# Petrology of the Obducted Mafic and Ultramafic Metamorphites from the Southern part of the Kohistan Island Arc Sequence

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*Abstract*: The ~ 36,000 sq km Kohistan region is a well-defined tectonic zone with unusual lithology when compared to the neighbouring regions. It is occupied mostly by plutonic and volcanic igneous rocks ranging from ultramafic to silicic. A few authors have suggested that some or all of the Kohistan zone represents a fossil island arc. Based on over 250 rock and minerals analyses, mainly from Swat, a petrological account of the mafic and ultramafic rocks of Kohistan is presented below, together with comments on their tectonic environments, metamorphism, and the duration of the presumed island arc.

The basic rocks occur in two NE-trending belts of amphibolite and pyroxene granulite stretching from Nanga Parbat to eastern Afghanistan, and in the wedge-like tectonically-emplaced Jijal Complex ( ~ 200 sq km) which comprises garnet granulites and alpine ultramafics. It is suggested here that most of the southern amphibolites (and the overlying metasediments of the Kalam group) represent the Tethyan oceanic crust, and the alpine ultramafics the underlying upper mantle. The pyroxene granulites, some amphibolites and, probably, Jijal garnet granulites have been derived from a high alumina tholeiite (calc-alkaline) magma that was intruded into the oceanic crust during the early phases of arc-building.

## INTRODUCTION

The Kohistan region, designated by Desio (1964) as a tectonic zone, covers more than 36,000 sq km area on the NW tip of Himalaya. The northern boundary of the zone is marked by a major fault, known for many years and extending along Hini-Chalt-Drosh-Kunar. The southern part of the zone is occupied by metabasites which (in Swat) were considered by Martin *et al.* (1962) to be thrust-faulted against the Palaeozoic Lower Swat-Buner schistose group. Later discoveries of ultramafic and high-pressure metamorphic rocks along this fault led Jan (1977a) and Tahirkheli *et al.* (1979) to conclude that this fault is also an extension of the 'Indus Suture' which, according to Cansser (1974), marks the subduction of the Indian plate under the 'Asiatic mass'. Tahirkheli *et al.* named this fault as the main mantle thrust (MMT).

The upper Swat valley constituting the middle part of Kohistan zone is occupied, from S to N, by belts of amphibolites, pyroxene granulites, diorites, metasediments, calc-alkaline volcanics, and granitic-dioritic rocks. These belts stretch NE into Indus valley and SW into Dir; the intermediate rocks with some amphibolites, and volcanics being 'repeated' in Dir-Drosh section (see map in Tahirkheli and Jan, 1979). Along the Indus, the southern amphibolites are separated from rocks of the Indian plate by the wedge-like Jijal complex.

Compared to other parts of the Hindu Kush, Karakoram and Himalaya, the Kohistan tectonic zone is unique for its high proportion and thickness of basic and intermediate rocks. The similarity of these rocks with those of the calc-alkaline (tholeiitic) basalt-andesite series found in continental margin orogenic belts and island arcs was pointed out by Jan and Kempe (1973), Jan (1977a) and Majid (1977). More recently, Tahirkheli *et al.* (1979; see also Jan, 1977b) proposed that the entire Kohistan rock sequence represents a complete remnant of the crust of a fossil island arc, its northern and southern limits being marked by the two major thrusts (referred to above), beyond which occur the 'sialic' rocks of the 'Asian' and Indian plates, respectively. Powell (1979) and Talent and Mawson (1979) also suggest the existence of a fossil Island arc(s) but, apparently, they refer only to the northern volcanic zone of Kohistan.

Metamorphosed to varying degrees the basic rocks have a widespread occurrence in the Kohistan zone and make up at least 40% of the outcrops. Their principal occurrence, however, is in the medium- to high-grade metamorphic belts of southern Kohistan. These, the subject of this paper, constitute the NE-SW-stretching belts of amphibolites and pyroxene granulites, and the NW-SE-trending wedge called the Jijal complex (Fig. 1). An understanding of the petrology of these and other (meta-)igneous rocks of Kohistan is of fundamental importance in the interpretation of the tectonics of northern Pakistan — the junction of Hindukush-Garakoram-Himalaya. In this discussion, an at-

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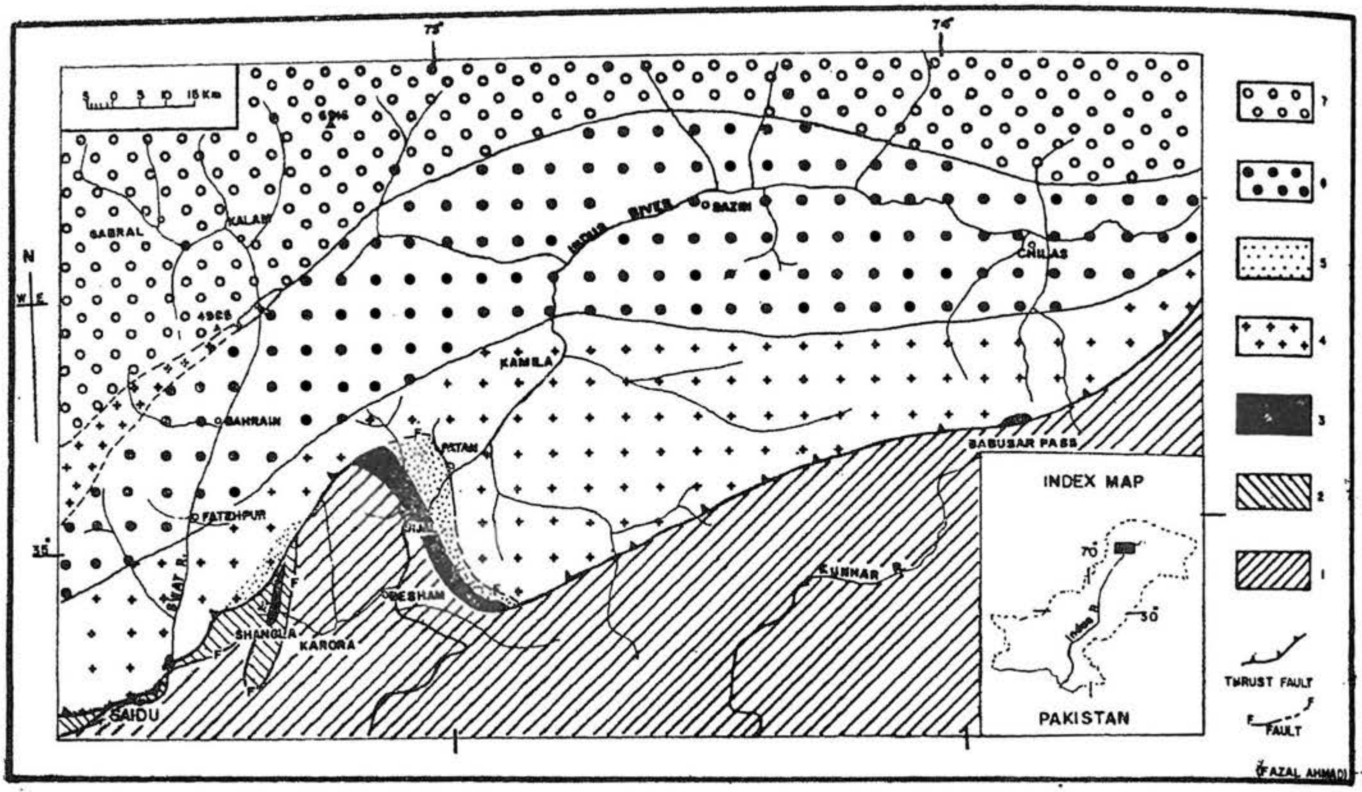


**Fig. 1.** Simplified geological map of south-central Kohistan zone.
(1) Palaeozoic to Precambrian metasediments and younger granites.
(2) Shangla-Kabal high-pressure metamorphic zone with blueschists.
(3) Alpine ultramafic rocks.
(4) Southern amphibolite belt. High-pressure garnetiferous 'amphibolites' around Lilaunai are dotted as 5.
(5) High-pressure Jijal garnet granulites.
(6) Pyroxene granulite-retrograde amphibolite belt.
(7) Intermediate to silicic plutonics, calc-alkaline volcanics, amphibolites, and metasediments.
Ages of 2-7 not known.

tempt is made to explain the basic rocks in the frame work of tectonics with the help of petrography and over 250 rock and mineral analyses (to be presented elsewhere). The intermediate plutonic, and volcanic rocks are being described by Majid and Paracha in a following paper of this volume.

## THE JIJAL COMPLEX

The Jijal Complex is a ~ 200 sq km, NW-trending tectonic wedge exposed along the Indus; much of it is comprised of garnet granulites whilst less voluminous alpine ultramafic rocks occupy its southern part. The complex is emplaced along the MMT which separates the Kohistan amphibolites from the Palaeozoic and older metasediments of the Indo-Pakistan plate. Structural, petrographic, and geochemical evidences suggest that the granulites and ultramafics are not comagmatic. There is a likelihood that the ultramafics were emplaced in the granulites as solid material capable of plastic flow, during or after the high-grade metamorphism but before the entire complex was tectonically carried into its present position.

### The Garnet Granulites

The granulites are characterised at most places by an abundance of garnet and can be classified into those with essential plagioclase (basic to intermediate in chemistry) and those with little or no plagioclase (ultrabasic to basic). The two types reflect differences in chemistry rather than in pressure: plagioclase disappeared more readily in the more basic, Na-poor rocks at pressures under which it was stable in the less basic rocks with higher Na. Out of 17 mineral assemblages identified, plagioclase + garnet + clinopyorxene/hornblene + rutile + quartz ± epidote is the most abundant. The plagioclase-free rocks are less abundant, found mostly in the southern part of the granulites, and are essentially composed of two or three of the mafic minerals; however, some are represented by garnetites, hornblende-rocks, and pyroxenites.

The basic granulites chemically resemble some volcanic as well as plutonic rocks; however, the intermediate members (with high Ca/(Na+K)) and the ultrabasic members do not have analogues in the com-

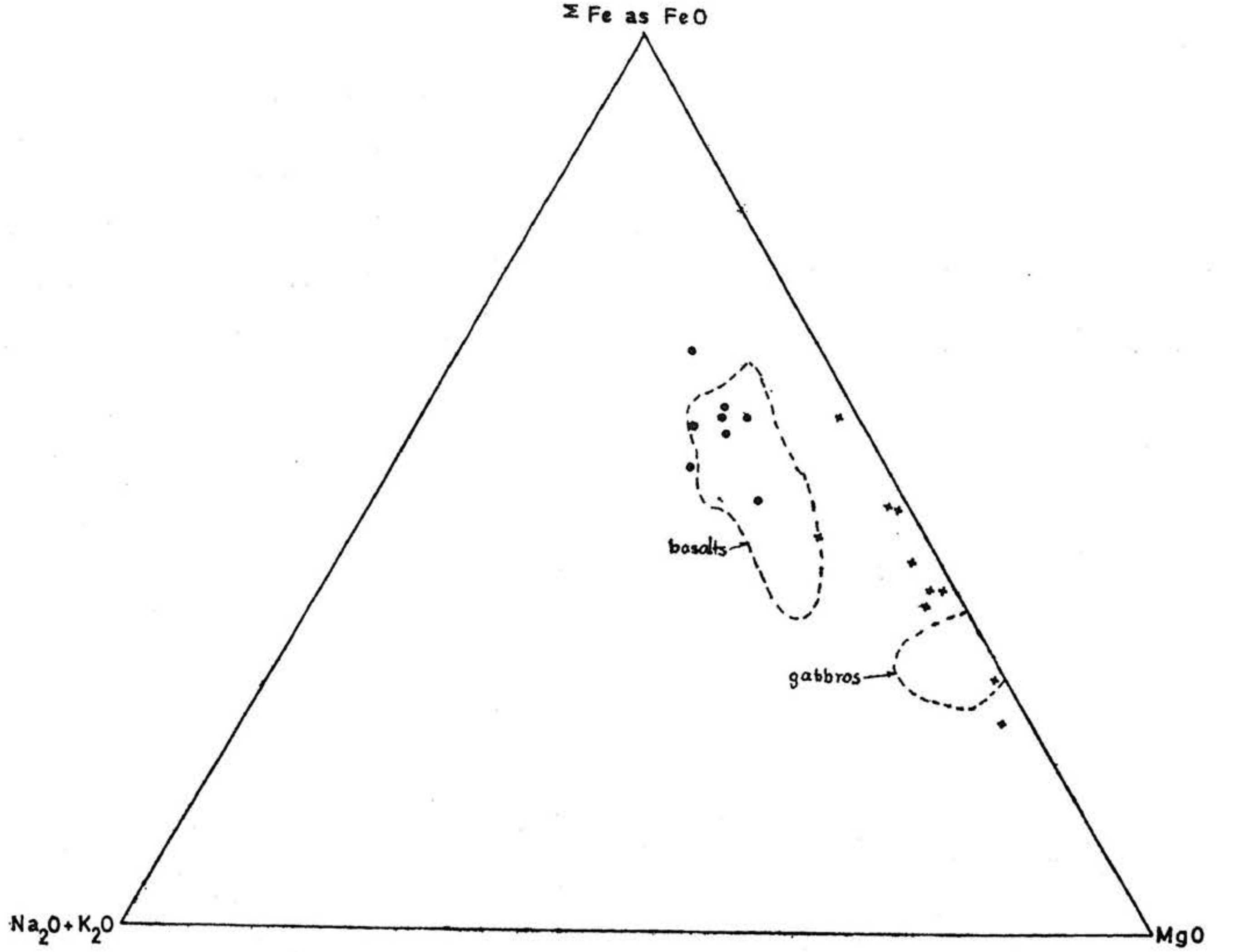


**Fig. 2.** MFA plots for the Jijal garnet granulites. Crosses: those with little or no plagioclase; dots: those with essential plagioclase. Supperimposed are the approximate fields of basalts and gabbros from ophiolitic and oceanic crustal rocks (from Coleman, 1971).

mon volcanic rocks. From this and field features it is concluded that the entire range of the Jijal granulites represents a metamorphosed differentiated mass of norites, with subordinate hypersthene-quartz diorites, olivine gabbros, troctolites, feldspathic allivalites, olivine anorthosites, and pyroxenites. The granulites are poor in $K_2O$ (up to 0.3%), Rb (generally $< 10$ p.p.m.), Ni ($<10$ to 80 p.p.m., except two analyses with 125 and 165 p.p.m.), and Cr (40 to 230 p.p.m., except a pyroxenite with 616 p.p.m.). Although some K, Rb (? and Na) may have been expelled to upper levels of the crust during metamorphism, the magma may well have been depleted in these elements to begin with. The high Na/K ratios of the granulites are closer to oceanic tholelites (Engel *et al.* 1965; Bryan *et al.,* 1976) than to other basalts and, generally, the feldspathic granulites plot in the field of oceanic basalts on MFA diagram (Fig. 2) of Coleman (1971).

These similarities, however, are not enough to suggest that the granulites are definitely oceanic in nature. They also show chemical differences with oceanic rocks: their basic members, which constitute most of the granulite terrain, have lower Mg and, especially Cr and Ni, and higher Sr and, especially, Ba than most oceanic basalts and gabbros. The normative composition of the basic members is noritic; that they have been derived from norites is further suggested by noritic relics, e.g., near Patan along the KK Highway. Since these relics are texturally and mineralogically very similar to the pyroxene granulites covering extensive areas to the north (see below), this raises the possibility that the parent rocks of the Jijal granulites may have been derived from the same high-alumina tholeiitic (calc-alkaline) magma which produced the parent rocks (norites) of the pyroxene granulites. Comparisons of the analyses of the basic and intermediate members from the two kinds of granulites show broader similarities; the main differences being in that the garnet granulites have lower K, Na, Rb, Sr, and higher Ca, total Fe, and much higher Ca/alk. These differences are reflected in the production of slightly diffrent trends on chemical variation diagrams for the two kinds of granulites; however, the differences are not significant to suggest that the two are definitely unrelated. Minor differences caused by local conditions in pools of magma bodies separated from the main magma body before or during early crystallisation are not unexpected. Besides, the more complex history of the Jijal garnet granulites might also have contributed to some of the differences.

The Jijal granulites have undergone polyphase metamorphism and deformation, the main events in their evolution are:

1. crystallisation of a layered complex of norites and related rocks in lower crust/upper mantle from a magma of high-alumina tholeiitic (calc-alkaline) or, less likely, oceanic tholetiitic nature,

2. metamorphism of this layered and differentiated complex in pyroxene granulite facies (~ 800°C, 7-8Kbar) as evidenced by relics of hypersthene and noritic granulites; this metamorphism might have been achieved after the rocks had passed through greenschist and amphibolite facies conditions,

3. subduction of the complex to more than 40 km pressures, causing the formation of high-pressure garnet granulites. Detailed geochemical and mineralogical studies (Jan and Howie, in preparation) suggest that temperature and pressure conditions of this metamorphic event were 670°-770°C, 12-14 Kbar, suggesting a geothermal gradient of 18°/km.
Steps 2 and 3 represent the principal phases of metamorphism,

4. obduction of the complex: subsequent amphibolite facies metamorphism seen as local patches and veins of amphibolites, local development of paragonite, alteration of garnet and pyroxene along fractures and development of secondary amphibole and clinozoisite,

5. further obduction to upper levels causing widespread alteration of plagioclase to zoisite (saussuritisation), chloritisation, epidotisation and amphibolitisation of, locally, large masses of rocks, and the production of veins with greenschist facies assemblages.

## The Ultramafic Rocks

These are mostly represented by diopsidites; peridotites, dunites, and websterites together make less than 50% of the outcrops. However, further field and petrographic work is needed before a final assessment of the relative abundances of the rocks is made. Ashraf (personal communication), for example, has found a higher proportion of peridotites and subordinate pyroxenites in the southeastward extension of the rocks beyond the Indus. Also in the Duber stream peridotites are not as infrequent as along the neighbouring Indus gorge. Texture and petrography suggest that the rocks are alpine-type. The mole % Mg/(Mg+Fe*+Mn) and $Al_2O_3$ contents of the rocks, and the compositions of their clinopyroxene ( $Mg_{49.5\text{-}48}$ $Fe_{2.8\text{-}6}$ ) and olivine ( $Fo_{92}$—$Fo_{89}$ ) are similar to those of the harzburgite sub-type ultramafic complexes of Jackson and Thayer (1972). The rocks are depleted in alkalis and alumina and are not capable of producing basaltic magmas on partial melting. Chromite is their common accessary whereas plagioclase and garnet have not been found. Their present mineralogy is suggestive of equilibration in granulite facies conditions (800°-850°C, 8-12 Kbar; thermal gradient 26°C/km.

The abundance of diopsidites is in marked contrast to other alpine ultramafic complexes where olivine-rich rocks are the most abundant. It is tempting to connect magmatically the ultramafics with the associated garnet granulite of the Jijal complex and with the pyroxene granulites of Kohistan found to the north. However, the distinct chemical and mineralogical differences, especially in the pyroxenite members from the three rock-types (Jan, 1977a), and structural considerations raise serious objections to such an interpretation. The occurrence of secondary diopsidite veins and bands in the peridotites raises the possibility that the abundance of diopsidites may be due to Ca and Si metasomatism during or before the granulite facies metamorphism. However, the averages for the minor and trace elements of the Jijal ultramafics are very similar to those of peridotite (Table 1). The significant departure in the Ni values of the Jijal rocks is a reflection of a lower quantity of olivine in the analysed rocks.

TABLE 1. COMPARISON OF MINOR ELEMENTS OF JIJAL ULTRAMAFICS WITH THOSE OF AVERAGE ULTRAMAFIC ROCK

| | Mn | Al | Na | K | Co | Cu | Sr | Cr | Ni | Rb | Ga | Y | Zn | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jijal Averages | 1085 | 7230 | 1172 | 191 | 87 | 44 | 17 | 2808 | 680 | < 10 | < 10 | < 10 | 31 | 155 |
| Average Ultramafic | 1040 | 10000 | 1040 | 200 | 110 | 30 | 20 | 2400 | 1500 | 1.0 | 5 | 5 | 30 | 170 |

Average values for Zn and P are from Vinogradov (1962), others from Goles (1967). All values are in p.p.m. Jijal averages based on 10 analyses

It is yet to be decided whether the Jijal ultramafics represent a faulted suboceanic crust/upper mantle slab, a mantle diapir emplaced into deep orogenic roots (possibly depleted harzburgite in either case), or a dismembered ultramafic suite differentiated from some basaltic magma. The P–T estimates for the rocks suggest an oceanic or suboceanic rather than a continental geothermal regime. Like most other alpine peridotites (Wyllie, 1967, 1969; Den Tex, 1969) they also have a complex history. One of the earlier events in their evolution is possibly recorded by the closure of their pyroxenes to the redistribution of Cr at temperatures greater than 1100°C (as deduced from Cr geothermometry). Amongst the latest events is their low grade and selective 'metasomatism' (development of serpentine, talc, tremolite, carbonate) which may be contemporaneous with the obduction of the Jijal complex and later episodes.

## THE AMPHIBOLITES

Amphibolites cover vast areas in Swat and the adjacent districts, but their principal occurrence is in an elongated belt ( > 300 km long and up to 45 km wide) extending from Nanga Parbat to eastern Afghanistan. Amphibolites are also common in a slightly less extensive belt of the pyroxene granulites which borders the amphibolite belt in the north. The two types have distinct characteristics.

### Amphibolites of the Pyroxene Granulite Belt

The amphibolites occur in small to large masses intimately associated with the pyroxene granulites and make over a fourth of the belt. The two types of rocks are very similar in chemistry and there is a possibility that the two are recrystallized norites at similar temperature and pressure and at the same time, the availability of water having played a major role in producing hornblende instead of pyroxene. Buddington (1963) has advocated such an origin for the Adirondack granulites and amphibolites. However, petrography and geothermometry suggest that the amphibolites, especially abundant along the southern margin of the granulite belt, are retrograde products of the granulites, mainly due to an influx of water probably during the obduction of the latter (Jan, in press, 1980; Bard *et al.*, this volume). This interpretation is consistent with the observation that whilst most of the retrograde amphibolites belong to the amphibolite facies, some are representatives of the greenschist facies.

### Amphibolites of the Southern Belt

The rocks of the southern amphibolite belt can be broadly classified into (1) medium to fine-grained non-homogeneous (banded, striped, streaky), and (2) homogeneous types; both types are gneissose and the former make > 1/3 of the belt. Modal studies from various parts of the belt show that the rocks range from mela-amphibolites to leuco-hornblende gneisses. The amphibolite members are essentially composed of hornblende and plagioclase and/or epidote, but a variety of other minerals is sporadically present. T–P estimates for these rocks suggest metamorphism between, generally, 570° and 680°C at 4 to 6 Kbar, suggesting a thermal gradient of 37°C/km. In the vicinity of Lilaunai, N of Shangla, the amphibolites have local horizons modally approaching the garnet granulites of the Jijal complex. Also, in general, garnet is more abundant in this area than anywhere else in the amphibolite belt. Immediately to the south of this area is the Shangla-Kabal high-presure metamorphic zone with blueschists and separated from the amphibolites by a N-dipping thrust. Thus the amphibolites in Lilaunai area probably have undergone a higher pressure metamorphism than elsewhere in the belt.

The non-homogeneous rocks, because of their banded aspect and rare association of metasedimentary rocks, were earlier classified as para-amphibolites. Chemical analyses of the amphibolites range from 'ultrabasic' to intermediate, whilst the leucogneisses are intermediate to acidic. Niggli-type variation diagrams (Leake, 1964), their discriminant functions for trace elements (Shaw and Kudo, 1965), low K and, in some cases, high Cr and Ni suggest their derivation from igneous material, mainly tuffs and some flows (Jan, 1977a). The local presence of rocks of undoubted metasedimentary origin (calc-silicate rocks, marbles, and quartzites — metamorphosed cherts and radiolarites) may, however, suggest local contamination of the tuffs by sedimentary material.

The homogeneous amphibolites, medium- to coarse-grained, have plutonic igneous aspects and appear to have intruded the banded rocks before the amphibolite facies metamorphism. They are classifiable into two types (Fig. 3): a) those derived from an earlier phase of tholeiitic plutonic rocks showing Fe-enriched differentiation trend on FMA diagram (Fig. 4), and b) those derived from noritic rocks and showing calc-alkaline trend. Detailed mapping of the various kinds of amphibolites in the southern belt may, thus, pose serious problems and too many chemical analyses may be needed. In addition to the derivation of homogeneous rocks from two different magma series, the banded rocks also pose problems of their own. Whilst most banding appears to be inherited from original compositional heterogeneity, some is produced by metamorphic/metasmatic differentiation, or shearing. A good example of the latter is seen in the north of Patan along the highway where lenses of noritic granulite pass into amphibolite which, in turn, has been changed into banded type along shear zones.

The origin of the noritic pyroxene granulite lenses is also debatable. These rocks may represent masses of

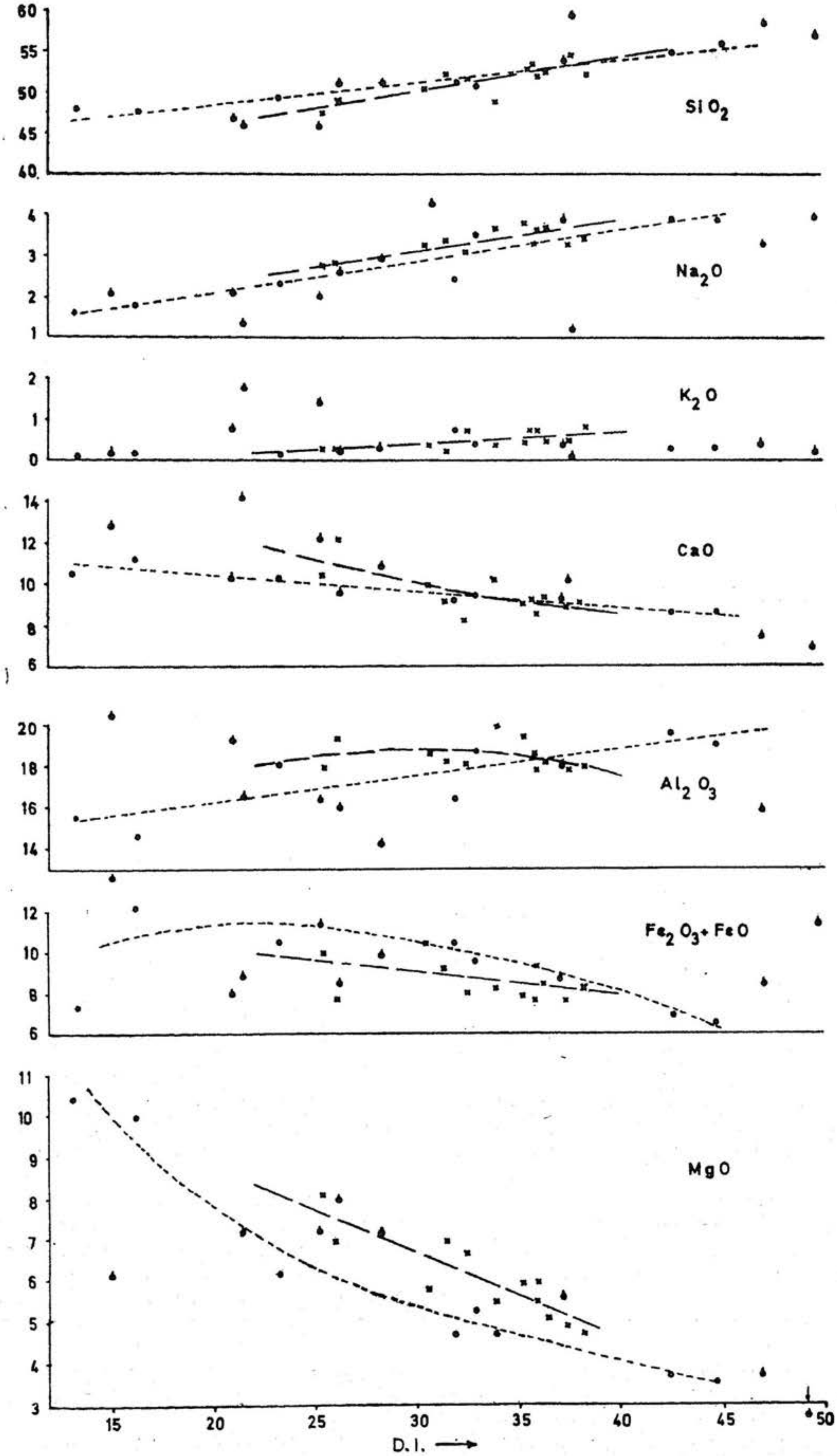


**Fig. 3.** Plot of oxide percentages against D.I. of Thornton and Tuttle (1960) for the amphibolites. Crosses: amphibolites derived from calc-alkaline plutonics (pyroxene granulites; circles: amphibolites derived from tholeiitic plutonics; ticked circles: banded amphibolites derived from tuffs and some flows. Note the difference in variation of calc-alkaline (broken lines) and tholeiitic (dashed lines) amphibolites.

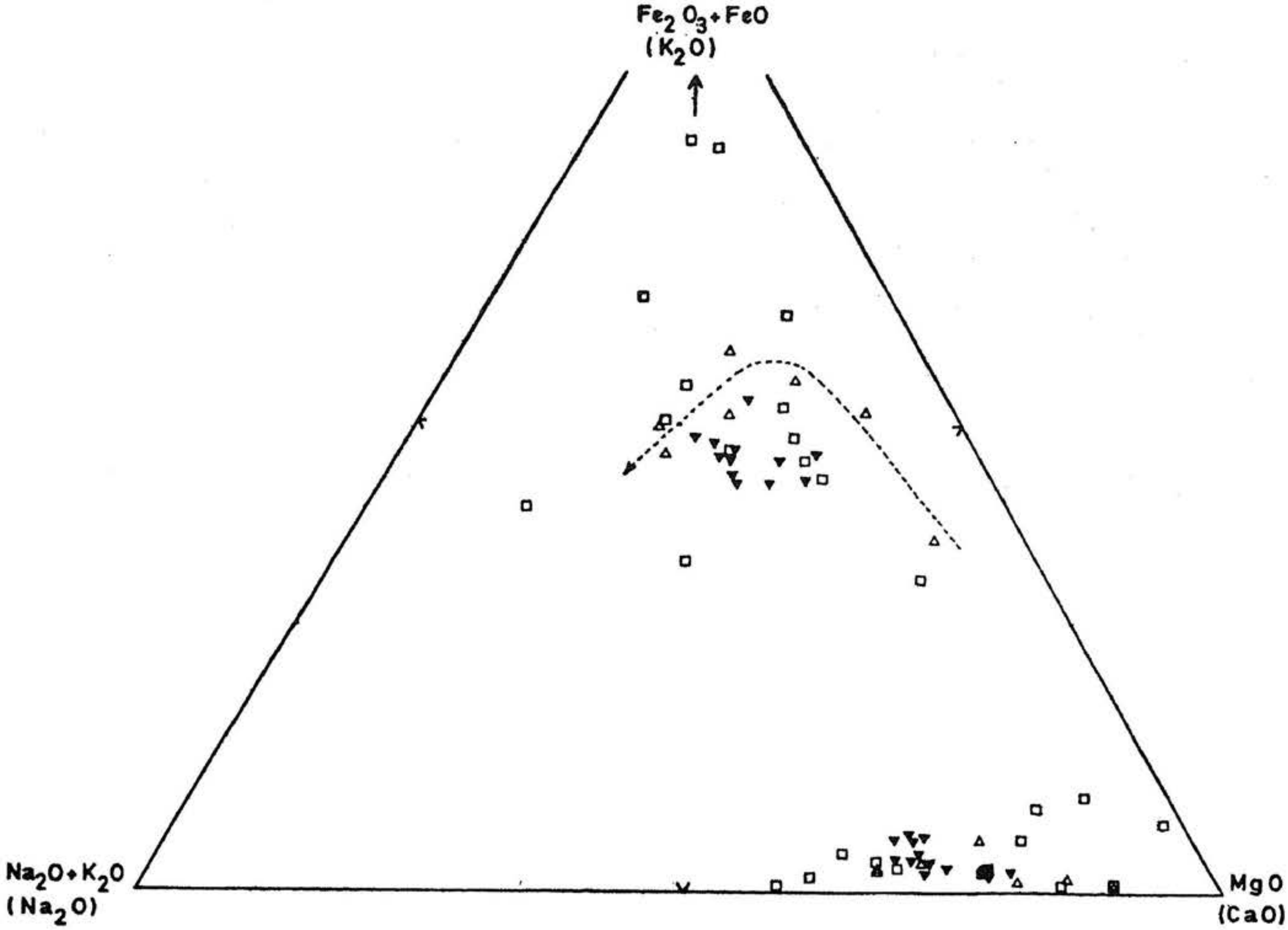


**Fig. 4.** MFA and Ca-alk plots for the amphibolites. Solid triangles: retrograde amphibolites associated with pyroxene granulites. Open triangles: southern belt amphibolites derived from tholeiitic intrusions. Open squares: Banded amphibolites. Arrowed curve shows the Fe-enriched differentiation trend for the amphibolites produced from tholeiitic intrusive rocks.

norite magma intruded before metamorphism; during the amphibolite facies conditions they were converted to anhydrous pyroxene granulites (Bard, personal communication) and, marginally where water was available, into amphibolites. No detailed mineralogical studies have yet been carried out on these lenses but their general petrographic features are identical to the noritic rocks of the pyroxene granulite belt found to the north and for which much higher T–P estimates have been deduced (see below). Thus the possibility should not be ruled out that the noritic (pyroxene granulite) lenses in the amphibolites are remobilised masses of granulites from depth before the amphibolite facies metamorphism converted them marginally into amphibolites.

On alumina *vs* alkali diagram (Kuno, 1967) the amphibolites of the southern belt straddle the fields of tholeiites and high-alumina basalts, whereas on silica *vs* alkali diagram, such as the one used by Macdonald and Katsura (1964) for the Hawaiian rocks, they plot in the field of tholeiites. Thus it appears that the parent material of the amphibolites of the southern belt, setting aside those derived from noritic (calc-alkaline) rocks, was of tholeiitic basalt affinity. Because of the scattered plots of the banded rocks (Figs. 3 and 4) it cannot be concluded whether or not they are comagmatic with the plutonic rocks that intruded them. The banded amphibolites, with some pillow lavas towards the top, and the homogeneous rocks with Fe-enriched trend probably represent oceanic layers 2 and 3. These rocks are separated from the rocks of the Indian plate by the main mantle thrust. However, in the Shangla-Kabal area, the two are separated by an association of greenschists, graphitic schists, prasanitic schists (meta-tuffs and agglomerates), piemontite schists, calcareous and phyllitic rocks, blueschists (both metaigneous and metasedimentary), talc and tremolite schists, serpentinised harzburgites, metagabbros and local dolerites. This association, especially the blueschists-ultramafics, resembles similar associations found in subduction-obduction zones.

## THE PYROXENE GRANULITES

The pyroxene granulites constitute up to 37 km broad belt extending from Nanga Parbat to south central Dir. Most of the rocks in the belt are represented by feldspathic 'norites' and are essentially composed of plagioclase, ortho- and clinopyroxene, with small amounts of quartz, opaque minerals, biotite, hornblende, and apatite. The amount of quartz increases in the intermediate members which may also contain K-feldspar. Garnet has not been found except in some rocks to the N of Seo, and in a few veins and pegmatites. The rocks are layered/banded, many of the layers being noritic but some are anorthositic or pyroxenitic; large bodies of dunitic and troctolitic differentiates occur around Chilas in the Indus valley. The rocks display features typical of layered complexes, e.g., rhythmic layering, graded and current bedding; Bard *et al.* (this volume) consider the rocks to have constituted a lopolith. Earlier investigators considered them to be igneous but Jan (1977a) suggested that many of their petrographic and mineralogic characteristics can be better explained if they are regarded to be meta-igneous. Arguments in favour of a metamorphic overprint include :

Presence of metamorphic textures, including annealing; gneissose structure, in some places characterised by lens-shaped grains or clusters of grains; abrupt grain-size variations in some alternate bands; short lateral extent of layers (setting aside the large ultramafic zones) in contrast to stratiform complexes where even the thin layers may persist for long distances (Jackson, 1967; Wager and Brown, 1968); veins of generally coarse-grained anorthosite, pyroxenite, and hornblende pegmatites; antiperthitic and perthitic feld-

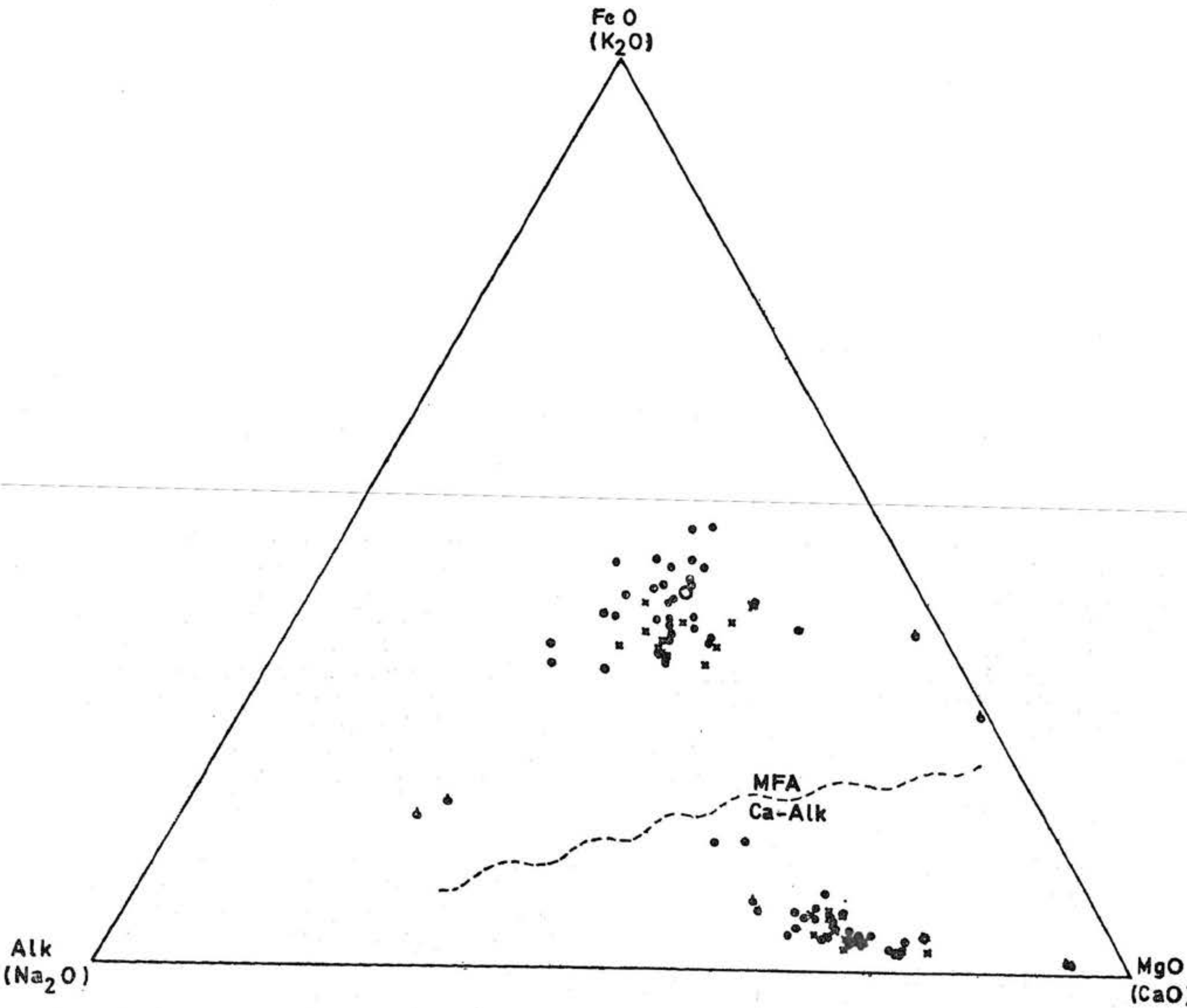


**Fig. 5.** MFA and Ca-alk plots for 49 analyses of pyroxene granulites (dots) and associated retrograde amphibolites (crosses). Also plotted are anorthosite and pyroxenite members (ticked dots) and average basic granulite (large circle). The MFA trend is apparently calc-alkaline.

**TABLE 2.** COMPARISON OF AVERAGE SWAT GRANULITE WITH OTHER SIMILAR ROCKS

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $SiO_2$ | 51.1 | 51.7 | 51.45 | 52.43 |
| $TiO_2$ | 0.83 | 1.0 | 0.34 | 0.90 |
| $Al_2O_3$ | 16.1 | 16.9 | 18.67 | 18.60 |
| $Fe_2O_3$ | 11.8* | 11.6* | 0.28 } 10.33 | 2.16 } 9.5* |
| FeO | — | — | 9.04 | 6.59 |
| MnO | — | — | 0.47 | 0.17 |
| MgO | 5.1 | 6.5 | 6.84 | 5.80 |
| CaO | 10.8 | 11.0 | 10.95 | 9.53 |
| $Na_2O$ | 1.96 | 3.1 | 1.58 x | 3.18 |
| K O | 0.40 | 0.40 | 0.14 ** | .46 |
| $P_2O_5$ | — | — | — | 0.18 |
| | | | | 100.00 |
| Cr | 50 | 40 | — | 85 |
| Ni | 25 | 25 | — | 49 |
| Co | 20 | 50 | — | 34 |
| Rb | 5 | 10 | — | 16 |
| Sr | 225 | 330 | — | 360 |
| Ba | 50 | 115 | — | 117 |
| Zr | 60 | 100 | — | 62 |
| Cu | — | — | — | 97 |
| Ga | — | — | — | 15 |
| Y | — | — | — | 10 |
| Zn | — | — | — | 76 |
| $Na_2O/K_2O$ | 4.9 | 7.75 | 7.21 | 6.91 |
| K/Ba | 66 | 30 | — | 33 |
| K/Rb | 660 | 344 | — | 239 |
| Rb/Sr | 0.022 | 0.029 | — | 0.044 |

1. Average Arc tholeiite (Low–K) } From Condie, 1976, p. 148.
2. Average high-Al tholeiite }
3. Fine-grained marginal group of Bushveld (Dely, 1928, p. 727, No. 129).
   x Considered to be 0.25 low, ** considered to be 0.10 low (Hess, 1960, p. 152).
4. Average Swat granulite (22 analyses of unaltered rocks with $\leq$ 54.0% $SiO_2$. Average may not be be meaningful because of the cumulus nature and complex history of the rocks. Recalculated to 100% on $H_2O$-free basis.

* Total Fe as $Fe_2O_3$

spar and relatively simple twinning in plagioclase; closer similarity of their pyroxenes and amphiboles with those from other high-grade metamorphic complexes; low $K_D$ Mg-Fe (0.57) of their pyroxenes (Jan and Howie, 1980); and the metamorphic nature of the small bodies intruding the noritic rocks. The compositions of their pyroxenes and their $K_D$ Mg-Fe, and the anorthite content of their plagioclase (generally $An_{43}$ to An[illegible]) show narrow ranges. The relatively narrow range in plagioclase composition in anorthosite complexes may indicate a narrow range of $P_L$ or $P_{H_2O}$ and/or close approximation to chemical equilibrium during slow crystallisation (Buddington, 1969; Yoder, 1969; Crosby, 1972). On the basis of these considerations and eight different methods of geothermometry, Jan and Howie (1980) suggest that the rocks were recrystallised uniformly at about 800°C and 7 to 8 Kbar (geothermal gradient 32°/km). However, the possibility of a slightly lower metamorphic grade in the Thak-Chilas areas cannot be ruled out (Proust, personal communication).

Large masses of amphibolites, pelitic, and calcareous rocks are found in the granulites but they do not display granulite-grade metamorphism. This means that either the granulites are allogenic (remobilised) in nature (cf. Thayer and Jackson, 1972), or that the other (lower grade) rocks are downfolded masses or fault-bounded slabs representative of upper levels. Jan (1977b) suggested large-scale remobilisation of the entire belt of granulites, however, this phenomenon may only be of local scale. Some of the 're-intruded' ultramafic bodies in Dir, Swat, Indus, and Thak valleys may be presented as examples.

Considering the immence volume of the rocks and the minor local variations in their chemistry, there may have been intrusions of several batches of magma that were chemically similar and genetically related. The Thak valley rocks (Shams, 1975) show some departures from the rest, as do the coarse-grained rocks of the Madyan-Fatehpur area in Swat; the latter have a restricted composition and higher silica. The rocks to the north of Parao, upper Swat, contain higher $TiO_2$, $P_2O_5$ and distinctly higher $K_2O$ than the rest of the granulites and may represent another mass of basic to intermediate granulites.

The non-ultramafic members of the pyroxene granulites are basic to intermediate in chemistry; no charnockites have so far been found in the belt. Jan and Kempe (1973) suggested that the Swat basic and intermediate rocks represent the plutonic equivalent of (calc-alkaline) tholeiitic basalt-andesite series found in orogenic belts. The noritic rocks of Thak valley were also regarded to be tholeiitic (Shams, 1975). Plots of 49 analyses of the granulites and their retrograde amphibolites on MFA diagram (Fig. 5) do not display an Fe-enrichment trend; their trend is apparently calc-alkaline which, incidently is also followed by the oceanic plutonic suite (Thayer, 1969). Comparison of the Swat granulite analyses with other basic rocks suggests their similarity with arc tholeiites and, especially, high-alumina tholeiites. But the cumulate nature of the rocks, high-grade metamorphism and complex history, and lack of analyses from chilled margins, if they exist, might render the comparison of limited use. Table 2 shows the similarity of average basic granulite of Swat with high-alumina tholeiite, but also with the chilled, fine-grained marginal group of Bushveld (Daly, 1928) except for the low alkalis in the latter. It is concluded that the granulites are metamorphosed norites and related rocks of a layered 'lopolithic' sequence which crystallised from an andesitic basalt magma of island arc or continental margin affinity. Their clinopyroxene is chemically similar to those form island arcs (Jan and Howie, 1980).

Where then was the site of crystallization of this magma ? An answer to this problem is of fundamental importance since this magma produced not only the parent rocks of the pyroxene granulites and some of the amphibolites, but possibly also the Jijal garnet granulites. At least three possible answers can be given to the above question. A) The norites may have constituted the lower layer of a continental plate margin that was subducted under the Tethyan oceanic crust, metamorphosed, and emplaced tectonically and/or by remobilisation in the oceanic crust (i.e., the southern amphibolites). B) The norite analyses are not truely representative and the rocks may be the plutonic equivalents of oceanic ridge basalts and may originally have crystallised as the bottom layer of the oceanic crust below the amphibolites. In this case remobilisation or faulting may have also occurred since they overlie most of the amphibolites. C) The magma, like the later calc-alkaline magma(s) that produced the diorites and volcanics of Kohistan (Jan, 1977b; Majid, 1977; Majid and Paracha, this volume), was a product of partial melting of the subducted oceanic lithosphere, causing the formation, in embryonic stage, of the assumed island arc. Each of these possibilities has its own merits and demerits but more arguments can be given in favour of the last possibility. Perhaps the answer lies in isotope studies and determination of the age of crystallisation of norites.

## SUMMARY AND DISCUSSION

The ~ 36,000 sq. km Kohistan tectonic zone is principally occupied by basic to intermediate (meta-) igneous rocks, dominantly plutonic in nature. Other rocks of Kohistan include granites, metasediments, acidic volcanics (independent or, more often, associated with more basic volcanics), and ultramafic rocks. The volcanics, represented by basalt and andesite-rhyolite type of (?) calc-alkaline association, are found in the northern part of Kohistan (Greenstone complex, Chalt Fm., Yasin Group, and Utror volcanics). This, probably, led Powell (1979) and Talent and Mawson (1979) to suggest the existence of fossil island arc(s) constituting northern Kohistan. Jan and Kempe (1973), Jan (1977a), Majid (1977), and Majid and Paracha (this volume), however, suggested that the basic and intermediate plutonic rocks found to the south of the volcanic belts also bear similarities with calc-alkaline rocks typical of island arcs and continental margins. Thus the likelihood exists, as suggested by Tahirkheli *et al.* (1979; see also Jan, 1977b), that the entire Kohistan zone represents the crust and mantle of a complete island arc.

The noritic pyroxene granulites and the intermediate plutonic rocks, together making the most voluminous rocks of Kohistan, are difficult to explain otherwise. It is preposterous to suggest that these rocks, together with the amphibolites, represent an oceanic crust. Apart from the calc-alkaline chemistry of the granulites and diorites, the entire association will constitute an abnormally thick oceanic sequence with no near equivalent. In the following, a summary and discussion of what has been stated in the previous pages is presented to illustrate these and some other points.

The principal occurrences of the basic rocks in the southern half of the Kohistan zone are in two NE-trending belts of amphibolites and pyroxene granulites which cover vast areas and stretch between Nanga Parbat and Afghanistan. Basic rocks are also abundant in the wedge-like Jijal complex of garnet granulites and alpine ultramafics, covering ~ 200 sq. km area and tectonically emplaced in the north of the MMT.

The Jijal ultramafics belong to the harzburgite subtype complexes of Jackson and Thayer (1972) and represent granulite facies metamorphosed upper mantle material plastically emplaced in the garnet granulites. The latter are meta-norites and related rocks that differentiated from a high-alumina tholeiitic (probably calc-alkaline) magma emplaced at the base of the Tethyan oceanic crust (i.e., amphibolites). Showing polyphase metamorphism and deformation the parent rocks of the garnet granulites were metamorphosed in pyroxene granulite facies, followed by subduction to a depth of more than 40 km to be metamorphosed to high-P garnet granulites. The dominant plagioclase+clinopyroxene+garnet+rutile+quartz assemblage and the high density (3.1 – 3.5) of the rocks indicate metamorphism at great depth. Later events of obduction in these granulites are recorded in the local presence of amphibolite and greenschist facies retrograde assemblages.

Rocks of the amphibolite belt are classifiable into banded and homogeneous types. The banded rocks are derived principally from tuffs and some lavas, whilst the homogeneous amphibolites are derived from plutonics intruded in the banded rocks before metamorphism to amphibolites. The homogeneous rocks can further be classified into those produced from an earlier (? oceanic) tholeiitic suite showing Fe-enriched variation trend, and a later calc-alkaline suite.

The banded amphibolites with some meta-pillows towards the top and ultramafics (mantle diapirs as well as ultramafic differentiates) towards the bottom, and the tholeiitic homogeneous amphibolites seem to represent oceanic layers 2 and 3. (Layer 1 sediments might be the meta-cherts/radiolarites and their associated minor amphibolites, meta-shales and calcareous rocks of the Kalam group). However, the amphibolites display some differences with classical oceanic crust (see also Bard *et al.,* this volume). Their apparent thickness (upto 15 km) is also abnormal for oceanic layers 2 and 3. But polyphase deformation (Jan, 1979), (?)isoclinal folding, and the production (by shearing and metamorphism) of banded rocks from the homogeneous types may be contributing to their apparent thickness.

The amphibolites locally display syntectonic remobilisation/partial melting and contain hornblende migmatites as well as granitic veins, sills, and dykes (Jan and Kempe, 1973; Jan 1979; Bard *et al.,* this volume). They would, thus, appear to be the source rocks for at least some of the younger diorites, volcanics, and granites of Kohistan. The conclusions of Jan (1977a), Majid (1977), and Majid and Paracha (this volume) that the Kalam diorites (and volcanics) are partial melting products of the subducted oceanic lithosphere are in harmony with this idea.

The calc-alkaline homogeneous amphibolites are metamorphosed noritic rocks produced from the same magma that crystallised into (now metamorphosed) norites and related rocks constituting the pyroxene granulite 'lopolithic' belt. Considerable amphibolitisation, again in amphibolite- as well as greenschist facies, also took place during the obduction of these granulites.

Deciphering the tectonic environments of the magma of the pyroxene granulites is of fundamental importance to understanding the geology of Kohistan. Because, as stated, not only the pyroxene granulites but a substantial quantity of the amphibolites and, probably, the Jijal garnet granulites also are derived from this magma. There also is the possibility that at least some diorites (? and volcanics) may be its differentiation products (Jan and Kempe, 1973). The chemistry of the granulites is quite unlike oceanic rocks and the suggestion is repeated that their magma was of high-alumina tholeiitic (calc-alkaline) affinity typical of island arc/continental margin environments. This magma was probably intruded into the Tethyan oceanic crust (now amphibolites) during the embryonic stages of arc-building. However, other possibilities discussed in this paper merit attention.

The study of the basic rocks thus favours the idea that the Kohistan zone may be the crust of an island arc with its metasediments, amphibolites and alpine-ultramafics representing the Tethyan oceanic crust and upper mantle. The island arc may have taken about 65 m.y. from infancy to maturity and decline. It is now considered that the Iranian, Afghan, and some other Asian blocks represent microcontinents that separated from Gondwanaland and drifted ahead of the Indo-Pakistan plate (Powell, 1979). Thus the arc building must have started after these blocks had drifted to the north of the would-be arc axis. It also appears that the first magma that contributed in producing an embryonic arc could not have been much older than late Early Cretaceous (~ 120 m.y.b.p.). The Indo-Pakistan plate in present-day N. Pakistan was in contact with the Eurasian plate before 55 m.y.b.p. (Powell, 1979), which suggests the closure of the Tethys and a rapid decline or end of the arc. This age coincides with the age of the youngest volcanic rocks of Kohistan (the Paleocene-Early Eocene Utror Volcanics). Post-Early Eocene volcanics or sediments that could have formed in oceanic or arc environments are unknown in the Kohistan zone although younger granitic and quartz dioritic rocks have been found.

Assuming then that the Kohistan zone is a fossil island arc, certain pertinent questions still need answering: the much higher proportion of plutonic rocks compared to volcanics; the rather thicker and to some extent unusual underlying oceanic crust; and the composition and distribution of its sediments when compared to most present day arcs (c.f. Windley, 1977). However, not enough details are available yet on the sediments, structure, geomorphology and erosion to reach final conclusions. We might be looking for prematurely for final answers to a very complex area; much more work is certainly needed.

K/Ar ages on hornblendes from the pyroxene granulites and a hornblende pegmatite from Swat valley fall in the Late Cretaceous (65 to 79 m.a.). These dates are interpreted as marking the final episodes (?obduction) of high-grade metamorphism, and are close to those deduced for the principal phase of subduction/obduction when blueschists were produced 70 to 80 m.y.b.p. (Bard *et al.* this volume; Shams, this volume). The post-Paleocene metamorphism in Kohistan was generally in the greenschist facies, as suggested by the metamorphic mineral assemblages in volcanic and sedimentary rocks extending from Kalam to northwestern Dir, and by the nicely preserved details in the Early Tertiary fossils in these rocks (Khan, 1972).

The southern part of Kohistan appears to be occupied by 'paired' metmorphic belts. A high-P 'belt' can be defined as consisting of the Jijal garnet granulites (T=670° to 770°C, P=12-14 Kbar; geothermal gradient ~ 18°C/km), the garnetiferous 'amphibolites' near Lilauni (approaching towards Jijal parageneses), and the Shangla-Kabal blueschist zone (of different lithology from the other two). Occurrence of piemen-tite schists (similar to those near Shangla) in Bajaur (Jan, unpub. data) and blueschists in Dir (Butt *et al.*, this volume) suggests that the high-pressure blueschist 'belt' may extend for long distances parallel to the amphibolite belt. Metamorphism in basic rocks to the north of this high-P 'belt' is of the intermediate-P facies: amphibolites having recrystallised generally between 570° and 670°C at 4 to 6 Kbar (geothermal gradient 37°C/km) and pyroxene granulites at ~ 800°C, 7-8 Kbar (geoth. grad. 32°C/km). The occurrence of amphibolites in the south, west, north and east of the pyroxene granulite belt might suggest the existence of an elongated 'thermal dome' with axis passing along the length of the pyroxene granulite belt.

It is thus concluded that the entire drama of basic igneous rocks and their metamorphism, and the intermediate rocks and at least some granites has a close connection with the Cretaceous and Early Tertiary northwards drift of the Indo-Pakistan plate, subduction of the leading oceanic lithosphere, creation of much of the Kohistan zone and its obduction. The geochemistry of the rocks suggests that most of the southern belt amphibolites, the overlying sediments, and the alpine ultramafics represent Tethyan oceanic crust and upper mantle. The high-alumina tholeiitic/calc-alkaline granulites, diorites, and volcanics may represent the crust of an island arc.

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