composition. Labradorite occurs in some rocks, reflecting a higher metamorphic grade and/or the influence of bulk chemistry and mineralogy. The epidote ranges from Ps_{10} to Ps_{27} but some rocks contain zoisite or clinozoisite. Bard (1983*b*) has reported coexisting Fe-poor and Fe-rich phases in some rocks. The garnet is almandine-rich (Alm_{54} to Alm_{68}) and clinopyroxene is diopside–salite. The hornblendic amphibole is rich in Al_2O_3 (averaging 14.6%), the content of Al, Ti and the *A*-site being controlled by bulk chemistry, mineralogy and metamorphic grade (Jan and Howie, 1982).

Origin of garnet and clinopyroxene. The sporadic development of garnet in mafic rocks has been attributed to variations in rock chemistry and/or metamorphic conditions (Leake, 1963; Buddington, 1966; De Waard, 1967; Manna and Sen, 1974). The occurrence of garnet in the southern amphibolite belt is also sporadic. In some places, garnetiferous bands are intimately associated with non-garnetiferous ones, suggesting a chemical control over garnet growth. Only six of the analysed rocks contain garnet and in these the low Mg/Fe and/or high normative An/Ab seem to have played the principal role.

The development of clinopyroxene in the southern amphibolites is also controlled by bulk chemistry, i.e. high CaO (>12%) and high normative Di/An. Studies in Ireland (Leake, 1972) and Greenland (Kalsbeek and Leake, 1970) on amphibolite terrains also suggest that high CaO leads to clinopyroxene growth.

P–T Estimates for southern belt

Temperature estimates based on eight geothermometers are presented for rocks from the southern belt (Table 1; see also Jan, 1979, 1980). Plyusina's method suggests that pressures ranged from 5 to 7 kbar. The Al^{vi}/Al^{iv} ratios of the amphiboles are high (Jan and Howie, 1982) and plot along the assumed 5 kbar isobar of Raase (1974). A pressure of 5.5 kbar is also estimated for the three samples in column 6 of Table 1 (after Dobretsov *et al.*, 1972). The system $CaO–Al_2O_3–SiO_2–H_2O$ has been investigated by Storre and Nitsch (1974), Chatterjee (1976), Chatterjee *et al.* (1984), and others. The reaction margarite = anorthite + corundum + H_2O is stable at 565 °C, 4 kbar to 630 °C, 7 kbar. In the reactions margarite + anorthite = zoisite + kyanite, and margarite + quartz = zoisite + kyanite + H_2O, the left-hand-side assemblages are stable at temperatures below 650 °C at $P < 7$ kbar. Margarite occurs in some amphibolites, whilst corundum + plagioclase at only four places, in two of which the corundum is marginally replaced by margarite. The kyanite + clinozoisite assemblage is very rare (Bard, 1983*b*). Thus, as expected, *P–T* conditions must have varied over the area of the southern amphibolites.

Table 1. T estimates (°C) for the southern amphibolite belt

		1	2	3	4	5	6	7
Swat Valley								
N	462	700	650	640	-	-	-	-
↑	191	675	-	-	-	-	-	680*
	66	630	610	570	-	-	-	-
	8	610	560	560	-	-	-	-
	4	570	570	550	-	-	-	-
middle of belt								
Indus Valley								
N	177	750	?850	730	680	640	680	-
↑	156	635	635	560	670	695	675	685**
	202	650	640	570	-	-	-	-
	355	530	550	510	-	-	-	-
	352b	580	550	545	-	-	-	-
	347	520	550	550	-	-	-	-
	369	630	650	560	725	675	680	-
↓	343	680	700	615	-	-	-	-
S	194	640	610	580	-	-	-	-

1,2,3 based on amphibole-plagioclase models of Perchuk (1966), Spear (1980), Plyusina (1982), respectively.
4,5 based on garnet-hornblende thermometers of Perchuk (1966) and Graham and Powell (1984), respectively.
6 based on reaction Ca-garnet+anorthite+iron oxide = epidote+ quartz, using Dobretsov et al.'s (1972) Fig. 91b, p.313.
7* based on Cpx-Hbl geothermometer of Perchuk (1969).
7** average temperature derived from biotite-garnet geothermometers of Perchuk (1969 , Thompsom (1976), Goldman and Albee (1977) and Ferry and Spear (1978), yielding estimates of 660°, 690°, 630°C and 755°, respectively.
194 is a retrograde amphibolite within the Chilas complex.

The estimates suggest that the rocks were metamorphosed at 550 to 680 °C, 4.5–6.5 kbar P_{H_2O}. These temperature estimates are higher than those proposed for epidote amphibolites (Hietanen, 1967; Sobolev *et al.*, 1967). In the Guiana shield, epidote and basic adesine coexist up to the boundary of the granulite facies (Cannon, 1966). Thus the presence or absence of epidote in the southern belt cannot be used as a reliable criterion of metamorphic grade. Evidence of partial melting has been found in a few places, and the occurrence of granitic rocks and 'migmatites' is consistent with temperatures in excess of 600 °C.

Chilas-like rocks of the granulite facies (marginally amphibolitized), are locally present in the southern belt. Thus, it has been suggested that either the granulite masses were remobilized or the entire amphibolite belt was degranulitized (Jan, 1980; Bard, 1983*b*). Whilst retrograde amphibolitization may have taken place along the southern margin of the amphibolite belt in the Indus valley, and elsewhere locally, sufficient evidence does not exist to suggest that the entire belt is retrograded. If the southern amphibolites represent a higher structural level of the arc than the Chilas complex, as thought by the present author and Coward *et al.* (1986), one would expect lower *P–T* conditions during their metamorphism. Hence some of the granulite lenses may have been remobilized from depth.

Near Alpurai, just north of MMT, garnet granulite assemblages are locally hosted by amphibolites. Here the proportion of migmatites and granitic bodies also appears to be greater. It is possible that, like the neighbouring Jijal complex (Jan and Howie, 1981), this area underwent higher *P–T* metamorphism (granulite facies), followed by retrograde equilibration of the amphibolite facies.

Table 1 shows that *T* estimates increase northwards from the centre of the amphibolite belt towards the noritic granulites of the Chilas complex. There are no estimates available for the southern half of the belt in the Swat valley, but in the Indus valley there is an increase also from the middle towards the south. This is either due to thermal effects associated with the Chilas complex and subduction process, or to large-scale synclinal folding in the Indus valley (cf. Coward *et al.*, 1982).

Geochemistry

Analyses and C.I.P.W. norms for representative rocks are presented in Table 2. (A complete list can be obtained from the author). Major oxide variation against Thornton and Tuttle's (1960) differentiation index (D.I.) is shown in Fig. 2. There is a general decrease in total Fe, TiO_2, CaO and MgO, and an increase in SiO_2 and Na_2O with increasing D.I. The non-banded amphibolites from the Chilas complex as well as the southern belt show systematic variation but the plots of the banded rocks are scattered. The non-banded rocks also show an increase in Al_2O_3 and K_2O with D.I., whereas the plots of the banded rocks are inconclusive.

Plots of Ba, Rb, Sr, and Y are scattered but Ni, Co and, ignoring a few analyses, Cr decrease and Zr increases with D.I. (figure not shown). Despite a regular variation of major oxides against D.I., it cannot be ascertained from trace element and other diagrams whether the non-banded amphibolites from the Chilas complex and the southern belt are comagmatic.

Origin of the banded amphibolites and gneisses. Amphibolites can form by metamorphism of: (a)

Table 2. Representative analyses for the Kohistan amphibolites and associated rocks

Wt.%	SI177	SK462	US4	SI343	SI352b	SI369	SI347	SI220	US23	SI363	SI351	SK395	US8	SK301b	SK407	SI194
SiO_2	39.89	45.88	51.01	58.40	64.84	65.87	47.72	51.04	51.38	55.00	56.66	49.01	49.07	51.62	52.59	54.50
TiO_2	1.40	0.69	1.11	0.65	0.43	0.37	1.06	0.93	1.04	0.61	0.66	0.84	0.64	0.56	0.46	0.87
Al_2O_3	20.55	16.52	14.29	15.95	14.62	16.69	14.74	18.84	16.47	19.62	19.16	19.30	19.98	18.17	19.59	17.75
Fe_2O_3	4.89	3.56	3.14	3.64	1.80	1.11	3.85	3.57	2.97	3.16	2.76	1.49	2.84	2.89	2.29	1.71
FeO	8.82	5.27	6.73	4.80	2.62	2.60	8.32	6.04	7.53	3.78	3.74	6.24	5.44	5.20	5.59	5.77
MnO	0.17	0.20	0.19	0.19	0.10	0.09	0.23	0.21	0.21	0.16	0.20	0.14	0.15	0.19	0.16	0.15
MgO	6.23	7.24	7.14	3.52	4.01	1.31	10.05	5.30	4.52	3.61	3.36	6.95	5.55	6.64	5.90	4.75
CaO	12.74	14.16	10.84	7.16	6.78	5.68	11.20	9.45	9.29	8.60	8.52	12.32	10.34	8.28	9.12	8.90
Na_2O	2.09	1.35	2.93	3.29	3.59	3.98	1.80	3.54	2.44	3.93	3.93	2.87	3.69	3.14	3.83	3.32
K_2O	0.20	1.77	0.30	0.39	0.49	0.07	0.19	0.43	0.72	0.34	0.33	0.32	0.47	0.70	0.50	0.56
H_2O^+	1.37	1.65	1.22	1.28	0.70	1.51	1.83	1.91	1.91	0.87	0.82	1.59	1.65	2.07	1.73	1.84
H_2O^-	0.24	0.35	0.27	0.09	0.09	0.13	-	-	0.25	-	-	-	0.08	-	-	-
P_2O_5	0.80	0.43	0.13	0.17	0.06	0.10	0.25	0.17	0.15	0.25	0.16	0.15	0.25	0.11	0.12	0.19
CO_2	-	0.33	-	0.05	-	-	-	-	0.36	-	-	-	-	-	-	-
TOTAL	99.39	99.40	99.30	99.58	100.13	99.51	101.24	101.43	99.24	99.93	100.30	101.22	100.15	99.57	101.88	100.31
	Trace elements (ppm)															
Ba	50	127	30	135	170	120	<30	93	70	185	85	155	69	375	115	220
Co	55	34	49	28	18	<10	78	37	60	28	21	37	38	35	35	33
Cr	26	255	200	60	55	100	800	<15	<15	<15	100	132	115	112	173	<15
Cu	<30	<30	<30	70	58	130	<30	60	69	<30	42	<30	600	60	105	68
Ga	<10	<10	<10	13	<10	54	<10	<10	31	<10	<10	<10	32	29	<10	<10
Ni	<15	106	60	58	126	18	153	28	35	45	<15	173	61	60	110	80
Rb	25	50	31	26	22	25	<10	10	10	12	40	11	35	38	<10	44
Sr	336	218	103	257	205	396	80	431	188	610	464	408	486	439	390	329
Y	<10	21	23	28	21	<10	39	19	17	10	21	<10	11	8	<10	20
Zn	104	100	80	75	47	<30	150	80	115	98	51	21	35	61	112	67
Zr	47	60	48	120	100	103	17	55	50	42	160	23	93	55	32	110
	C.I.P.W. Norms															
Q	-	-	1.61	16.90	22.85	27.09	-	0.46	7.01	7.43	9.62	-	-	1.87	-	6.18
or	1.18	10.46	1.77	2.30	2.90	0.41	1.12	2.54	4.25	2.01	1.95	1.89	2.78	4.14	2.95	3.31
ab	9.53	10.76	24.78	27.83	30.36	33.66	15.22	29.94	20.64	33.24	33.24	24.27	31.21	26.56	32.39	28.08
an	46.10	33.79	24.96	27.61	22.34	27.47	31.58	34.25	31.86	34.90	33.67	38.84	36.57	33.42	34.79	31.88
ne	4.41	0.36	-	-	-	-	-	-	-	-	-	-	-	-	-	-
di	9.68	25.27	22.59	5.27	8.70	0.04	18.01	9.34	9.03	4.93	6.09	17.27	10.59	5.57	7.83	9.00
hy	-	-	15.14	11.28	8.63	6.65	20.60	15.67	16.84	10.23	9.29	0.67	0.34	20.43	14.83	15.44
ol	15.27	8.54	-	-	-	-	4.70	-	-	-	-	12.59	11.02	-	2.88	-
mt	7.09	5.16	4.55	5.28	2.61	1.61	5.58	5.18	4.31	4.58	4.00	2.16	4.12	4.19	3.32	2.48
il	2.66	1.31	2.11	1.23	0.82	0.70	2.01	1.77	1.98	1.16	1.25	1.60	1.22	1.06	0.87	1.65
ap	1.90	1.02	0.31	0.40	0.14	0.24	0.59	0.40	0.36	0.59	0.38	0.36	0.59	0.26	0.28	0.45
cc	-	0.75	-	0.11	-	-	-	-	0.82	-	-	-	-	-	-	-

Foot Note to Table 2

XRF analyses distinguished from wet analyses by the absence of H_2O^- in the former. 177-369 banded amphibolites and associated gneisses from the southern belt; 347-351 *non-banded* amphibolites from the southern belt; 395-194 amphibolites of the Chilas complex. The presence of nepheline in two norms may reflect underestimation of SiO_2.

177 : Garnetiferous amphibolite, 1.7 km N of Jalkot, Indus valley (I.V.). 462 : Cpx-bearing amphibolite, Asrit, Swat, Kohistan, I.V. 4 : Amphibolite 6.5 km N of Khwaza Khela, Swat. 343 : Amphibolite 1 km S of Kayal, I.V., 352 : Gneiss with amphibolite bands, ½ km N of Kiru, I.V. 363 : Garnetiferous gneiss with amphibolite bands, 2 km NW of Kayal, I.V. 347 : Amphibolite, 3.5 km NE of Kayal. 220 : Amphibolite, 1 km SW of Richa, Kandia valley, 23 : Amphibolite, 3.5 km E of Kabal, Upper Swat. 363 : Amphibolite, 5 km NW of Kayal. 351 : Amphibolite, 2 km SW of Kiru. 395 : Amphibolite, 2 km N of Kedam, Swat. 8 : Amphibolite, ½ km N of Fatehpur, Swat. 301b : Amphibolite, 1 km S of Madyan, Swat. 407 : Amphibolite, 2 km N of Bahren, Swat. 194 : Amphibolite 20 km E of Chilas, I.V.

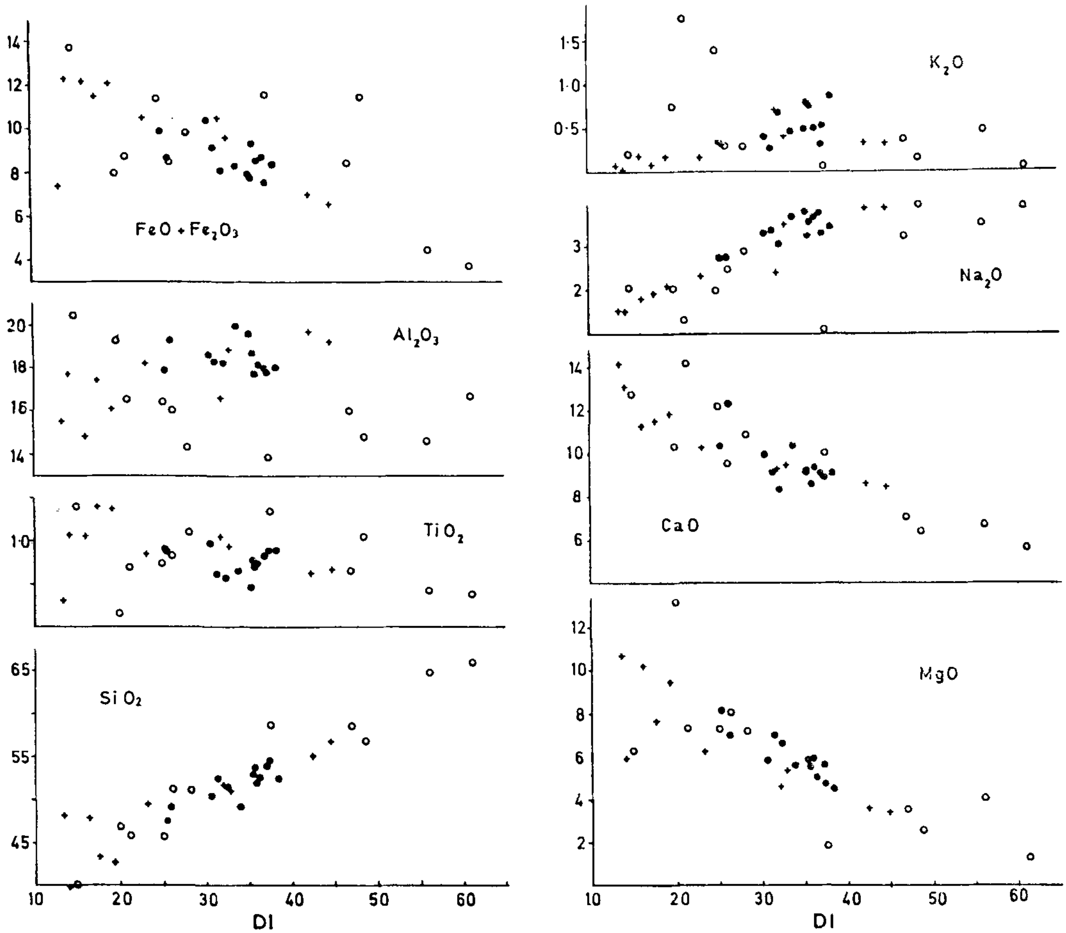

FIG. 2. Plot of oxide percentages against differentiation index of Thornton and Tuttle (1960). Crosses show non-banded and circles show banded amphibolites and associated rocks from the southern belt. Amphibolites associated with the Chilas complex are shown as dots. Note their restricted composition. These and subsequent plots include three analyses each from Jan and Kempe (1973), and Jan and Khattak (1983).

basic igneous rocks including tuffs; (b) appropriate mixtures of pelite, dolomite and limestone; (c) mixtures of sediments and tuffs, and (d) by metasomatic processes from sedimentary as well as igneous material. In the past, a banded structure and associated sediments were taken as evidence of a sedimentary origin of certain amphibolites (Poldervaart, 1953; Wilcox and Poldervaart, 1958; Walker *et al.*, 1960; Heier, 1962). Other workers, however, have shown that neither banding nor sedimentary association is conclusive evidence that the amphibolites themselves are metasedimentary. Banding can be produced by metamorphic and/or metasomatic segregation (Evans and Leake, 1960; Orville, 1969), shearing, or be a relict igneous/sedimentary feature.

Although amphibolites rich in Cr, Ni, Ti and having low Niggli k values can be derived only from igneous precursors (Leake, 1963), the absolute concentrations of elements may not be sufficient to distinguish their parentage. Leake (1963, 1964) strongly advocated comparing the variation trends of amphibolites with those of igneous and sedimentary rocks on diagrams based on Niggli (1954) values. Because some banded amphibolites from Kohistan were considered metasedimentary by Jan and Kempe (1973) and Chaudhry and Chaudhry (1974), an attempt was made to decipher geochemically their parentage. The 100 mg–c–(al–alk) and c *v.* mg plots of the amphibolites closely follow the igneous trend of Karroo dolerites, and on al–alk *v.* c diagram they fall

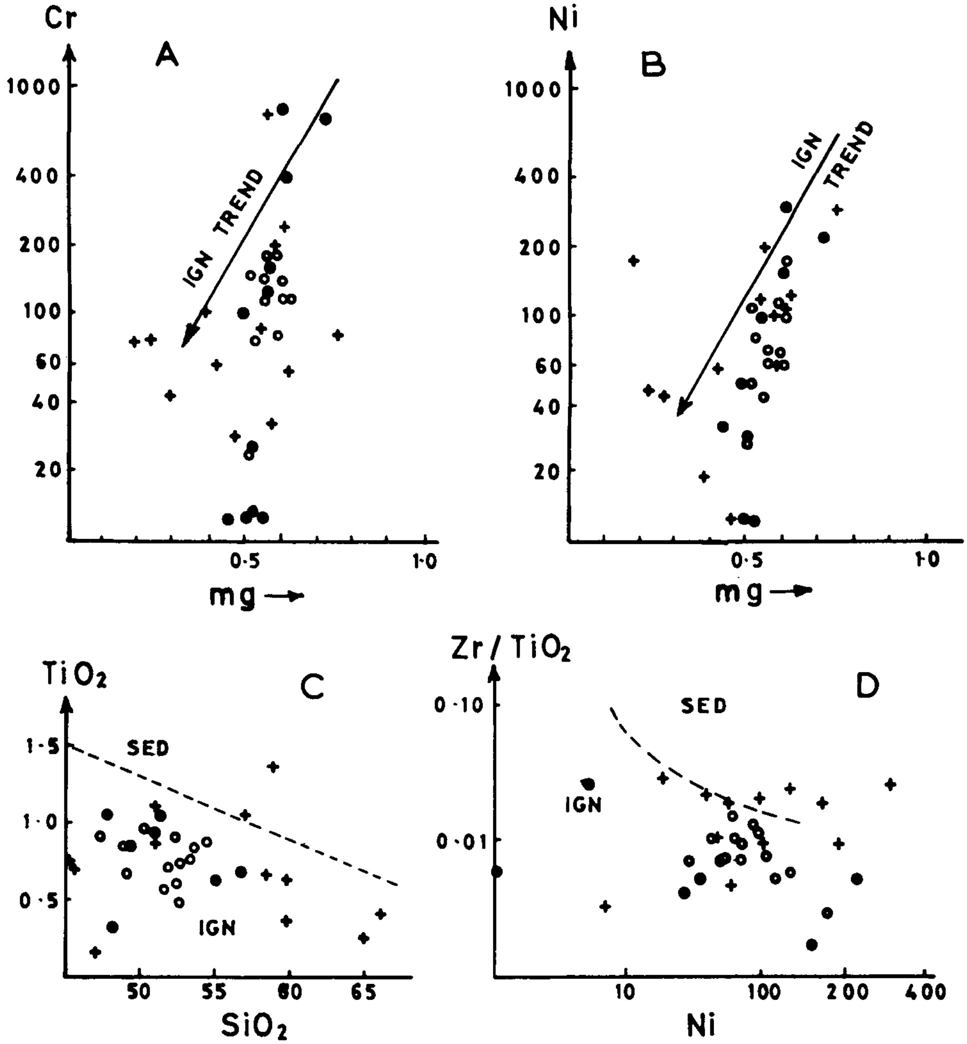

FIG. 3. Plots of Cr and Ni against Niggli mg, TiO_2 against SiO_2, and Zr/TiO_2 against Ni. Boundary between sedimentary and igneous fields in Fig. 3C is after Tarney (1977) and in Fig. 3D after Winchester and Max (1982). Crosses are for banded amphibolites and associated rocks, dots for non-banded amphibolites from the southern belt, and circles for non-banded amphibolites from the Chilas complex. Plots include two metasediments not plotted elsewhere.

within, or at the edge of, the field for Karroo dolerites (cf. Leake, 1964).

The Cr–mg, Ni–mg, TiO_2–SiO_2, and Zr/TiO_2–Ni relations of the rocks are shown in Fig. 3. A positive correlation between Cr, Ni and mg is a characteristic feature of igneous rocks, whereas mixtures of pelite and calcareous rocks produce almost perpendicular trends to those of igneous rocks (Leake, 1964; Van de Kamp, 1969). The Ni–mg relation of the rocks is akin to that of igneous rocks and although a positive correlation cannot be seen clearly in Cr and mg, the trend is certainly not indicative of sediments. On the TiO_2–SiO_2 diagram (Fig. 3C) of Tarney (1977), all but two analyses plot in the igneous field. In the Zr/TiO_2 *v.* Ni diagram (Fig. 3D); Winchester and Max, 1982) only four rocks classify as sedimentary: a banded amphibolite with low (possibly underestimated) TiO_2 (0.15%); a banded gneiss; an impure marble and a sedimentary rock containing 3.2% MnO. It is, therefore, concluded that the banded amphibolites are largely of igneous origin as no evidence of sedimentary parentage can be found even in the gneisses.

In addition to a relict feature, banding in the Kohistan amphibolites can be attributed to several factors. In many places, banded amphibolites have developed along shear zones in homogeneous amphibolites. Some 7 km north of Patan, pink orthoclase megacrysts in shear-banded amphibolites suggest the introduction of potash. Banding in some places may have resulted from metamorphic/metasomatic segregation. Along the Indus south of Jaglot, pillow lavas have been locally stretched so that their crusts and cores produce distinct banding. By analogy, some banding in the southern amphibolites may have formed in a similar way.

The possibility of thin volcanic flows or tuffs cannot be totally ruled out, but this would require bimodal/alternate volcanism of basaltic and soda-rhyolite/quartz latite composition now represented by amphibolites and plagiogranite. In Ladakh (Dietrich *et al.*, 1983) and Chalt (Ivanac *et al.*, 1956) minor acid volcanics are interbedded with basic and intermediate flows, but the acid flows are generally over a metre thick and thin-bedded sequences of such rocks have not been reported. Rare intrusive relationships suggest that the leucocratic bands and even larger bodies in some cases may represent plagiogranitic injections that might be partial melting products of the amphibolites during metamorphism.

Tectonic settings. The discriminant diagrams used in distinguishing the tectonic environments of igneous rocks are generally based on well-known volcanic examples. Their application to medium- and high-grade metamorphic rocks can, therefore, be challenged. High-grade metamorphism generally results in the depletion of rocks in Rb, K, Ba and, to a lesser extent, Sr, Th, U, Pb, Na, etc. (Sighinolfi and Gorgoni, 1978; Rollinson and Windley, 1980; Weaver and Tarney, 1981; Sheraton, 1984). Plots of the elements against Ti and Zr (considered as immobile) reveal a considerable scatter in K_2O, Rb, K/Rb, Ba, Sr, and Na; some scatter was also observed in Cr and Ni. In the absence of other means, however, the various discriminant diagrams were also applied to the amphibolites; fortunately, they yielded consistent results.

On Ba, TiO_2, Ni and Cr against FeO*/MgO diagrams of Miyashiro (1975) and Miyashiro and Shido (1975), the rocks fall mainly in the field of volcanics from island arcs and continental margins, but some lie in the overlapping field of arc lavas and abyssal tholeiites. The Y content of the Kohistan rocks is low and on Cr *v*. Y diagram (Fig. 4A, after Pearce, 1982) they classify, as expected, as arc basalts. A similar conclusion can be drawn from a Ti–Zr plot in Fig. 4B (cf. Pearce *et al.*, 1981). The Ti–Cr and Ti–Zr–Sr relations of the rocks (Fig. 4C,D) are akin to those of arc lavas (cf. Pearce, 1975; Pearce and Cann, 1973).

The TiO_2–MnO–P_2O_5 and FeO*–MgO–Al_2O_3 diagrams (Fig. 5A and B, respectively after Mullen, 1983, and Pearce *et al.*, 1977) can distinguish volcanic rocks in several tectonic settings. In Fig. 5A they plot predominantly as island arc tholeiites and calc–alkaline basalts. In Fig. 5B most analyses classify as island arc–continental margin rocks but some extend into the MORB field (possibly due to cumulate effects). These rocks have lower SiO_2 (51–56%) than those of the analyses used by Pearce *et al.* (1977) for construction of the diagram. Note also that the two analyses in the SC field have $SiO_2 > 58\%$.

Several diagrams were used to investigated the magmatic character of the rocks. Whilst the Chilas complex amphibolites have clearcut calc–alkaline character, the tholeiitic *v*. calc–alkaline affinity of the rocks from the southern belt poses some problems. On the Y *v*. FeO*/MgO diagram of Winchester and Max (1982), most rocks appear calc–alkaline but some plot in the tholeiite field (Fig. 6A). The FeO*/MgO against SiO_2 relations of the rocks (Fig. 6B, after Garcia, 1982) show that most follow the calc–alkaline trend of the Quaternary Mt. Hood volcanics but a few fall along the trend of Oman tholeiites. The MFA plots of the analyses, together with fields for tholeiitic and calc–alkaline rocks after Barker and Arth (1976), are shown in Fig. 7. With a few exceptions, the rocks are confined to the calc–alkaline field. The calc–alkaline characteristic is also suggested by a decrease in TiO_2 and FeO with differentiation (Miyashiro, 1975). It is therefore concluded that the southern amphibolite belt is derived from arc-related volcanic and plutonic rocks. Most of the 37 analyses display calc–alkaline characteristics, but the presence of arc or oceanic tholeiites cannot be unequivocally ruled out on the basis of the present data.

Discussion

There is a common consensus that the Indus–Zangbo Suture (IZS) represents the northern limit of the Indian plate (Gansser, 1980). The IZS is characterized by the association of ophiolitic mélanges and blueschists, and island arc-type magmatic rocks are abundant to the north in Kohistan and Ladakh. It has therefore been suggested that northward subduction of the neo-Tethyan lithosphere along the IZS led to the development of the Kohistan–Ladakh arc (Tahirkheli

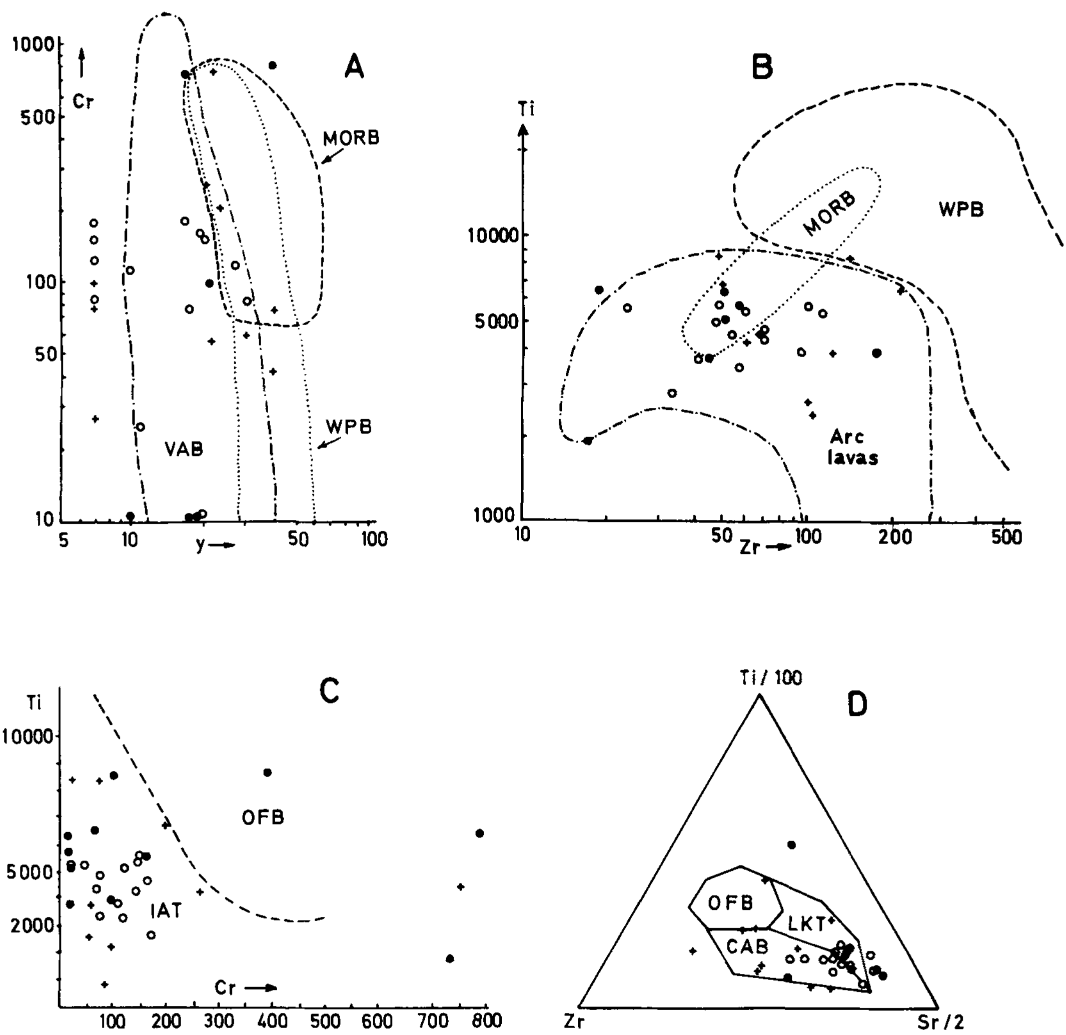

FIG. 4. Comparison of the Kohistan analyses with basalts in mid-ocean ridges (MORB), volcanic arcs (VAB), within plate (WPB), calc-alkaline basalts (CAB), island arc tholeiites (AT), and low-K tholeiites (LKT) on Cr–Y (Pearce, 1982), Ti–Zr (Pearce *et al.*, 1981), Ti–Cr (Pearce, 1975), and Ti–Zr–Sr (Pearce and Cann, 1973) diagrams. Symbols as in Fig. 3.

et al., 1979; Virdi, 1981; Andrews-Speed and Brookfield, 1982; Coward *et al.*, 1982, 1986; Honegger *et al.*, 1982, Jan and Asif, 1983; Thakur and Sharma, 1983; Jan, 1985; Petterson and Windley, 1985). Fossil evidence, radiometric dates and paleomagnetic data indicate that arc magmatism started in late Jurassic and continued during the Cretaceous, before the closure of the neo-Tethys during the Eocene (Powell, 1979; Dietrich *et al.*, 1983; Molnar, 1986). The post-Eocene plutons may be a product of crustal anatexis (Jan and Asif, 1983; Petterson and Windley, 1985).

The sequence of magmatism in island arcs generally begins with tholeiitic, followed by calc–alkaline and alkaline series (Jakes and White, 1970; Ringwood, 1974; Miyashiro, 1975; Condie, 1976; Windley, 1984). Sugimura (1968) reported that the tholeiitic series is by far the most abundant volumetrically. The oldest rocks are: in the Ladakh arc the Dras volcanics, many of which are tholeiitic (Dietrich *et al.*, 1983); and in the Kohistan arc the Chalt volcanics and the southern amphibolites. Although the latter are volcanic and plutonic, they may represent a metamor-

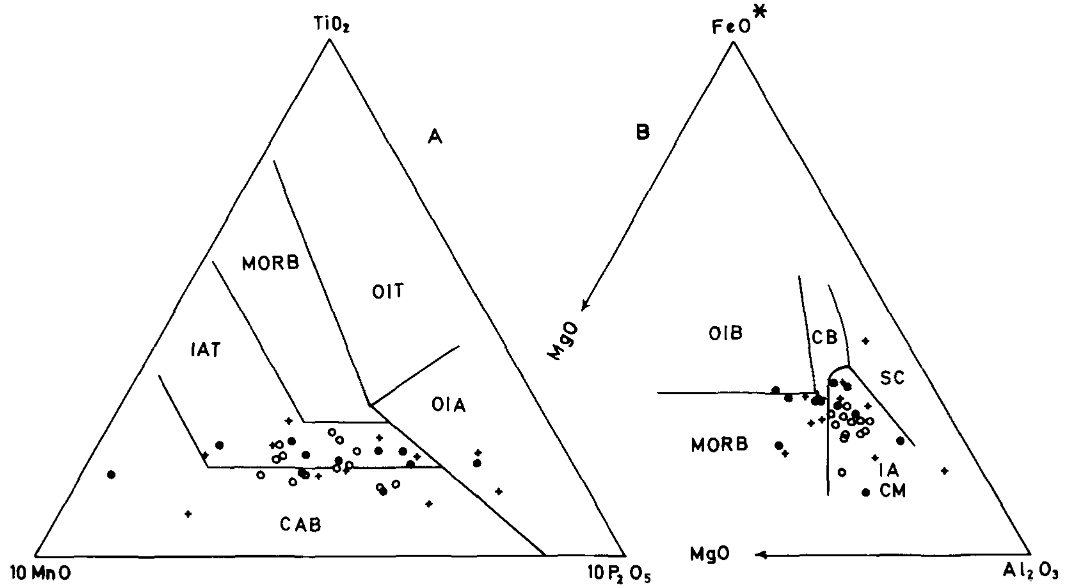

FIG. 5. Ti–Mn–P_2O_5 and FeO–MgO–Al_2O_3 plots of the Kohistan rocks on Mullen (1983) and Pearce *et al.* (1977) discrimination diagrams. OIA and OIT, oceanic island alkali basalts and tholeiites; OIB, oceanic island basalts; CB, *continental basalts*; SC, *spreading centres island*; IA, *island arc*; CM, *continental margin*; CAB, *calc–alkaline* basalts. Symbols as in Fig. 3.

phosed limb of the Chalt volcanics around the Jaglot syncline (Coward *et al.*, 1982). The Chalt volcanics consist of pillow-bearing, primitive island arc-type, tholeiitic lavas succeeded by calc–alkaline andesite to rhyolites (I.W. Luff, reported in Petterson and Windley, 1985).

A number of suggestions can be put forward to explain the apparent abundance of calc–alkaline over tholeiitic rocks. (1) The complex structure of the southern amphibolite belt has not been investigated in sufficient detail to explore the possibility that calc–alkaline rocks are younger than the rare tholeiitic rocks. (2) The calc–alkaline rocks may be related to the Chilas complex which is slightly younger than, and seemingly intrusive into, the southern amphibolites. (3) The chemistry of some southern amphibolites has drastically changed during polyphase deformation and medium- to high-grade metamorphism. This possibility is difficult to assess but partial melting may have affected the alkali content of the rocks.

Another problem with the southern amphibolite belt is the apparent lack of ophiolitic components, since the arc is presumed to have grown over ocean floor. There are some small ultramafic lenses within the southern belt that are petrographically and texturally similar to 'alpine-type' peridotites. However, typical oceanic sediments have not been found and the present study suggests a lack of the volcanic components as well. Presumably, much of the oceanic crust was uplifted as blocks in the repeated pulses of magma eruption, to subsequently be eroded away.

Metamorphic conditions in the southern belt seem to have ranged from 550 to 680 °C, 4.5 to 6.5 kbar P_{H_2O}. The southern and northern margins of the belt, in the vicinity of the Chilas complex and IZS, may have undergone higher grade metamorphism or the belt may be synclinically folded so that rocks of higher structural level (and lower T metamorphism) now occupy the middle part of the belt. Under the estimated metamorphic conditions, partial melting of the amphibolites would lead to production of granitic melts. The amphibolites are locally migmatized and they contain veins, sheets and bosses of granitic rocks. These have not been dated but most appear to be syntectonic, synmetamorphic. The plagiogranite components in the banded amphibolites may also have been produced during metamorphism.

Petterson and Windley noted that the $^{87}Sr/^{86}Sr$ initial ratios of five granitic plutons in the Kohistan batholith vary between 0.7039 and 0.7052, suggesting that the source of granitoides may be (a) the upper mantle, (b) the lower crust which is depleted in Rb and has a similar Rb/Sr ratio to the mantle, or (c) the middle–upper crust with

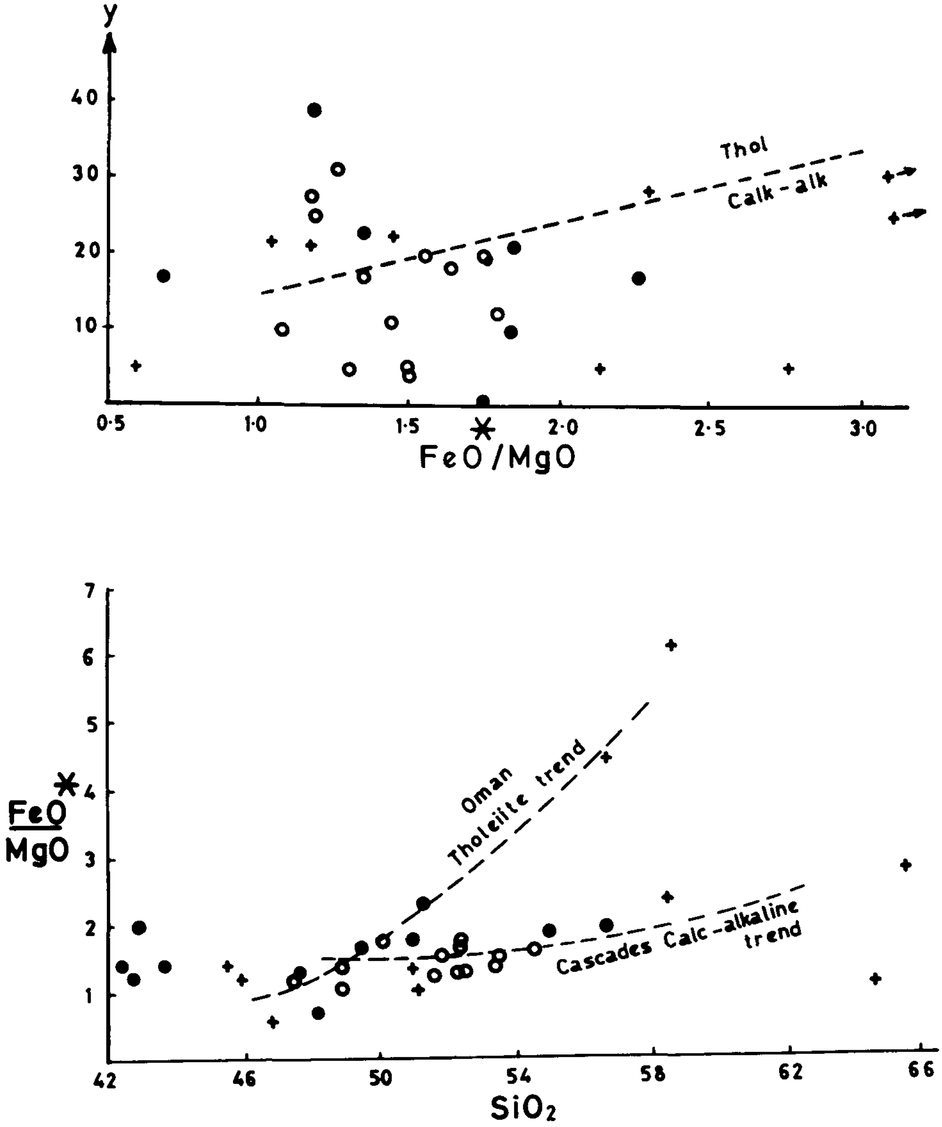

FIG. 6. Y *vs.* FeO*/MgO and FeO*/MgO *vs.* SiO_2 relations. Broken line separating tholeiitic and calc–alkaline fields in Fig. 6A is after Winchester and Max (1982). Oman tholeiite and Cascades (Mt. Hood volcanics) calc–alkaline trends are adopted from Garcia (1983). Symbols as in Fig. 3.

a low $^{87}Sr/^{86}Sr$ initial ratio and a short crustal residence time. Since the southern amphibolites represent the lower–middle crust of the Cretaceous arc, there is a possibility that some of the granitoids in the Kohistan batholith are derived from these rocks.

$^{40}Ar/^{39}Ar$ ages of hornblende in samples 177 and 462 are 50 and 42 Ma, respectively. It is doubtful that these ages record prograde metamorphism. Since the initial collision between the arc and Indian plate took place 55–50 Ma ago (Powell, 1979), the two dates reflect cooling and uplift. Jan and Kempe (1973) reported a 67 Ma K/Ar hornblende age for a secondary pegmatite in the Chilas complex. Zeitler (1985) has reported several fission track zircon ages (14 to 53 Ma) and an $^{40}Ar/^{39}Ar$ hornblende age (86 Ma) from the southern amphibolites and the adjoined Chilas

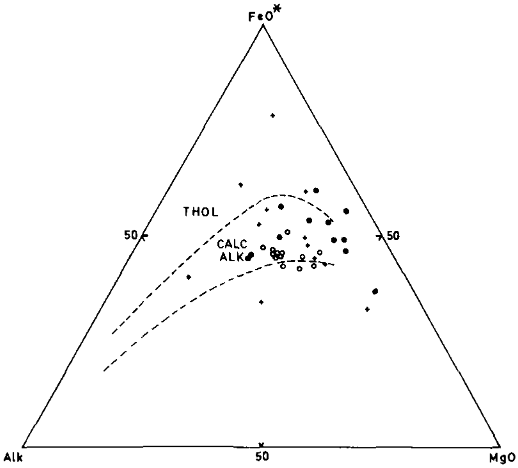

FIG. 7. MFA plot of the analyses. Boundaries between tholeiitic and calc–alkaline fields are after Barker and Arth (1976). Symbols as in Fig. 3. Plots also include two analyses from Shams (1975).

complex. He regards all these dates as cooling ages. Thus, metamorphism in the southern belt may have taken place during Mid Cretaceous in response to subduction and emplacement of the Chilas complex.

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