AN ABSTRACT OF THE THESIS OF

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Robert D. Lawrence

Two major faults, the Kohistan and Kishora thrusts separate the study area into three different tectonic terranes; the Indian shelf, Garai melange, and Kohistan terranes. Stratigraphy, deformation, and metamorphism within each of these terranes developed independently until they were juxtaposed by motion on these faults. An important aspect of the study area is that it records younger Swat deformation phases of the Himalayan orogen.

The Indian shelf is composed of Kashala and Saidu formations of the Alpurai group and underlain by the Chakdara granite gneiss. Three deformation phases (D_1, D_2, D_3) are recorded, during which fabrics S_1, S_2, and S_3 developed in association with folds F_1, F_2, and F_3. S_1 is preserved as relicts in the porphyroblasts, pressure shadows, and as intrafolial folds in the S_2 fabric. S_2 is defined by the orientation of platy or elongated minerals and axial planes of preserved F_1 and F_2 folds. Garnet, ferroan pargasite, and calcite porphyroblasts grew during and just after the formation of S_2. Earlier F_1 folds are locally preserved. F_1 are associated with movement on the Kishora thrust. F_2 folds are strongly developed and

strike NNE and SSW. These are tight to isoclinal folds on both large and small scales. Small scale folds are parasitic to large regional folds. One of the large scale F_2 has folded the Kashala and Saidu formations. The Saidu formation occupies the synclines of these large F_2 folds. F_2 folds are associated with southeastward thrusting of the Kohistan thrust. F_3 folds strike NNW and NS. F_3 folds may probably associated with the Kohistan thrust during the development of the Indus syntaxis. These are small scale upright folds and oblique to the main foliation. The axial planes to F_3 folds, S_3, locally involve a new crenulation cleavage and create the only major lineation in the rocks. Microscopic features indicate that the development of S_1 and S_2 took place synchronously with a progressive metamorphism that reached amphibolite facies. This was followed by a retrograde recrystallization in which garnet was altered to chlorite, amphibole to biotite, and biotite to chlorite.

The Garai melange is characterized by exotic blocks of talc-carbonate, serpentine, limestone, marble, and greenstone in a matrix of greenschist, metavolcanic rocks, graphitic phyllite and non-graphitic phyllite. They are faulted onto and into the Indian shelf sediments. The blocks and the matrix record different deformation events. Apparently the blocks preserve pre-emplacement structures, while the matrix reflects only emplacement in and deformation of the suture zone. Two deformation phases are recorded in the blocks. During D_1, the foliation developed by calcite growth. During D_2, the S_1 foliation was folded. S_1 occurs as relicts in S_2 foliation. This deformation occurred during greenschist facies conditions. The matrix is complexly deformed.

Three phases of deformation are recorded. D_1 of the matrix produced a locally preserved foliation during growth of the greenschist facies minerals chlorite, albite, and muscovite. During D_2, the main S_2 was formed with the development of feldspar porphyroblasts and F_2 folds. During D_3, S_2 was folded with the development of minor crenulation cleavage, S_3. These phases occurred during greenschist facies conditions.

The Kohistan terrane suffered two deformation phases. During D_1, S_1 and F_1 developed under amphibolite facies conditions. This deformation appears to have occurred before the Kohistan arc was associated with the other rocks of the area. It was followed by retrograde recrystallization in which amphibole altered to chlorite and high temperature plagioclase to a lower temperature plagioclase. It was accompanied by a minor deformation, D_2.

Structure and Metamorphism of the Chakdara Area Northwest of Swat River, Pakistan

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DEDICATED TO MY LOVING DAUGHTER ZIRKA AHMAD AND LATE NEPHEW AZAZ AHMAD

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STRUCTURE AND METAMORPHISM OF THE CHAKDARA AREA NORTHWEST OF SWAT RIVER, PAKISTAN

INTRODUCTION

Lower Swat is located in the hinterland of the Pakistani fold and thrust belt on west side of the Nanga Parbat-Haramosh massif and Hazara-Kashmir syntaxial bend (Figure 1). This area is composed of complex Precambrian to Mesozoic shelf and platform metasedimentary rocks, including pelitic, psammitic, calcareous, and graphitic lithologies (Martin and others, 1962; Calkins and others, 1975; Ashraf and Chaudry, 1980). A series of intrusive granitoid bodies occurs in this hinterland; they range in age from late Precambrian (?) to Tertiary. These rocks were affected by polyphase metamorphism and deformation throughout the Himalaya (Gansser, 1964; Ghazanfar and others, 1983; Shams, 1983; Coward and others, 1982; Kazmi and others, 1984; Rosenberg, 1985; Ahmad, 1986; DiPietro and Lawrence, in press). In the south, the area is bounded by a series of north dipping thrust faults of the Hill Ranges, equivalent to the Main Boundry thrust (MBT) of lesser Himalayas (Tahirkheli, 1979; Jan, 1979; Bard and others, 1980; Yeats and Lawrence, 1984) (Figure 1).

The study area west and north of the Swat River near Chakdara and Garai village is important to the study of collision tectonics in the Himalayas. It is located at a major suture zone (the Main Mantle thrust) that separates the Indian plate from the Kohistan arc sequence. Previous work in this area was done before plate tectonic

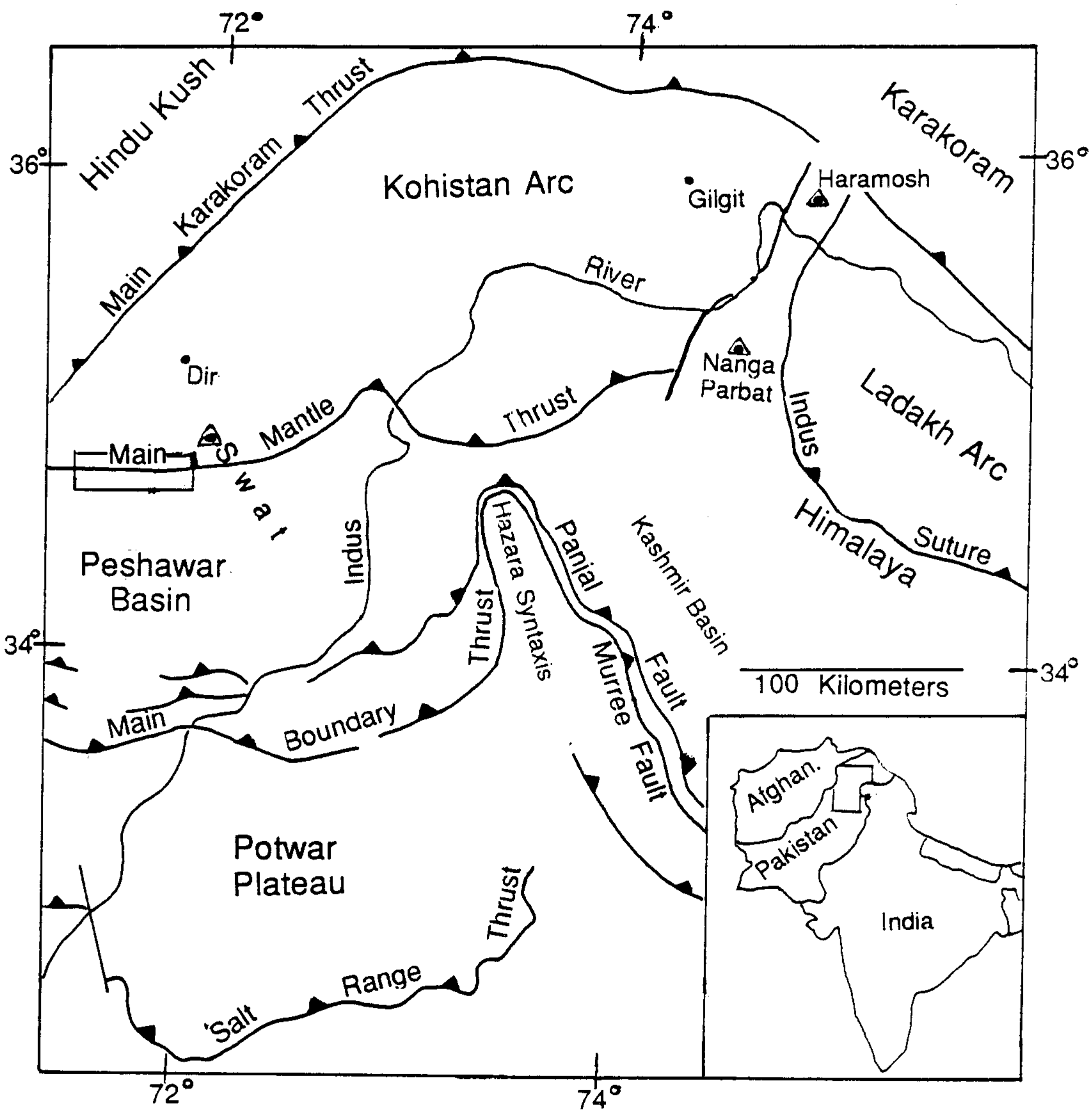

Figure 1. Tectonic map of northern Pakistan. Box surrounding the location of the geologic map Plate 1, modified from DiPietro (1990).

concepts were developed and involved only small scale mapping. Near Ladakh, east of the study area (Figure 1), more than 500 km crustal shortening has been reported in the shelf and platform sediments of the Indo-Pakistan plate based on preliminary balanced cross sections (Searle and others, 1987). In contrast, crustal shortening in the lower Swat area is smaller, 300 km (Lawrence, pers. comm., 1990; Lillie and Lawrence, 1989), and no structure equivalent to the Main Central thrust (MCT) is recognized west of the Nanga Parbat massif (Yeats and Lawrence, 1984). Hence, these rocks may document more clearly the earlier stages of the tectonic evolution of the Himalayan orogen prior to the development of the MCT. Detailed mapping, structural study and petrographic analysis are needed for a more complete understanding of the different tectonic episodes related to the collision. This thesis will: (1) describe the stratigraphy and petrography of the shelf and platform sediments of the Indian plate, (2) describe the structures of the suture zone in the area, (3) describe the rocks of the Kohistan arc adjacent to the suture zone, and (4) detail the structural, metamorphic, and deformational history of the area through analysis of mesoscopic and petrofabric elements.

REGIONAL GEOLOGY OF THE SWAT AREA

Structurally, the Swat area is composed of three tectonostratigraphic terranes (Kazmi and others, 1986; Lawrence and others, 1989). From south to north, these are: (1) the shelf and platform sediments of the Indo-Pakistan plate; (2) the Indus suture melange group (Kazmi and others, 1984); and (3) the Kohistan arc sequence (Jan, 1977,1980; Tahirkheli and others, 1979; Bard, 1983).

The shelf and platform sediments are generally pelitic, calcareous, graphitic, and psammitic in nature and were deposited on the northern margin of Gondwanaland before and after its Permo-Triassic breakup. These rocks range in age from late Precambrian to early Mesozoic. The older parts of the section have been intruded by early Paleozoic granitic plutons (LeFort and others, 1980; Ashraf and Chaudry, 1980; Butt, 1980,1983). In the Swat area, the stratigraphy of these rocks has been reinterpreted by many workers since the reconnaissance work by Martin and others (1962). Kazmi and others (1984) subdivided the lower Swat-Buner schistose group of Martin and others (1962) into the Swat granite gneisses, Manglaur schist, Alpurai schist, Saidu schist, and the Indus melange group. They distinguished three different types of sediments in the lower Swat-Buner area, which are: (a) twice metamorphosed crystalline schists (Manglaur) probably of Precambrian age, (b) once metamorphosed shelf sediments of probable Paleozoic age (Alpurai), and (c) once metamorphosed possible Indus flysh equivalents (Saidu). According to this new interpretation, the Swat granite gneisses intrude into the Manglaur schist, and both are unconformably overlain by the Alpurai schist unit. Palmer-Rosenberg (1985), Ahmad (1986) and Ahmad and others (1987) found that the tourmaline granite gneisses intrude the lower part of the Alpurai schist and, therefore, questioned the existence of an unconformity. The Alpurai schist unit has been further subdivided by DiPietro and Lawrence (in press) into four distinct members. (a) The Marghazar member occurs at the base and consists of a variable sequence of alkali feldspar-bearing psammitic schists, phlogopite-bearing-calc-schists, garnetiferous pelitic schists, and quartz-hornblende. The amphibolite horizon of Martin and others (1962) occurs at the top of the Marghazar. (b) The Kashala member overlies the Marghazar member and consists principally of garnetiferous calc-schists, calc-phyllites and marble. (c) Most of the overlying Saidu member is made up of graphitic phyllites. (d) The Nikani Ghar member is a thick sequence of marbles and dolomitic marbles. It is stratigraphically equivalent to the Saidu member (Ahmad and others, 1988). The Alpurai formation can be traced southward into fossiliferous strata near Baroch (Pogue and Hussain, 1988). Lawrence and others (1985) reported a large overturned orthogneiss nappe in the rocks of the lower Swat-Buner region. Rosenberg and others (1985) suggested three different phases of deformation (D1, D2, D3) in the rocks south of the MMT. More recently, rocks of the lower Swat have been found to have undergone multiple deformation with at least four periods of folding (DiPietro and Lawrence in press). Early F_1, F_2, F_3 folds trend north to north-northwest and verge west, whereas youngest F_4 folds trend east-west and verge southward.

South of the MMT, the lower Swat sequence contains granites of various ages from Precambrian (?) to Tertiary. The Swat granitic gneisses made up of several separately named plutons, intrude the Manglaur formation. The Choga granite occurs east of lower Alpurai village east of Shangla Pass (Martin and others, 1962). The Loe Sar granite is south of Manglaur, and the Illum granite is south of Mingora (Palmer-Rosenberg, 1985; Ahmad, 1986). These granites are referred as the Swat gneisses (Lawrence and others, 1989). Ages of these granites are uncertain. Most workers consider the Swat gneisses to be contemporaneous with the Mansehra granites and gneisses of Hazara, Pakistan. Le Fort and others (1980) reported a late Cambrian whole rock Rb/Sr date of 516 $\pm$16 Ma for the Mansehra granite. The Mansehra granite intrudes Precambrian siliceous schists of staurolite to sillimanite grade called the Tanawal Formation (Calkins and others, 1975). These schists resemble the Manglaur schist. If this correlation and the Rb/Sr dates are correct, the Manglaur schist is Precambrian and the Swat gneisses intruded it in the early Paleozoic.

In addition to Swat gneisses, younger tourmaline granite gneisses and biotite granite-granodiorites occur. Tourmaline granite gneisses intrude the sequence principally along the unconformity below the Alpurai group. Based on synmetamorphic intrusive relations with the Kashala, these granites are considered to be Paleogene in age (Ahmad, 1986; DiPietro, 1990). An $^{40}Ar/^{39}Ar$ muscovite date of 23 Ma for the Malakand granite is reported by Maluski and Matte (1984). Southeast of the Swat River, K-Ar dates determined on biotites from the Loe Shilman and Silai

Patti carbonatites yielded 31 ± 2 Ma (Le Bas and others, 1987). Near Baroch, biotite granites of the Ambela complex intrude the Kashala formation. Further south Rb/Sr determinations on the Koga carbonatite in the Ambela complex yield dates of 297-315 Ma (Le Bas and others, 1987). Radiometric dates ranging from Cambrian to Lower Ordovician have been reported from other granitic gneisses in Lesser Himalaya, (Le Fort and others, 1983; Le Fort, 1986). Thus the age of the younger granites has been variously interpreted and is not yet well established.

The Indus Suture Zone is predominantly composed of melanges of diverse oceanic origin. Lawrence and others (1983,1989) and Kazmi and others (1984,1986) subdivided this zone into three fault-bounded melange units. (a) The Mingora ophiolitic melange, composed of tectonized blocks and clasts of serpentinite, talc carbonate, greenstone metabasalts, greenschist metapyroclastic rocks, metagabbro, metasediments and metacherts, has been metamorphosed with the underlying metasediments of the Indo-Pakistan subcontinent. Its mineral assemblage indicates an epidote amphibolite metamorphic facies (Lawrence and others, 1989; DiPietro, 1990). It is bounded in the north by the Kohistan thrust and in the south by the Kishora thrust. (b) The Charbagh greenschist melange, containing greenstone metabasalts, and greenschist-facies metapyroclastic rocks with minor tectonized layers and wedges of metasedimentry rocks, crops out between Charbagh and Shangla Pass. It forms a thick tectonic wedge between the overlying Shangla blueschist melange to the north and Mingora ophiolitic melange to the south. (c) The Shangla blueschist melange is best exposed at

Shangla Pass and is characterized by blocks of glaucophane and crossite-bearing blueschist (Shams, 1972,1980; Shams and others, 1980; Jan, 1985), metavolcanic rocks and schists with smaller lensoidal masses of serpentinite, metadolerite, metagreywacke, metachert and marble (Kazmi and others, 1984). Metamorphism associated with these blueschists indicates pressure conditions of approximately 7 Kb at a temperature of about 380° C on the basis of its mineralogy (Jan and others, 1981b). Isotopic dates on the blueschist metamorphism have a K/Ar age of 84±1.7 Ma for the muscovite from a metasedimentary type blueschist near Topsin (Shams, 1980). Maluski and Matte (1984) obtained a $^{40}Ar/^{39}Ar$ date of 83.5±2 Ma on phengite in a blueschist block. Kazmer and others (1983) report fossils of Jurassic to middle Cretaceous age from a limestone block in the Kabal area. On the basis of these ages, the blueschist metamorphism is considered to be late Cretaceous in age and related to subduction adjacent to the Kohistan andesitic arc (Coward and others, 1986).

The Kohistan arc sequence represents an andesitic arc terrane. In Swat adjacent to the MMT, it is composed of a southern amphibolite belt which extends from southwest of the Nanga Parbat-Haramosh massif through Babusar Pass, Kohistan, and Dir to eastern Afghanistan (Tahirkheli and others, 1977,1979; Tahirkheli, 1979a,1979b; Bard, 1983; Bard and others, 1980; Ahmad and Chaudry, 1976; Jan, 1979a,1980a; Ashraf and others, 1980; Butt, 1983). The Jijal complex, documented only along the Indus River, includes garnet granulites and alpine type ultramafic rocks (Jan, 1977,1979a,1980; Jan and Kempe, 1973; Jan and Howie, 1980b,1981). The southern amphibolite belt includes 6-8 km of multiply folded fine- to coarse-grained banded or homogeneous amphibolites, flaser gabbros and blastomylonitic amphibolites. The banded amphibolites are locally migmatitic with quartzofeldspathic injections. The lower part of the complex encloses large "patches" of mafic-ultramafic rock (mainly harzburgites, dunites, diopsidites and garnet spinel diopsidites) surrounded by more or less amphibolitized and (or) garnetiferous noritic gneiss (two pyroxene granulites). These are called the north Mingora complex in Swat valley and the Jijal-Pattan complex along the Indus River (Jan, 1977; Jan and Howie, 1981) in Indus valley. The Jijal granulites represent metamorphosed norites, with subordinate hypersthene-quartz diorites (Jan, 1979c), olivine gabbro, troctolites, feldspathic gabbros, olivine anorthosites and pyroxenites. The pyroxene granulites were affected by polyphase metamorphism and deformation (Jan, 1980). P-T estimates ($T=600^{o}$ C?, P=10-14 Kb) for these rocks suggest an oceanic or suboceanic rather than a continental geothermal regime (Jan, 1980).

The study area is composed of the MMT zone and the Indian plate sediments. The Indian plate units exposed are the Alpurai group and the Saidu schist which are overthrust by the Indus suture melange group. The Alpurai group is represented by the Marghazar, Kashala, and the Saidu formations. The Marghazar is exposed only as a small wedge which is thrust over the Saidu graphitic phyllites. The upper unit of the Alpurai group, the Nikani Ghar formation is not exposed. Tourmaline-bearing granite gneiss of the Chakdara pluton has a contact with the Kashala formation of the Alpurai group. The contact relationship is not clear, whether this contact is an unconformity, a fault, or a greatly sheared unconformity (see discussion in Chakdara granite section).

The Indus melange group is the westward extension of the Mingora ophiolitic melange and occurs as an oceanic suit in the form of slivers and thrust sheets of talc-carbonate and serpentine in association with metavolcanics and metasediments between the other tectonized blocks (schist, phyllites). Emeralds are reported in the talc-carbonate blocks near Garai village (S. Hussain, pers. com., 1990). The Indus melange group is overthrust by the Kohistan arc amphibolites.

LOCAL STRATIGRAPHY

Metasedimentary and metaigneous rocks in the area NW of Swat River are shown in (Plate 1). They can be subdivided into three major terranes: the Indian shelf sediments, the Kohistan arc, and the Indus melange group. Ages of Paleozoic to Tertiary were assigned to these rocks south of the study area (Martin and others, 1962; King, 1964; Tahirkheli, 1979; Kazmi and others, 1984; Ahmad, 1986; Ahmad and others, 1987; DiPietro, 1990). Stratigraphic and structural columns from the lower Swat area are given in (Table 1). In this study, the nomenclature used by DiPietro (1990) has been followed.

The Indian shelf sediments

Alpurai group

The Alpurai group rests unconformably upon the Manglaur formation and Swat gneisses. It takes its name from lower Alpurai village 32 km east of Saidu (Kazmi and others, 1984). DiPietro (1990) divided it into four formations: the Marghazar, Kashala, Saidu, and, Nikani Ghar formations. The Marghazar formation occurs at the base and consists of pelitic, amphibolitic, psammitic schists, phlogopite marbles, and amphibolites. It is overlain by the Kashala formation which consists of garnetiferous calc-schists, calc-phyllites, marbles and dolomitic marbles. The Kashala formation is overlain by black graphitic phyllites of the Saidu formation in the north, and by marbles and dolomitic marbles of Nikanai Ghar

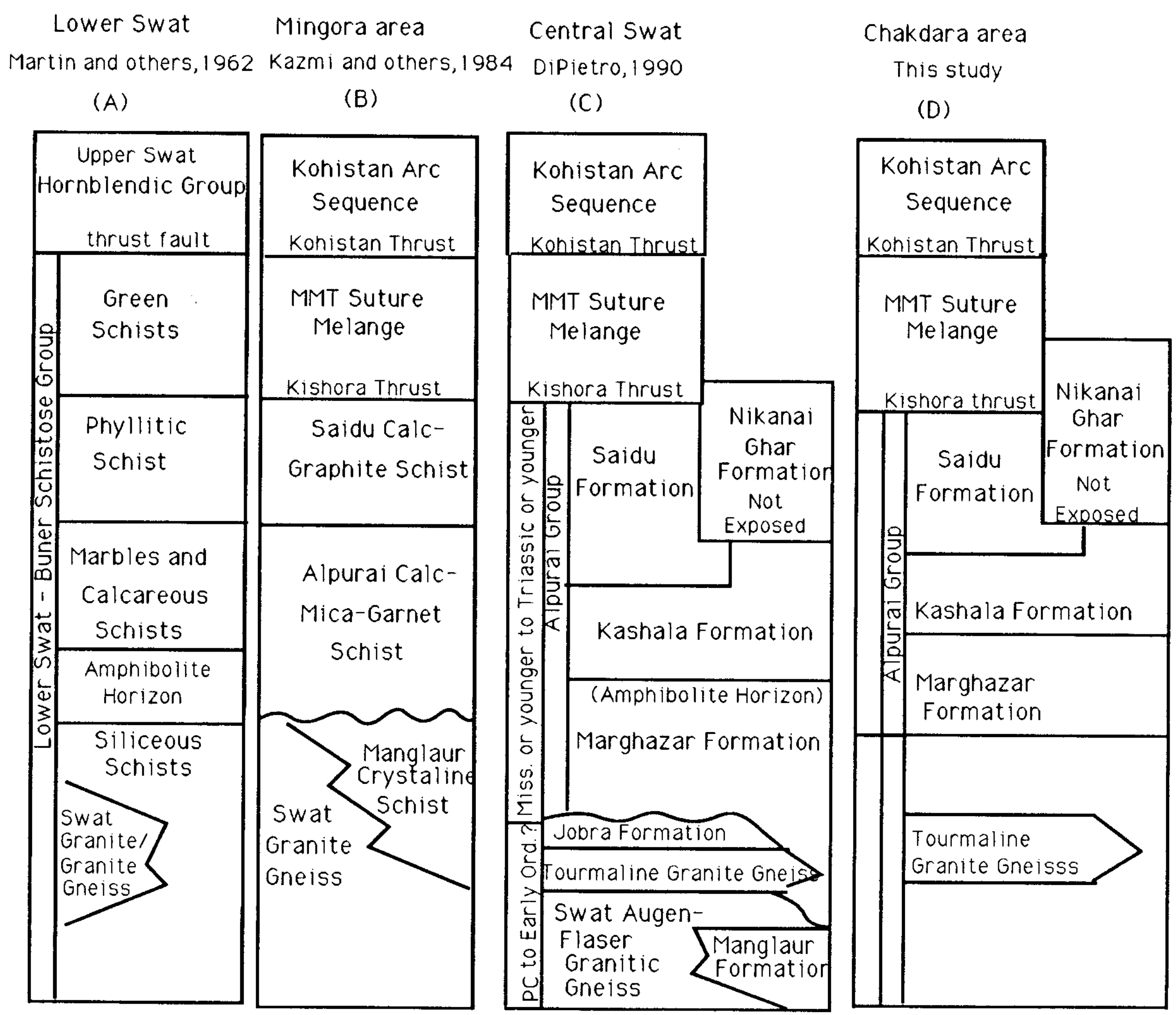

Table 1. Comparative structural/stratigraphic columns from lower Swat, modified from DiPietro (1990).

formation in the south. The Marghazar, Kashala, and Saidu formations are exposed in the study area.

Marghazar formation

The Marghazar formation takes its name from Marghazar village, 6 km south of Saidu. The proposed type locality is along Saidu Khwar (creek) and the adjacent road north and south of Marghazar village (DiPietro, 1990). The Marghazar formation is composed of dark-gray weathered phlogopite marble, garnetiferrous muscovite schist, epidote biotite schist, amphibolite schist psammitic schist, feldspathic quartzite, calcite marble, amphibolite and rare graphitic schist (DiPietro, 1990). The lower part of the Marghazar formation is intruded by tourmaline granite gneiss.

In the study area, a small wedge of quartz-rich garnetiferous schist is present south of Nimogram (Plate 1). It is a whitish rock composed of fine-grained quartz, garnet porphyroblasts mostly 2 mm in size, and muscovite which defines the foliation. No similar rock type is exposed in other parts of the study area. It is interpreted to be the garnetiferrous muscovite schist of the Marghazar formation. This small body has been thrust over the Saidu graphitic phyllite.

Kashala formation

The Kashala formation takes its name from Kashala mountain about 13 km SSW of Saidu. The proposed type locality is along roadcuts at Dop Sar, just south of Saidu (DiPietro, 1990). It consists almost entirely of calcareous rocks. Pelitic schists and argillite occur but amphibolites, psammitic schists and quartzites are absent (DiPietro, 1990).

The Kashala formation is the largest unit exposed in the field area (Plate 1). It extends from near Ramora along the roadside to Khazana village. It is also well exposed along the road between Zarikhela and Kabal. The thickness is several hundreds meters. It consists about five rock types: calc-mica-garnet schist, schistose marble, white marble, dark-gray foliated marble, and quartzite. The calc-mica-garnet schist is the major unit. It contains interbeds of gray marbles. The marble layers vary from a centimeter to tens of meters thick. The contacts between the marbles and schists are sharp. The calc-mica-garnet schist grades upward into schistose marble. The quartzite bed is exposed only near Kohi village and is about two meters thick.

The base of the Kashala may not be exposed. It is in contact with the Chakdara granite (Plate I), but it is not clear whether this contact is an unconformity, a fault, or a greatly sheared unconformity (see discussion in Chakdara granite section). The upper contact with the graphitic schist of the Saidu formation is gradational.

Saidu formation

The type location of the Saidu formation is along roadcuts east of Mingora, one kilometer north of Saidu (Martin and others, 1962; Kazmi and others, 1984).

In the study area the Saidu formation is the second largest unit and overlies the Kashala formation (Plate 1). The thickness varies from tens of centimeters in the melange zone to hundreds of meters away from the melange zone in the south. The Saidu and Kashala formations are repeated by folding near Khushmaqam and Chingai villages. The Saidu formation consists of fine to medium-grained gray to black phyllite. It commonly contains dark-gray non-micaceous and brown schistose marble layers that vary from few centimeters to tens of centimeters in thickness. The dark-gray marble is foliated by flattened calcite crystals and folded. The graphitic phyllite occupies the crests of these folds in Figure 2.

The upper contact of the graphitic phyllite with the phyllite of the melange is a sharp thrust contact.

Chakdara granite

The Chakdara granite crops out NW of the Swat River. It extends from near Chakdara Fort further north into the Dir area. It is generally medium-grained and well foliated. The contact relationship with the Kashala formation is not clear. Near Chakdara and Warsak (Plate 1) the strongly foliated granite gneiss underlies the Kashala formation and no indication of large magnitude shearing or faulting has been observed along the contact (Figure 3). The parallelism of the foliation in the granite and the Kashala confirms that these rocks were deformed together. Elsewhere in the region, the units of the Alpurai are unconformable on the Swat granite gneisses, but the lower units are intruded by the Ambela and

Figure 2. Folded dark-gray marble. The graphitic phyllite occupies the crests of these folds. Photograph taken facing NNW.

Figure 3. Contact relationship between granite gneiss and calc-mica-garnet schist. Photograph taken facing westward. Locality, Warsak (Plate 1).

tourmaline granites (DiPietro, 1990). If the contact relations could be clearly interpreted, the age of the Chakdara granite might be determined. Near Uskai village (Plate 1) extensive shearing is present at, above, and below the contact. No inter-inclusion of the granite and Kashala rocks was observed. This suggests that the relationship of the granite with the Kashala formation is not intrusive, but is either unconformable or a thrust contact. Figure 3 suggests an unconformity, but is not conclusive. Thus, the nature of this contact must remain open for further study.

The Kohistan arc

The Kohistan arc in the study area is composed of epidote amphibolites. It is several hundred meters thick. It extends from Kabal (Swat) into Dir district in the study area. The contact with the greenstone of the melange terrane is a thrust contact. Brecciation and shearing along this contact occur throughout the area (Figure 4). The amphibolites were thrust onto the melange rocks.

Field relations in the melange terrane

Definition of melange and its application

The concept of melange has developed since the early work on such rocks by Greenly, 1910; McCallien, 1953; and Schakleton, 1951. They used the term melange to denote an assemblage of rocks apparently disrupted by chaotic brittle structures. Later definitions, offered by Gansser, 1974; Hsu, 1971; McCall, 1983;

Figure 4. Contact relationship between Kohistan amphibolites (brown), and greenstone (grayish). Photograph taken facing westward. Locality, Baber Ghakhi Kandao (Plate 1).

Moores, 1981; Silver and Beutren, 1980; Cowan, 1978; Berkland, 1972; and Raymond, 1984, were formulated mostly after plate tectonic concepts appeared, and suggest that most of these rocks developed in subduction complexes. The definition of the term melange offered by Berkland is apropos to the present investigation and is paraphrased below.

> Melange is a mappable body of deformed rocks characterized by the inclusion of native and exotic blocks (`knockers') which may range up-to several miles long in a passively sheared, commonly pelitic, matrix (Berkland, 1972).

In the Swat area, the melanges are characterized by exotic blocks of talc-carbonate, serpentine, limestone, marble, and greenstone in a matrix of chloritic phyllite, greenschists, metavolcanic rocks, and graphitic phyllite. They are faulted onto and into the Indian shelf sediments. It is appropriate to use the term ophiolitic melange (after Gansser, 1974, and Coleman, 1978) for most of this material because of the abundant blocks of talc-carbonate and serpentine.

Rock types and field relation of the matrix

The matrix is mostly composed of sheared chloritic phyllites, graphitic phyllites, and greenschists, and rarely calc-mica schist. Shear textures are almost everywhere visible in the field. The sheared chloritic phyllites are greenish brown to brown in color and mark the thrust contact between the greenstones and metavolcanics. They have well developed crenulation cleavage and are commonly lineated. Small scale isoclinal folds are common. The graphitic phyllite is usually calcareous and locally contains laminated marble. Greenschist is derived from volcanic flows and volcaniclastic rocks. Chert fragments are observed in the volcanic flows east of the Garai village (Plate 1).

Rock types and field relation of blocks

The blocks are composed of talc-carbonate, serpentinite, limestone, marble and greenstone. The talc-carbonate blocks are rounded to elongated. They range in size from 1 meter to several meters in largest dimension. Their elongation within the matrix is mostly vertically oriented. A few are elongated parallel to the strike of the foliation. They are not well foliated internally. In most cases they are associated with the phyllites. East of Garai village, they make a chain of blocks and an intensely brecciated contact between the blocks and matrix can be seen. The blocks present in the graphitic phyllite of the Saidu formation may occur along successive faults that cut deeper into the section as the Kishora fault system developed (Plate 1 and Figure 8). Serpentinite blocks occur as thin lenses along thrust contacts in the matrix (Figure 5) and in some cases in the greenschist. Greenstone blocks are randomly distributed, several meters in size, and very fine-grained. Limestone blocks are generally found along faulted

Figure 5. Serpentine lenses in a sheared matrix (phyllite) near the contact with the greenstone. Photograph taken facing northeast. Locality, Baguai Kandao (Plate 1).

contacts. They are moderately recrystallized. The marbles, on the other hand, are highly deformed with a prominent mineral lineation.

Age and Correlation

The oldest stratigraphic unit in the Swat area is the Manglaur formation which is intruded by the Swat granite gneisses and unconformably overlain by the Alpurai group. There are no fossils in the Manglaur formation. Its age is however constrained by the age of the intrusive Swat gneisses. The Swat gneisses are not radiometrically dated, but LeFort and others (1980,1983) and Jan and others (1981) consider the Swat gneisses to be contemporaneous with Cambrian to Ordovician augen granite gneisses that are present throughout the lesser Himalaya; including the Late Cambrian Mansehra granite in Hazara. If this correlation is correct, then the Manglaur formation can be no younger than Cambrian. DiPietro (1990) and Baig (1990) considered the Manglaur formation to be Pre-Cambrian to Cambrian in age and correlate it with the Tanawal formation of Calkins and others (1975) and Pogue and Hussain (1988). DiPietro (1990) also suggested that the Manglaur and Tanawal formations are stratigraphic equivalents but that the top of the Manglaur formation may be younger than the top of the Tanawal formation.

The Alpurai group unconformably overlies the Manglaur formation and the Swat gneisses. The Marghazar formation, the basal member of the Alpurai group, is the lithologic equivalent to Jafar Kandao formation (DiPietro, 1990), which unconformably overlies the early to early Late Devonian Nowshera formation of the Peshawar basin (Pogue and others, submitted). On the basis of conodonts, the Jafar Kandao formation ranges in age from early Mississipian to Middle Pennsylvanian (Pogue and others, submitted). The Marghazar formation is overlain by an amphibolite horizon east of the study area in Swat (Martin and others, 1962; Rosenberg, 1985; Ahmad, 1986; Ahmad and others, 1987; DiPietro, 1990) and its stratigraphically equivalent Karapa greenschist (metamorphosed lava flows) is on the top of the Jafar Kandao formation in the Peshawar basin (Pogue and others, in prep). The metabasalts are tentativelly correlated with the Permian Panjal basalts of Kashmir. The age of the Karapa greenschist is broadly constrained from Middle Pennsylvanian by (underlying Early Mississipian Jafar Kandao formation) to Late Triassic (Kashala formation).

The amphibolite horizon and Karapa greenschist are overlain by the Kashala formation. The low grade marbles of Kashala formation in the Peshawar basin yielded Late Triassic Conodonts (Pougue and others, in prep.). The Kashala formation is locally overlain by Saidu formation and Nikanai Ghar formation (DiPietro, 1990). The Saidu and Nikanai Ghar formation are tentatively assigned Late Triassic or younger ages (Pogue and others, in prep; DiPietro, 1990).

The Kohistan arc is part of a vast belt separated from the Indus melange group and the shelf sediments by the Kohistan thrust. Isotopic, K/Ar, Ar/Ar, and fission track ages are available. Based on these dates the Kohistan arc terrane is interpreted to be a Jurassic to early Cenozoic island arc (Tahirkheli and others, 1979; Majid and

Paracha, 1980; Honegar and others, 1982; Bard, 1983; Verplanck, 1987; Coward and others, 1987; Windley, 1983; Baig, 1990).

The Indus melange group is considered to be Jurassic to Cretaceous. Isotopic dates from the Shangla ophiolitic melange metamorphism are: (a) a K/Ar age of 84 $\pm$ 1.7 Ma for muscovite from a metasedimentary type blueschist near Topsin (Shams, 1980) and (b) an $^{40}Ar/^{39}Ar$ date of 83.5 $\pm$ 2 Ma on phengite in a blueschist block (Maluski and Matte 1984). Baig (1990) reported a fuchsite yielding a plateau date of 82 $\pm$ 0.22 Ma from fuchsite bearing schist in the Mingora ophiolitic melange.

PETROGRAPHY

In the following section megascopic and microscopic features of the different rock units are presented. The mineral assemblages are listed in (Table 2).

Marghazar formation

Quartz rich garnetiferous schist

In handspecimen this is a grayish white, fine-grained, schistose rock containing garnets, muscovite, and minor biotite. Garnet occurs as porphyroblasts about 2 mm in diameter. Very rare xenoblasts of quartz and feldspar are present.

In thin section the essential minerals include quartz + albite + muscovite + garnet + chlorite. Accessory minerals are biotite, opaques, and epidote. The rock is well foliated and the texture is granoblastic.

Quartz + albite occur as equigranular aggregates about 0.1 mm in size and make up most of the rock. Twinning in albite grains is common. Most of the grains have sharp boundaries and are rounded to subrounded in shape.

Muscovite and biotite occur as flakes and tabular elongated grains in close association and define the foliation. Muscovites are kinked around the garnet porphyroblasts.

Chlorite is common in association with muscovite and biotite but also occurs as separate grains along the planes of foliation. Chlorite has altered to biotite (chlorite = biotite + water). Chlorite

FORMATION	Alpurai Group							Chakdara Granite	Kohistan Arc	Melange		
	Marghazar Formation	Kashala Formation				Saidu Formation						
Main mineral assemblages	Quartz rich garneti-ferous Schist	Calc-mica garnet schist	Calc-mica schist	Marble	Quartzite	Graphitic Phyllite	phyllite	Granite gneiss	Amphibolite	Greenschist	Talc-carbonate	Limestone
Calcite		≡ +	≡	=		—	—	—	—	—		≡
Dolomite				—							≡	
Siderite			—									
Quartz	≡	=	=	=	≡	≡	≡	X ≡ +	—	=	—	—
Plagioclase	≡	=	—	—	≡	=	=	≡	≡	=	—	
K-feldspar								X = +				
Hornblende									≡ +			
Pargasite		— +										
Biotite	....	....	....			—	—	—				
Muscovite	—	=	—	—	—	=	=	—	....			....
Paragonite		—										
Fuchsite											=	
Chlorite	—	....	....			—	=	—	—	≡		
Epidote		=	—					....	=	=		
Zoisite		—				—			—			
Clinozoisite									—	—		
Garnet	# = X	# = X				# = X						
Sphene							....	—	—			
Apatite									—	—		
Opaque	—	—	—	—	—	—	—	—	—	—	—	—
Tourmaline					....			—				
Magnesite											—	
Graphite		....	....			=						
Chromite												
Talc							....				=	

EXPLANATION

- ≡ Abundant
- = Common
- — Present
- \+ Porphyritic or porphyroblastic
- X Crushed Porphyroblast
- # Two Generation of porphyroblast
- ..... Relict

TABLE 2. Metamorphic mineralogy of the rocks of the Chakdara area.

itself in some cases replaces magnetite (magnetite + silica + water = chlorite) and garnet.

Garnet occurs as porphyroblasts as well as poikiloblasts with inclusions of quartz, albite, biotite, and muscovite. Garnets are syn- to pre-kinematic. The internal fabric (s_i) is consistent with the external foliation (s_e). There is also deflection of the external foliation against these garnets. A very few seem to be post-kinematic where s_e is consistent with s_i, but there is no deflection of s_e against the garnet porphyroblast.

The mineral assemblage quartz + albite + muscovite + garnet + biotite + chlorite represents a high grade greenschist facies or low grade amphibolite facies metamorphism. Alteration of garnet to chlorite represents a retrograde metamorphism. Abundant quartz, albite, and muscovite suggest the protolith may be a silicic tuff.

Kashala formation

Calc-mica-garnet schist

Light brownish-gray calc-mica-garnet schist is the dominant constituent of the Kashala formation. In handspecimen it is a fine- to medium-grained (<1-3 mm) rock. Foliation is defined by the segregation of calcite and white mica. It grades from a schistose marble into a dark-gray foliated, but non-micaceous, marble. Similar to tight isoclinal folds are common. Crenulation lineation can easily be observed on the cut surface of handspecimens. Kyanite is present in quartz veins, but none was found in the rock itself.

Kyanite is reported to the southeast of the study area by DiPietro (1990) and Imtiaz Ahmad (pers. comm. 1990).

In thin section, typical calc-mica-garnet schist contains the mineral assemblage, calcite + muscovite + paragonite + ferroan pargasite + quartz + albite + zoisite + epidote + garnet + magnetite + ilmenite ± chlorite ± graphite ± biotite. Ferroan pargasite and paragonite are identified on the basis of microprobe analysis. The texture is granoblastic. The main foliation is defined by the later S_2 where the earlier foliation, S_1, occurs as a relicts in S_2.

Calcite occurs both as xenoblasts and porphyroblasts that in some cases show polysynthetic twining. The calcite poikiloblasts have inclusions of quartz, albite, and muscovite. Some calcite grains have been replaced by epidote in association with quartz. Calcite makes about 40-55% of the modal volume.

Quartz + albite makes up about 10-20% of the modal volume. They are mostly surrounded by flakes of muscovite and are aligned along the foliation. A few grains show undulatory extinction. In IR-7, quartz + albite make up about 35% of the of the modal volume. Quartz + albite layers without calcite are present.

Muscovite constitutes about 10-15% of the modal volume and occurs as well-oriented fine-grained tabular flakes. The fine flakes of muscovite with little biotite, opaques, and graphitic dust are folded at places. They are also folded and truncated in pressure shadows adjacent to garnet porphyroblasts. Mica fish structure is also present.

Garnet constitutes about 1-3% of the modal volume. The grain size ranges from < 2 mm to 4 mm. It is surrounded by flakes of muscovite and dust of graphite. Pressure shadows adjacent to the porphyroblasts are composed of quartz, muscovite and rare biotite. Most of these garnets have inclusions of quartz, albite, muscovite, and rare epidote. Garnets are pre- to syn-tectonic. Garnets have inclusions which are parallel to the external foliation. The external foliation is truncated arround the porphyroblast and the pressure shadow is also developed. This suggests that the garnet grew during the early deformation and before the later deformation. In section IR-1 the internal foliation is rotated with respect to the external foliation which also suggests that the garnet is pre- to syn-tectonic with respect to the external foliation.

Ferroan pargasite occurs as idioblasts as well as poikiloblasts with inclusions of calcite, quartz, muscovite, and epidote. It is pale yellow in color and shows weak pleochroism. The internal foliation within the porphyroblast is aligned with the external foliation. The external foliation is deflected against the poikiloblasts. This suggests that the poikiloblast of the ferroan pargasite is pre-to syn-tectonic. Ferroan pargasite in some cases has altered to biotite.

Zoisite occurs as fibrous aggregates, thin elongated fibers and prismatic grains that are well oriented. Some of the grains that have grown across the foliation probably developed during the later deformation phases.

The mineral assemblage calcite + muscovite + quartz + albite + garnet + ferroan pargasite + magnetite indicates epidote amphibolite facies metamorphism. Alteration of amphibole to biotite and biotite to chlorite represent a retrograde phase.

The calcite grains do not show a sedimentary character and have been completely recrystallized during metamorphism. This rock also has abundant quartz, albite, calcite, and muscovite which suggests that the protolith was a calcareous pelitic tuff.

Calc-mica schist

The calc-mica schist is the second largest member of the Kashala formation. In handspecimen, it is a fine to medium-grained, brown colored rock with grayish bands of quartz and mica. White mica flakes define the foliation. Mineral lineation has also developed which is defined by late micas. Late calcite and quartz veins are common.

Under the microscope the rock contains the mineral assemblage, of calcite + siderite + muscovite + quartz + albite. Minor minerals include opaque ores, graphite, biotite, epidote, and chlorite. The texture is granoblastic schistose.

Calcite occurs as xenoblasts to idioblasts, some of which are poikiloblastic. The poikiloblasts have inclusions of muscovite and quartz. Some calcite grains are curved and broken. They have also altered to epidote in association with magnetite and quartz. Calcite + siderite makes about 80-85% of the modal volume, substantially more than in the calc-mica-garnet schist.

Muscovite occurs as thin flakes and thin elongated tabular grains. It constitutes about 5-10% of the modal volume. Mica fish type structure is present. Some mica flakes are kinked.

Quartz and albite make up about 5% of the modal volume. They range from 1-2 mm in grain diameter. They occur as rounded grains to xenoblasts. Some of the grains are elongated along the foliation. They also show undulatory extinction. Some have very sharp boundaries and are recrystallized.

In contrast to the calc-mica-garnet schist, the calc-mica schist does not contain garnet, ferroan pargasite, or zoisite. This is most probably because the rock composition is not favorable to formation of the above minerals. It cannot be explained as a lower metamorphic grade because the two rock types are interlayered, so calc-mica schist also formed under epidote amphibolite facies conditions. Abundant calcite with quartz and albite suggests that the protolith was an impure limestone.

Marbles

Laminated gray-marble and massive white marble occur interlayered in the Kashala and Saidu formation. Near Uskai Kili stylolites, probably due to tectonic pressure solution, are present. At Kohi prismatic radiating tremolites are found in the laminated gray-marble.

In thin section the typical mineral assemblage of these marbles is calcite + muscovite with minor amounts of quartz, albite, and magnetite.

Calcite occurs as idioblastic to xenoblastic grains. It shows polysynthetic twining. The modal calcite composition is 95-98%.

Veins of finely crystalline calcite also occur along the foliation. Calcite grains are strained on the margin of these veins. Brucite and pyrite crystals are found in them. Evidently, more than one brittle fracturing event is recorded in these rocks.

These rocks are also inlerlayered with the calc-mica-garnet schists and so formed in amphibolite facies conditions. The lack of aluminum is probably the main constraint preventing formation of garnet or other higher grade calc-silicate minerals.

Quartzite

This is a pale- to white rock occurs in a few meter thick beds at the base of the calc-mica-garnet schist. It is a medium-grained, well foliated rock. Foliation is defined by flattened quartz and feldspar, and is enhanced by scattered micas. Little mica is visible on the outer surfaces of foliation partings.

In thin section the mineral assemblage contains quartz + plagioclase + muscovite + magnetite with minor tourmaline and zircon. Quartz and plagioclase (quartz=52%; plagioclase=48%) occur as xenoblasts and have serrate boundaries. Some have recrystallized and have straight boundaries. They also exhibit undulatory extinction.

Muscovite occurs as elongated tabular grains. The muscovites lie along the foliation planes and also occur as inclusions in quartz and feldspar grains. The protolith of the rock was probably an arkosic sandstone or tuff.

Saidu formation

Graphitic phyllite

In handspecimens and outcrop, the graphitic phyllite is a grayish black rock. It is a fine- to medium-grained rock with an average grain size of quartz and feldspar about 0.2 to 2 mm. Garnet porphyroblasts vary from <1 mm to 2 mm in size. The graphitic phyllite has a well developed segregation banding defined by alternating quartzo-feldspathic microlithons 1-4 mm in thickness bounded by white mica and graphite cleavage domains about 1 mm or less in thickness.

Under the microscope the rock contains the mineral assemblage quartz + albite + muscovite + chlorite + graphite + zoisite $\pm$ garnet. Accessory minerals include opaque ores, biotite, pyrite, and calcite.

Xenoblastic quartz is the major phase in most of the sections and constitutes about 40-45% of the modal volume. Quartz exhibits undulatory extinction and sutured boundaries in the pressure shadows around garnet porphyroblasts.

Albites also occur as xenoblasts and exhibit undulatory extinction. Together quartz + albite make up greater than 60% of the modal volume.

Muscovite, biotite, and chlorite constitute about 15-20% of the modal volume. Mica flakes and elongated graphite dust streaks define the foliation. Graphite is concentrated along mica boundaries. Muscovite fish structures are common, and the bounding graphite emphasizes the grains in an "eye shadow" effect. All of the micas have been folded. Crenulation lineation and cleavage are also observed in IR-43. Relicts of the earlier foliation also exist in the main foliation of these rocks.

Garnet is idioblastic to porphyroblastic. The idioblastic to porphyroblastic garnets are both pre-tectonic and syn-tectonic with reference to the early foliation. In IR-36 the garnets are post-tectonic with respect to the early foliation. The external foliation is aligned with the internal foliation. There is no deflection of the external foliation against the garnet porphyroblast. IR-61 has both post-tectonic and syn-tectonic garnets where as IR-55 and IR-19 have syn-tectonic garnets. In IR-61, s_i is oblique to s_e which suggest that the garnets have rolled during the later foliation.

Zoisite occurs as elongated tabular grains along and across the foliation. It makes up about 1% of the modal volume. Those lying across the foliation are syn- to post-kinematic with respect to the foliation, where the foliation truncates against these grains.

In most of the sections the groundmass is fine-grained with some angular fragments. In some, alternating fine- and coarse-grained groundmass layers occur. This suggests that these rocks have been cataclasstically deformed. In one section, the groundmass is entirely very fine-grained and the rock may be mylonitized. This brittle overprint is mostly developed in those rocks which are near the Kishora thrust.

The mineral assemblage quartz + albite + muscovite + garnet + zoisite + chlorite is typical of fully recrystallized upper greenschist facies or lower grade amphibolite facies rocks. The protolith of these graphitic phyllites is probably quartzo-feldspathic shale or tuff with organic and silt-clay constituents.

Chakdara granite

Granite Gneiss

In handspecimens and outcrop, the granite gneiss is a whitish rock with dark bands of biotite which define the foliation. At some places the biotite also occurs as patches and clusters. It contains about 25% quartz, 65% feldspar, and up to 10% micas. Alkali feldspar is more abundant than plagioclase. Fresh and altered magnetite spots are common on the surface. Along the road near Chakdara, manganese dendrites are common near the contact with the calc-mica-garnet schist. At the same place, 1 cm long crystals of tourmaline are associated with the calc-mica-garnet schist and in a calcite vein in the granite gneiss. Xenoblasts of feldspar occur and are in most cases flattened along the foliation.

Under the microscope the rock contains the mineral assemblage: feldspar (plagioclase, orthoclase, perthitic microcline) + quartz + muscovite + biotite + magnetite + sphene with minor minerals epidote + sericite + zircon. The texture is granoblastic gneissose.

Feldspar and quartz occur in the groundmass and as xenoblasts and poikiloblasts. The inclusions in the poikiloblasts are recrystallized feldspar, quartz, epidote and muscovite. Most of the feldspar grains are strained and show undulatory extinction. Recrystallization and polygonization is common. Some of the poikiloblasts have pressure shadows around them. poikiloblasts have inclusion trails that are consistent with the external foliation and indicate that they are pre-to-syn-kinematic with respect to the external foliation. Some of the feldspars are sericitized and also altered to epidote.

Muscovite and biotite together define the foliation. In IR-68 the rock is inequigranular with very few porphyroblasts. Along fractures, chlorite and muscovite have developed, possibly due to later hydrothermal liquids.

IR-69 and IR-66 show brecciation along fractures. These sections are from the contact with the calc-mica-garnet schist.

The mineral assemblage is compatable with either greenschist or epidote amphiblite facies metamorphism. The modal volume percent of the minerals 65% feldspar (alkali feldspar more than plagioclase), 25% quartz, and 10% mica indicate that the rock is granite in compostition.

Kohistan arc

Amphibolite

In the outcrop, amphibolite is a pale-green to grayish rock with porphyroblasts of amphibole and feldspar. The porphyroblasts of feldspar are about 5 mm in size. The amphiboles are aligned. The rock is mostly weathered. Compositional layering is common.

Under the microscope the essential minerals include hornblende + albite + quartz + epidote ± zoisite ± clinozoisite + muscovite + chlorite. Accessory minerals include calcite, opaque ores, sericite, and apatite.

Hornblende occurs as poikiloblasts with inclusions of epidote and albite. Prismatic grains are also present. Most of the amphibole grains are fractured, and chlorite has developed in the fractures.

Plagioclase and quartz occur both as xenoblasts and fine-grained matrix. Most of the plagioclase is now converted to pseudomorphs of albite and minor kaolinite and sericite. Myrmekitic growth of quartz in the albite is common. Both albite and quartz are recrystallized and polygonized. In section IR-30, later veins of fine-grained quartz and albite occur along fractures in large cloudy albite(?) grains which are probably pseudomorph after earlier plagioclase. These veins are at a high angle to the foliation. Most of the albite and quartz grains are flattened and some of them show wavy extinction.

Epidote and clinozoisite (section IR-30) occur as xenoblasts, poikiloblasts and elongated prismatic grains. The poikiloblasts have inclusions of quartz and albite.

Muscovite occurs along foliation planes and also as random grains in the groundmass. In some cases muscovite replaces feldspar. Chlorite is mostly formed from amphiboles.

The mineral assemblage hornblende + albite + epidote + clinozoisite + quartz indicates epidote amphibolite facies metamorphism. Alteration of amphibole to chlorite and plagioclase to albite + muscovite represents a retrograde phase. The protolith is a basaltic rock.

Melange units

Phylite

Olive-gray to green phyllite occurs as the matrix rock in the melange. The rock unit varies from thin fissile phyllite to a compositionally banded rock featuring thick light-gray, quartzo-feldspathic layers and thin grayish black phyllitic layers. The quartzo-feldspathic layers are boudinaged and also occur as microlithons.

In thin section, the major mineral assemblage includes quartz + albite + chlorite + muscovite + epidote. Minor minerals include opaques, sphene, graphite, biotite, and talc.

Quartz + albite occur as xenoblasts as well as the fine-grained matrix. The grain size ranges from <1 mm-4 mm. Both quartz + albite constitute about 80-85% of the modal volume. They show boudinage structure. Some of the albite xenoblasts may be post-kinematic with respect to the external foliation (s_e). The external foliation is aligned with the internal inclusions trail and there are no pressure shadows developed which suggest that they are post-kinematic. Undulatory extinction in albite in pressure shadows is common.

Muscovite as sheete grains and chlorite as lath shapes defines the foliation. The micas show a fish type microstructure and are also kinked. The S_1 fabric lies in the axial planes of the small folds. In section IR-18 both fine and coarse-grained layers of quartz + albite occur. There are later veins across the foliation. Along fractures and schistosity muscovite has developed. In thin section

IR-83 muscovite is more common than chlorite. In thin section IR-25 and IR-70 at least three phases of fabrics are present. S_1 occurs as relict in the S_2 where S_2 has also folded to produce a crenulation lineation.

The mineral assemblage quartz + albite + muscovite + chlorite represent a typical low grade greenschist facies rock. Abundant quartz + albite suggest that the protolith of the rock seems to be a tuff.

Greenschist

In handspecimen the greenschist is a grayish-green chlorite rich rock with albite porphyroblasts. It occurs both as blocks and matrix in the melange zone. Most of the rocks are schistose and have flattened porphyroblasts of albite and quartz in a matrix dominated by chlorite. Albite porphyroblasts range from 0.2 mm to 5 mm in thickness and are mostly clearly visible on weathered surfaces. Pyrite cubes are common.

In thin section greenschist contains the mineral assemblage chlorite + albite + epidote + quartz + muscovite + clinozoisite + calcite + hematite + pyrite + ilmenite, with minor apatite and zircon.

Chlorite occurs as flakes as well as laths and defines the foliation. It is pleochroic from colorless to light green.

Albite also occurs as poikiloblasts and has inclusions of epidote, quartz, and chlorite. Twinned grains are also common.

Xenoblastic strained quartz is very common. Samples IR-71 and IR-42 contain stretched ribbon quartz. Sample IR-71 has also a quartzo-feldspathic vein which is deformed and brecciated. Angular mineral fragments are set in a matrix of calcite.

Clinozoisite and epidote occur as xenoblastic and idioblastic grains in a fine matrix of chlorite, quartz, and albite.

Calcite occurs as patches in the matrix in sections IR-75 and IR-42 and also as a secondary vein mineral. Some calcite veins crosscut the foliation. Ilmenite occurs as elongated tabular grains.

The mineral assemblage of chlorite + albite + quartz + muscovite + epidote is representative of low grade greenchist facies metamorphism.

The protoliths of these rocks are most likely mafic to intermediate (mostly basaltic) volcanic flows, tuffs or volcaniclastic sediments. In one of the section IR-42, ophitic texture is preserved indicating at least in post a basaltic (gabbroic) protolith.

Talc-carbonate rock

Brownish to brownish-gray talc-carbonate rocks occur as blocks in the melange zone. Shiny talc surfaces and its soapy character make this rock easily distinguished in the field. The brown color is due to weathering of ferroan dolomite and magnetite to yield goethite. Fuchsite (green Cr-bearing mica) is common. Emeralds are reported from these talc-carbonates at Garai village. Xenoblasts and microlithons of quartz and feldspar are common.

Under the micrscope the talc-carbonate contains dolomite + magnesite + quartz + albite + talc + magnetite + chromite + fuchsite as essential minerals. Accessory minerals include chlorite, sericite, and epidote.

Dolomite occurs as xenoblasts as well as idioblastic grains. Dolomite poikiloblasts also occur and have inclusions of quartz, albite, and talc. Siderite also occurs as xenoblasts with iron alteration on the margins.

Quartz and albite occur as patches and layers of fine aggregates. Rare xenoblasts occur. Most of the grains are subangular. Talc occurs as flakes and shreds throughout the matrix. Chlorite occurs as flakes along the foliation planes and defines the foliation. Chlorite has been kinked in section B2/13 and B2/62. Magnetite occurs as poikiloblasts with inclusions of quartz, albite and talc. Pyrite crystals are also common.

The mineral assemblage dolomite + quartz + albite + talc + chromite + magnetite + chlorite is representative of low grade greenschist facies metamorphism. The protolith of the rock was an ultramafic rock subsequently altered by CO_2-rich fluids to yield carbonate-rich rock.

Limestone blocks

Gray and reddish (probably manganese-bearing) limestone are the two major types of blocks in the melange zone. The gray one is an oolitic limestone. The reddish limestone is fine-grained. Quartz and calcite veins are common. The veins are folded and represent buckle folding.

In thin section, the gray limestone is composed of oolites and chert fragments. The rock is recrystallized where porphyroblasts and idioblasts of calcite replace the oolites. A few muscovite grains are present.

The reddish limestone is very fine-grained and is composed mostly of calcite.

CONDITIONS OF METAMORPHISM

Thin section study reveals that the metamorphism of the blocks and matrix rocks of the melange took place under conditions of the greenschist facies (Winkler, 1979 p. 244). In Indian plate rocks in the south and the Kohistan arc rocks in the north, metamorphism took place under amphibolite facies conditions. Generalized P/T estimates based on the present mineral assemblages, some of which are non-equilibrium assemblages, from the three terranes are presented in (Figure 6).

Melange blocks

The mineral assemblage dolomite + chromite + magnetite + talc + quartz + albite + magnesite + fuchsite of the talc-carbonate rock and antigorite + chlorite + calcite of the serpentinite rock indicate conditions of at least greenschist facies (Miyashiro, 1973) The mineral assemblage of the greenstone, chlorite + albite + quartz + epidote + magnetite + ilmenite, is also appropriate to low grade greenschist facies conditions Winkler, 1979).

The mineralogy of the serpentinite along the Kohistan thrust gives some constraint on the temperature. Antigorite is bladed and typically schistose. In general terms, antigorite is the high temperature serpentine mineral whereas lizardite and chrysotile are the low temperature minerals (Wenner and Taylor, 1974; Evans, 1977). The antigorite is estimated to grow at temperatures between 250-550° C. Infiltration of fluids from below the thrust into the antigorite serpentine rock is indicated by the

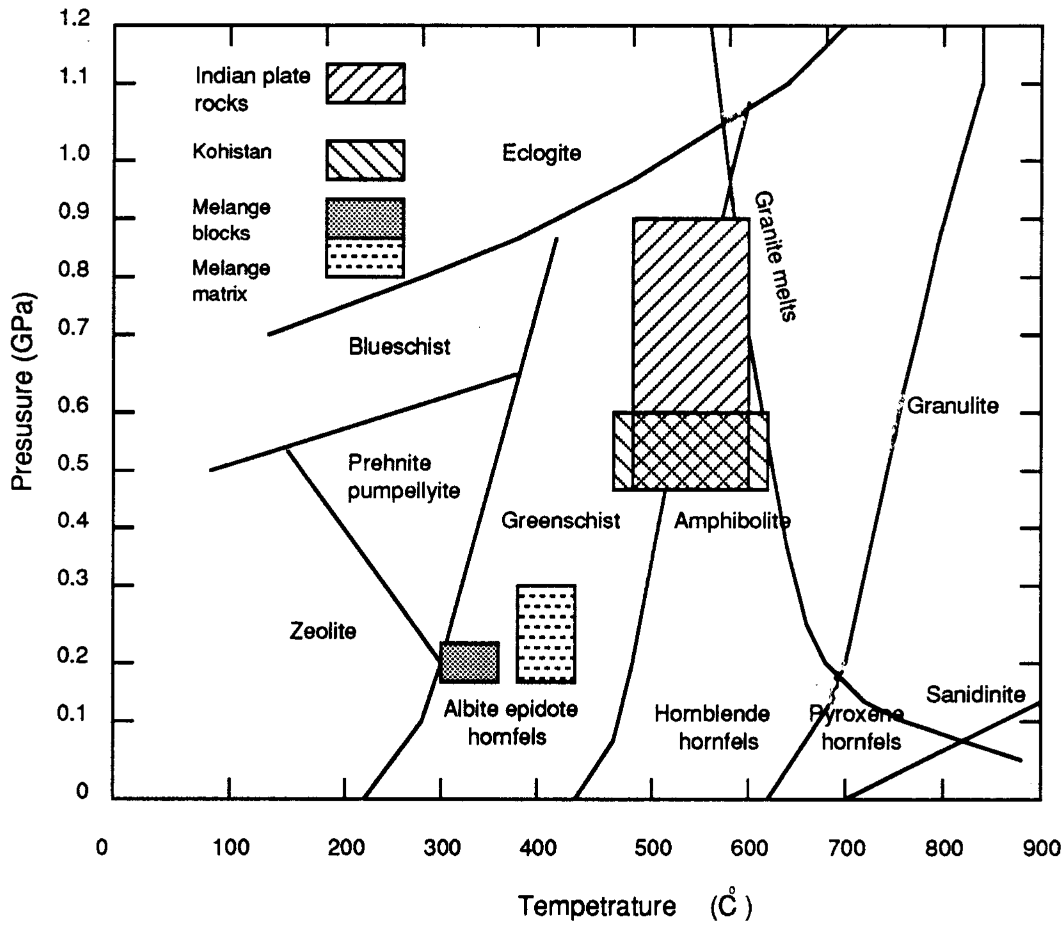

Figure 6. Genralized P/T estimates for the study area.

metasomatism that added substantial water and carbon dioxide to form the talc, chlorite, and carbonate minerals of the blocks. Emerald mineralization in the talc-carbonate blocks gives absolute constraint on P/T conditions. Homogenization temperatures of primary fluid inclusions hosted by emerald, corrected at 900 bars range from 378-449° C (Barton, 1986).

Melange matrix

The matrix rocks contain the principal mineral assemblage of albite + quartz + chlorite + muscovite + calcite + epidote + opaques ± biotite and ± sphene. This mineral assemblage indicates greenschist facies conditions (Winkler, 1979, p.74, 244; Turner, 1981). The absence of high P/T minerals such as lawsonite and sodic amphibole in the greenschist indicate that pressures attained were low, probably less than 3 kb. Some clues to the temprature of metamorphism of the melange matrix can be found in the texture and mineralogy of the matrix. Thermal modeling of the subduction zone environment and analyses of the textures and mineral assemblages of melange matrix rocks by Cloos (1983, 1985) has shown that temperatures greater than 200° C are necessary to coarsen pelitic sediments and obtain phyllitic and schistose rocks. Temperatures above 200° C are indicated by the fine- to medium-grained size (0.1-4 mm) of quartz, albite and mica of the matrix phyllite and schist of the present melange. Assuming conditions of greenschist facies, temperatures > 200° C and pressures < 3 kb can be suggested for the matrix rocks.

Indian shelf sediments

The metasedimentary rocks are divided into two groups (1) calc-pelitic (calc-mica schist and calc-mica-garnet schist), and (2) psammo-pelitic (quartz rich-garnetiferous schist and graphitic phyllite). The calc-pelitic rocks contain the mineral assemblage calcite + siderite + muscovite + paragonite + epidote + zoisite + quartz + albite + garnet + ferroan pargasite + magnetite + ilmenite ± chlorite ± biotite and ± graphite. Garnet, ferroan pargasite and paragonite are absent in the calc-mica schist. No microprobe analysis have been done for the calc-mica schist rock. Paragonite may be present or absent is not conformed. However the absence of garnet and ferroan pargasite in the calc-mica schist may be due to lack of aluminous minerals or this mineral assemblage may represent a retrograde phase. The psammo-pelitic rocks contain the mineral assemblage quartz + albite + muscovite + epidote + zoisite + chlorite + graphite + garnet ± biotite ± opaque ores. These assemblages correspond to the epidote amphibolite facies of Miyashiro (1973) or to the greenschist-amphibolite transition facies of Turner (1981).

The presence of zoisite and garnet can give an estimate of temperature. The high-temperature stability limit of the zoisite + quartz assemblage was experimentally determined by Newton (1966a) to be about 670^{o} C at 6 kb in the presence of aqueous fluid.

Garnet in the graphitic phyllite changes composition from pyrope-rich rims to almandine-rich cores. CaO and MnO contents also decrease from rims to cores (Table 3). Sturt (1962) and

Atherton (1968) reported similar changes from the Barrovian region of the Scottish Highlands. Plotting the mineral assemblages on the P/T diagram of Spear and Cheney (1989), the temperature ranges from 480 to 570^{o} C (Figure 7). The pressure ranges from 1 to < 10 kb. The upper limit of the pressures is consistent with pressures in the south of the Swar River (DiPietro, 1990).

Muscovite and paragonite can also give some constraint on the temperature. The existence of the muscovite-paragonite assemblage is dependent on the grade of metamorphism. At 2000 bars muscovite and paragonite are stable up to 715^{o} C and 660^{o} C, respectively (Eugster, 1956). Below 660^{o} C the join is binary with a broad two-phase region in which muscovite and paragonite coexist (Eugster, 1956). Therefore temperatures in the study area must have been below 660^{o} C. Ferroan pargasite can give some constraint on the pressure. Pressure for ferroan pargasite is estimated to be 3-4 Kb on the basis of the tetrahedral Al and Ti contents of the mineral composition (Raase, 1974). Analyses of ferroan pargasites from the study area are presented in (Table 3).

The epidote amphibolite facies conditions determined here, coupled with the reported occasional occurrence of kyanite in the same rock types to the south-east (Imtiaz Ahmad, pers. comm. 1990) indicate that the metamorphism is probably of the medium pressure series or Barrovian type (Miyashiro, 1973).

A very approximate determination of the pressure and temperature can be made. If a temperature is assumed of 580^{o} C for the epidote amphibolite facies and the metamorphism is of barrovian type a pressure of about 5.5 kb can be estimated (Turner, 1981, Fig.

11-14). A depth of approximately 20 km is indicated for these P/T conditions (Winkler, 1979).

Kohistan arc amphibolite

The Kohistan arc amphibolite contains the mineral assemblage hornblende + albite + epidote + quartz + magnetite + sphene + apatite. The assemblage is typical of epidote amphibolite facies conditions. The mineral assemblage suggests a temperature 400-540^{o} C (Apted and Liou, 1983; Maruyama and others, 1983).

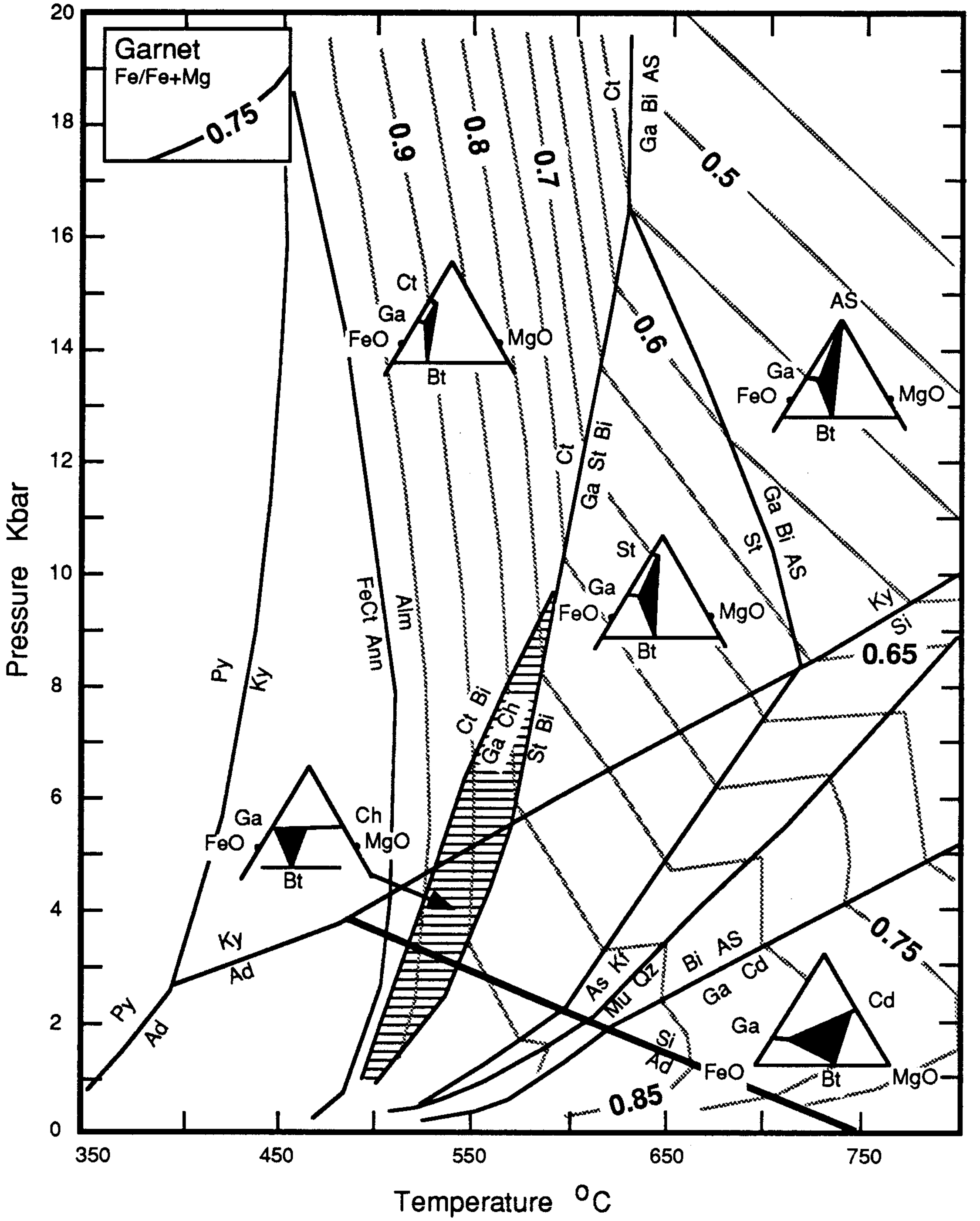

Figure 7. P/T diagtam after Spear and Cheney (1989). Horizontal lines represent the present minearal assemblage.

Table 3. Mineral composition Indian plate rocks.

Garnet composition

Sample No. IR-61

SiO_2	39.44	39.99	37.08	36.82	37.67
TiO_2	0.35	0.31	0.09	0.08	0.06
Al_2O_3	22.23	22.52	21.41	21.31	21.56
Fe_2O_3	0.00	0.00	0.00	0.00	0.00
MgO	6.86	6.90	2.02	1.85	1.78
CaO	14.13	14.11	7.36	7.13	6.99
MnO	0.72	0.69	0.15	0.16	0.13
FeO	15.71	16.10	30.05	30.05	32.42
	99.44	100.02	98.16	97.40	100.61

Cation on 24 (O) basis

Si	5.99	5.96	6.00	6.00	5.99
Ti	0.04	0.04	0.01	0.01	0.006
Al	3.99	4.02	4.08	4.10	4.04
Fe^{+2}	1.99	2.03	4.06	4.10	4.31
Mg	1.55	1.56	0.49	0.45	0.42
Ca	2.30	2.29	1.28	1.25	1.92
Mn	0.09	0.09	0.02	0.02	0.02
	{ Pyrope rich	}	{	Almandine rich	}

Analytical method

Selected minerals were analyzed using the automated Cameca electron probe microanalyzer at Oregon State University using natural and synthetic minerals as standards.

Samples IR-6 and IR-7 are calc-mica-garnet schists. IR-61 is graphitic phyllite.

Table 3. Continued

Amphibole composition

Sample No. IR-6

SiO_2	41.68	41.47	41.35
TiO_2	0.58	0.53	0.42
Al_2O_3	18.80	19.03	19.14
MgO	7.94	7.80	7.85
CaO	10.84	10.77	10.98
MnO	0.05	0.09	0.09
FeO	16.36	16.20	15.89
Na_2O	2.07	2.16	2.09
K_2O	0.51	0.51	0.56
F	0.34	0.35	0.29
Cl	0.00	0.00	0.00
	99.17	99.91	98.66
O=F+Cl	-0.14	-0.15	-0.12
	99.03	99.76	98.54

Cation on 24 (O,OH,F,Cl) basis

Si	6.11	6.09	6.08
Ti	0.06	0.06	0.05
Al	3.24	3.29	3.32
Fe	2.00	1.98	1.95
Mg	1.73	1.70	1.72
Ca	1.70	1.70	1.73
Mn	0.006	0.01	0.01
Na	0.59	0.62	0.60
K	0.10	0.10	0.11
	{	Ferroan pargasite	}

FeO expressed as total Fe. Ferroan pargasite is determined, using Leake (1978) nomenclature of amphibole.

Table 3. Continued

Muscovite and paragonite compositions

Sample No. IR-7

SiO_2	46.31	46.54	44.02
TiO_2	0.38	0.27	0.08
Al_2O_3	34.10	33.80	40.51
MgO	0.91	1.17	0.04
CaO	0.02	0.02	1.87
MnO	0.006	0.00	0.00
FeO	1.39	1.32	0.38
Na_2O	1.19	1.19	5.40
K_2O	8.96	8.72	0.75
F	0.33	0.45	0.37
Cl	0.00	0.00	0.00
	93.596	93.48	93.42
O=F+Cl	-0.14	-0.19	-0.16
	93.582	93.29	93.26

Cation on 24 (O,OH,F,Cl) basis

Si	6.25	6.29	5.77
Ti	0.04	0.03	0.01
Al	5.42	5.38	6.26
Fe^{+2}	0.16	0.15	0.04
Mg	0.18	0.23	0.01
Ca	0.002	0.00	0.26
Mn	0.00	0.00	0.00
Na	0.31	0.31	1.37
K	1.54	1.53	0.12

STRUCTURAL GEOLOGY

Major faults separate the study area into three different tectonic terranes: the Kohistan, the Garai melange, and the Indian shelf terranes. Metamorphic structures within each of these terranes developed independently until they were juxtaposed by motion on these faults. Accordingly, I will discuss (A) the terrane bounding faults, (B) the structure of each terrane, and (C) the structures which are contemporary with or subsequent to terrane juxtaposition.

Faults

Two major faults, the Kohistan and Kishora thrust (Kazmi and others, 1986), dominate the structure of the study area. They bound the Garai melange on the north and south respectively, and separate the three terranes (Plate 1).

The Kohistan thrust dips moderately steeply about 55-65^{o} to the northwest and strikes approximately WSW. The map trace of the fault is mostly straight with a few deflections due to topography. It extends both east through Mingora and west into Dir area beyond the study area. A large brecciated zone can be observed along the contact with the greenstone (Figure 8). Serpentine lenses occur along the fault contact.

The Kishora thrust is also northwest-dipping and WSW striking. It dips less steeply than the Kohistan thrust (Figure 9). This fault separates the Indian shelf sediments from the melange. It is drawn at the northernmost location of Indian shelf sediments.

Figure 8. Fault breccia from the Kohistan thrust (see Figure 11.24a p. 228 in Marshak and Mitra, 1988). Clasts of amphibolite are included in a calcite matrix.

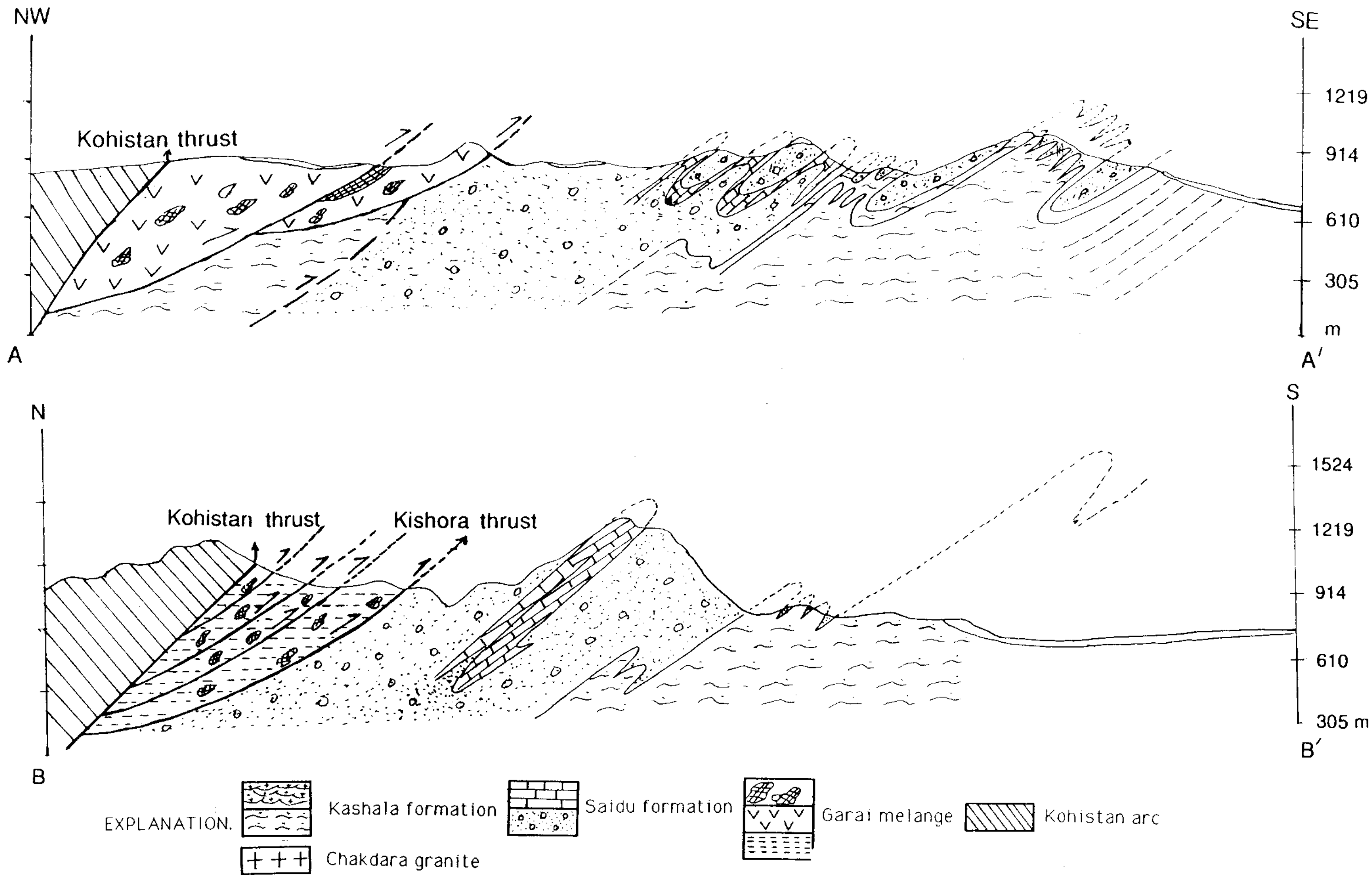

Figure 9. Geological cross sections of the Chakdara area. Location of cross sections are given in Plate 3.

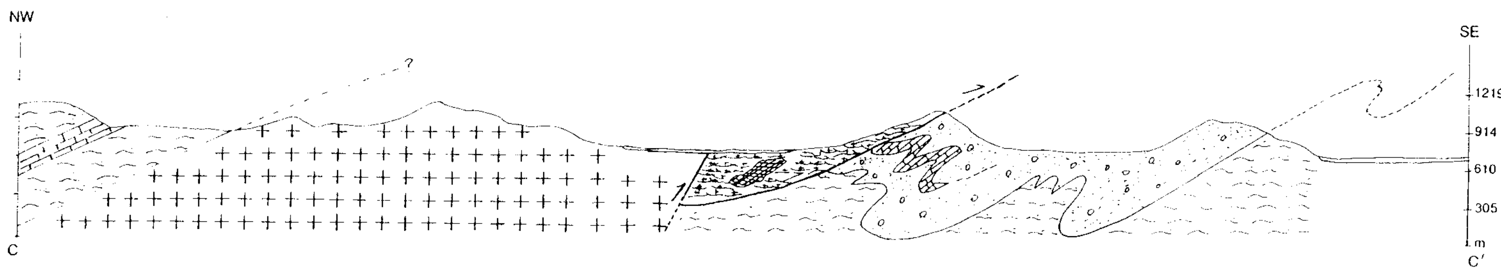

Figure 9. Continued

Numerous small blocks of melange material are found beneath the thrust (see below). East of the study area, the Kishora thrust brings melange over Saidu formation, but in the study area it also brings melange over Kashala formation (Plate 1). In the west portion of the study area, the Kishora thrust disappears under extensive alluvium and its location is speculative.

The upper portion of the Indian shelf sediments contains numerous blocks of melange material including serpentinite and talc-carbonate ultramafic blocks. Most of this material is localized along small imbricate faults related to the Kishora thrust, but some blocks are distributed within the sediments. This suggests that the upper sediments layer became involved in the process that created the melange. The small imbricate faults are considered also to be formed as part of this process.

Microfaults are present in the phyllites and marbles of the Indian shelf sediments. In one example near Uskai village (Figure 10), a minor reverse fault has movement of the hanging wall from northwest towards the southeast.

Metamorphic structures

Rocks of the study area record a polyphase deformation history. Three phases of deformation are outlined in the ensuing descriptions and Table 4. This section will summarize the microscopic features and analysis of the folds and fabric elements related to different deformational phases.

Figure 10. Microfault in the marble near Uskai village (Plate 1). The fault show sense of movement from northwest to southeast. Photograph taken facing north-north east.

Table 4. Observed structural elements of Garai melange blocks and matrix, Indian shelf sediments, and Kohistan rocks of the Chakdara area.

MELANGE BLOCKS

	Greenschist	Talc-carbonate and Limestone
D_1	S_1 = Dominant foliation	S_1 = Relict muscovite fold hinges
D_2		S_2 = Dominant foliation

MELANGE MATRIX

	Phyllite
D_1	S_1 = Relict muscovite fold hinges
D_2	S_2 = Dominant foliation
D_3	S_3 = Crenulation cleavage

Table 4. Continued

INDIAN SHELF SEDIMENTS

	Quartz rich garnetiferrous schist, Calc-mica-garnet schist, Calc-mica schist, Graphitic phyllite, and Marbles
D_1	S_1 = Relict muscovite fold hinges
D_2	S_2 = Dominant foliation
D_3	S_3 = Crenulation cleavage

KOHISTAN ARC

	Amphibolite
D_1	S_1 = Dominant foliation
D_2	Minor deformation

Microscopic features

The data presented here are based on criteria obtained from over one hundred thin sections cut normal to foliation and both normal and parallel to the dominant lineation. Observed structural elements are given in Table 4.

Microscopic features of melange blocks

The blocks within the schistose matrix are the least deformed rocks of the area. They show little evidence of multiple recrystallization. The greenschist shows only one phase of deformation where a single foliation is the only structure developed. The talc-carbonate and limestone blocks are recrystallized and show at least two phases of deformation. During the first phase, D_1, the foliation has developed by dolomite and magnetite crystal growth. During the later phase, D_2, the first foliation, S_1, was folded. S_1 occurs as relicts in the S_2 foliation.

In one limestone block (IR-16) later quartz veins are buckled due to variable competency of quartz and carbonate (Ramsay and Huber, 1987).

Microscopic features of the Matrix

Rocks of the matrix are complexly deformed. They show at least three phases of deformation. The microstructures indicate the following sequence of events.

(1) An early S_1 phase of foliation.

Associated F_1 folds are not observed

(2) A main S_2 phase with development of feldspar porphyroblasts and F_2 folds.

(3) An F_3 phase with the development of minor crenulation cleavage, S_3.

S_1 phase

S_1 is the predominant foliation in the greenschist. This foliation is the result of the alignment of randomly located chlorite crystals. It is obscure in hand specimens, but visible in thin section. In contrast, S_1 in the phyllites occurs as intrafolial folds within the S_2 foliation or as foliation relicts in the hinges of the F_2 folds (Figure 11) and also as inclusion trails in the albite grains. F_1 folds have not been observed.

S_2 phase

The S_2 phase, recognized only in the phyllites, is recorded by locally developed asymmetric kink folds, F_2, which form kink bands in the predominant foliation S_1. Axial surfaces to these folds define the S_2 cleavage. Feldspar porphyroblasts have overgrown S_1 prior to this phase, during which they were rotated and the new foliation flattened against them. The internal foliation in the feldspar is parallel with the external foliation, but there is also deflection of the external foliation around the feldspar porphyroblast. This suggests substantial flattening of the rocks during this later phase.

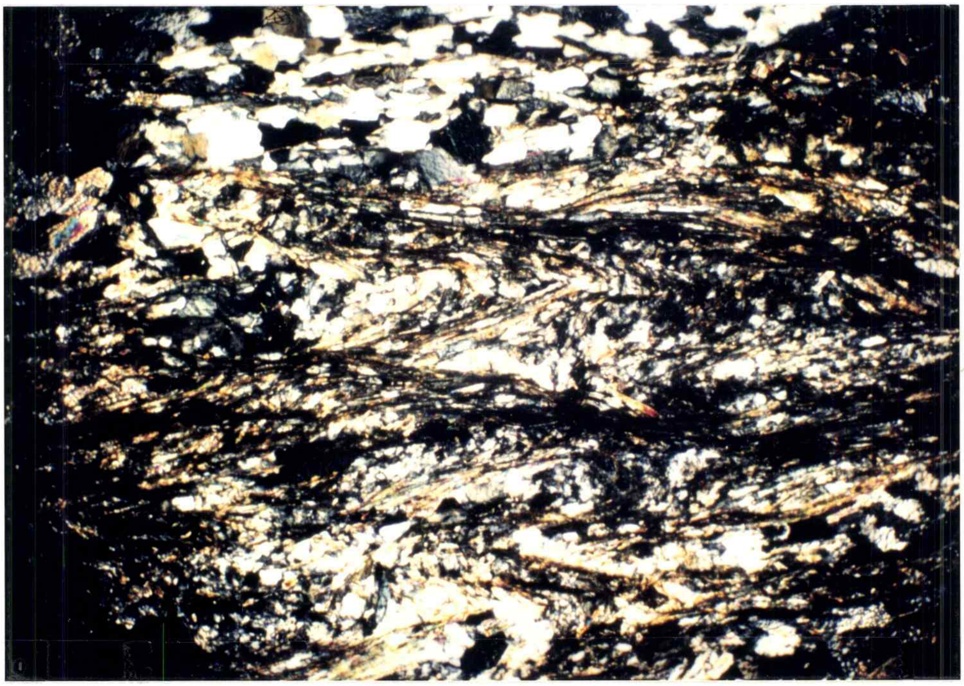

Figure 11. Small intrafolial folds representing relict S_1. Axial planes to these microfolds describe the S_2 foliation. Phyllite IR-35 (Plate 2), crossed polars, field of view 5 mm.

F_3 phase

In the phyllites the F_3 phase has been crenulated the S_2 fabric, where the axes of F_3 folds represent the major lineation in these rocks (Figure 12). Crenulation cleavage, S_3, has locally developed.

Microscopic features of the Indian shelf sediments

The Indian plate sediments are also complexly deformed and show three main phases of deformation. Later brittle deformation associated with thrust faults affects many rocks in shear zones. Only in the less sheared areas is evidence for the early phases of deformation and recrystallization clearly preserved. The microstructures observed are as follows.

(1) Very locally, S_0, transposed bedding is preserved.

(2) An early S_1 phase of foliation and garnet development. S_1 and F_1 are locally preserved.

(3) A main S_2 phase of foliation development with associated high grade recrystallization and development of garnet and ferroan pargasite porphyroblasts.

(4) A post S_2 phase of mineral growth mainly in veins.

(5) An F_3 phase with the development of crenulation folds and destruction of early S_1 foliaton and garnets.

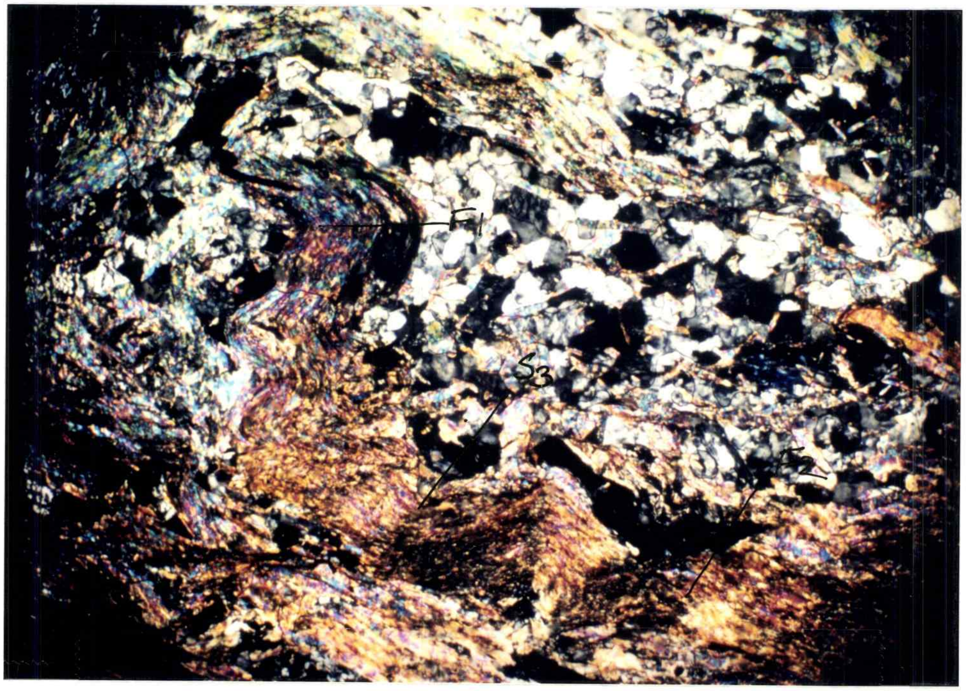

Figure 12. F_3 phase defined by crenulation of S_2, which shows local crenulation cleavage S_3. F_2 folds are also present. Phyllite IR-70 (Plate 2). Crossed polars, field of view 5.5 mm.

(6) A retrograde phase in which garnet is altered to chlorite and amphibole to biotite.

S_0

Bedding S_0 has been identified only in one thin section of graphitic phyllite of the Saidu and one calc-mica schist of the Kashala formation. Bedding is preserved by calcareous layers which show pressure solution along grain boundries. In the Saidu, the primary foliation, S_1, is parallel to bedding, except where it occurs as relicts or kinks in the later foliation, S_2. In the Kashala, S_1 is axial plane to intrafolial folds in S_0.

S_1 development

S_1 is the predominant foliation in the marbles and quartzite of the Kashala formation. This foliation is the result of transposition of an early compositional banding or layering. Whether this lithological layering reflects bedding or is the result of metamorphic differentiation and mineral segregation is not known. In contrast, the quartz-rich garnetiferous schist, calc-mica-garnet schist, calc-mica schist, and graphitic phyllite preserve the S_1 only as inclusion trails within porphyroblasts, as pressure shadow areas created by the deflection of the dominant S_2 foliation around the porphyroblasts, and as relict intrafolial microfolds (Figure 13).

Figure 13. Garnet porphyroblasts show deflection of S_2. Inclusion trails of S_1 in the porphyroblasts, and S_1 as relict kink folds in pressure shadow can also be seen. Graphitic phyllite IR-54 (Plate 2). Plane light, field of view 4.5 mm.

S_2 phase

The S_2 foliation is strongly developed and is defined by the orientation of platy or elongated minerals and axial planes of preserved F1 folds. Growth of garnet, ferroan pargasite, and calcite porphyroblasts is recorded with the S_2 foliation. The internal fabric in the garnet and ferroan pargasite porphyroblasts is parallel with the external foliation. There is also deflection of the external foliation against these porphyroblasts. This suggests that they were formed during and shortly after this phase (Figure 14). In this figure, S_1 occurs as relict kinks in the pressure shadows adjacent to the amphibole porphyroblast. Inclusions in some of the garnets from the calc-mica-garnet schist and the graphitic phyllite are oblique and crenulated compared to the straight external foliation. This suggest that the porphyroblast of the garnets were later rolled during the formation of S_2 (Figure 15). Overgrowths with large, unoriented inclusions in garnet porphyroblasts are also present (Figure 16). This garnet, which formed with a flat or elongated shape in the graphitic phyllite has been overgrown to its final subidioblastic shape.

Post S_2 brittle deformation and vein growth

After S_2 growth ended, the rocks were sheared and fractured during a brittle deformation phase. Where sufficiently intense, this event obscures nearly all of the earlier metamorphic history. Later, calcite veins grew along many of these fractures. These veins crosscut the foliation where along the margins the earlier calcite

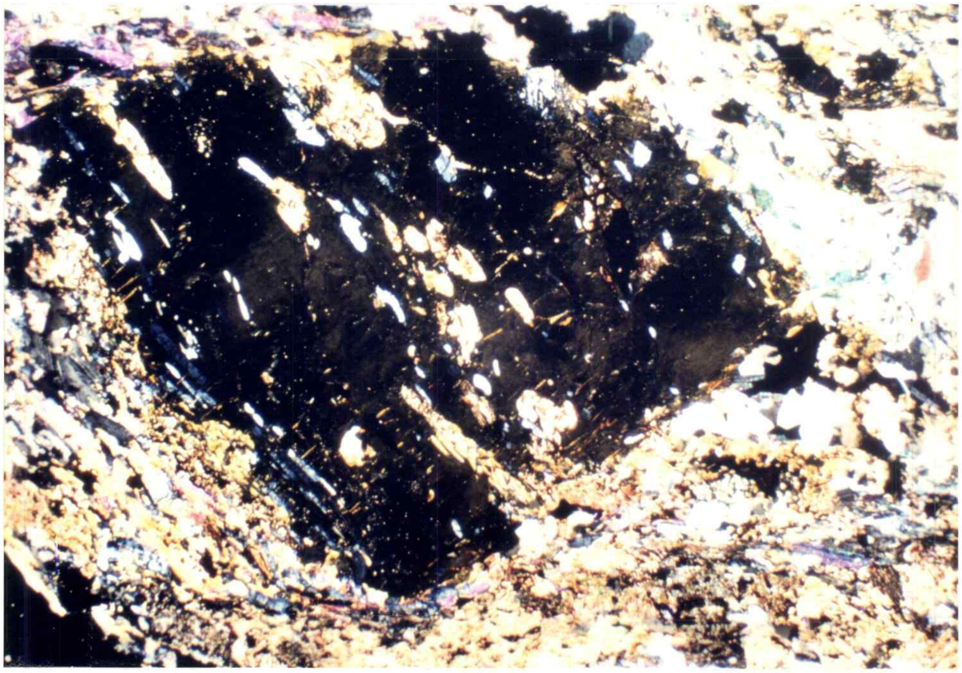

Figure 14. Ferroan pargasite grains showing inclusions which are aligned with the external foliation, and there is deflection of the external foliation against the porphyroblast. This suggests that it was formed during and shortly after this phase. Calc-mica-garnet schist IR-11 (Plate 2). Crossed polars, field of view 4 mm.

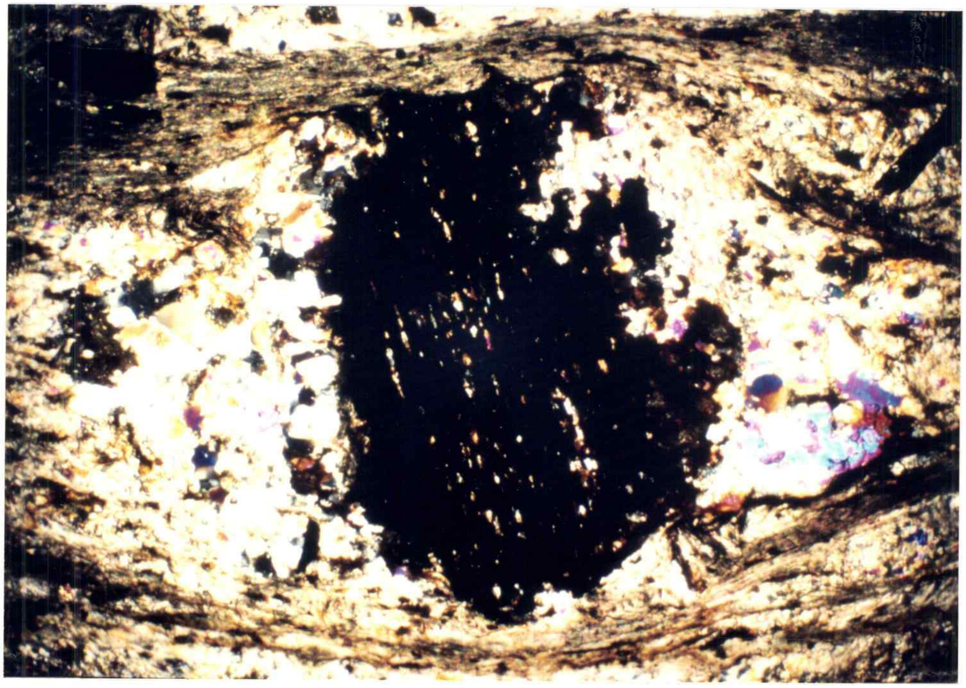

Figure 15. Garnet porphyroblast shows inclusions trail which are oblique or at high angle to the external foliation S_2. There is also deflection of the external foliation against the porphyroblast. This suggest that the garnet porphroblast was rolled during the development of S_2. Graphitic phyllite IR-51 (Plate 2). Crossed polars, field of view 3.5 mm.

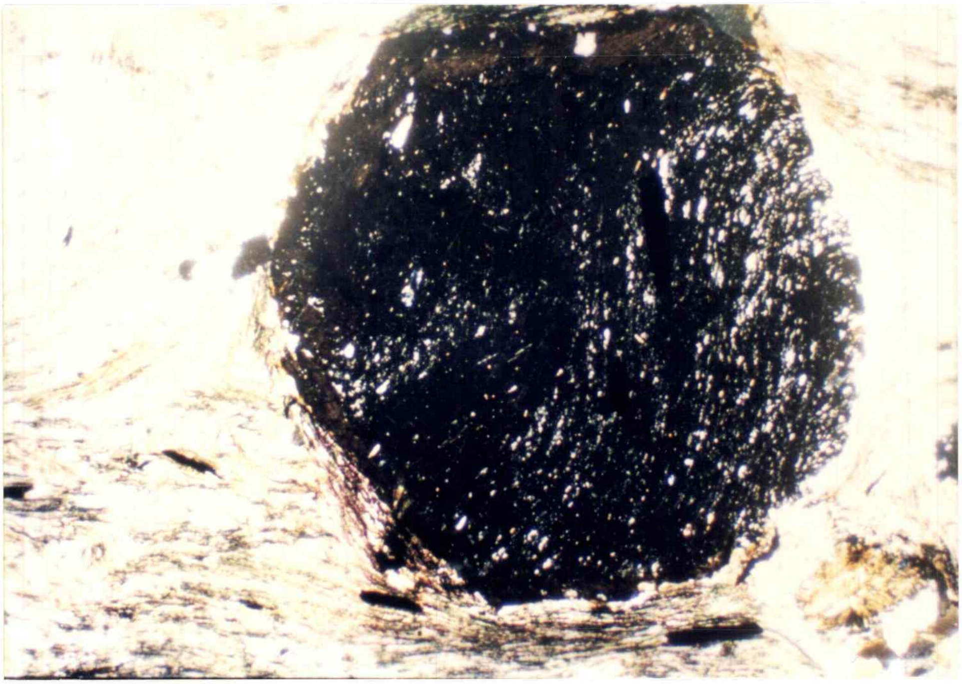

Figure 16. Overgrowth of garnet porphyroblast. It probably grew as flat grain. The inclusion trails on the left of the porphyroblast are straight which indicate that this side of the garnet porphyroblast is early to the S_2 foliation. On the right margin of the porphyroblast the inclusion trails are crenulated which suggest that this portion of the garnet is syntectctonic to the S_2 foliation. Relict of S_1 in the pressure shadow can also be seen. Graphitic phyllite IR-59 (Plate 2). Crossed, polars field of view 4 mm.

porphyroblast are deformed (Figure 17). Such brittle deformation continued throughout the remaining metamorphic history of these rocks.

F3 phase

In the graphitic phyllite and calc-mica-garnet schist, F_3 involved crenulation of the S_2 fabric. The axial planes to F_3 folds, S_3, locally involve a new crenulation cleavage and create the only major lineation in the rocks. S_1 is totally obliterated in those rocks in which F_3 is best developed. In the most sheared calc-mica-garnet schists, garnet has been crushed and occurs only as relicts. This may relate to the different competency of the segment or layers in the rock. Garnets which occur in the quartzo-feldspathic layers are crushed whereas those in the calcite + mica matrix are survived.

Retrograde phase

Retrograde recrystallization in the calc-mica-garnet schist and the graphitic phyllite is recorded by the alteration of the garnet to chlorite, amphibole to biotite, and biotite to chlorite.

Summary

The microscopic features suggest that in the study area the development of S_1 and S_2 took place synchronously with progressive metamorphism to as high as amphibolite facies. During these phases the rocks were pervasively foliated and locally tightly to isoclinally

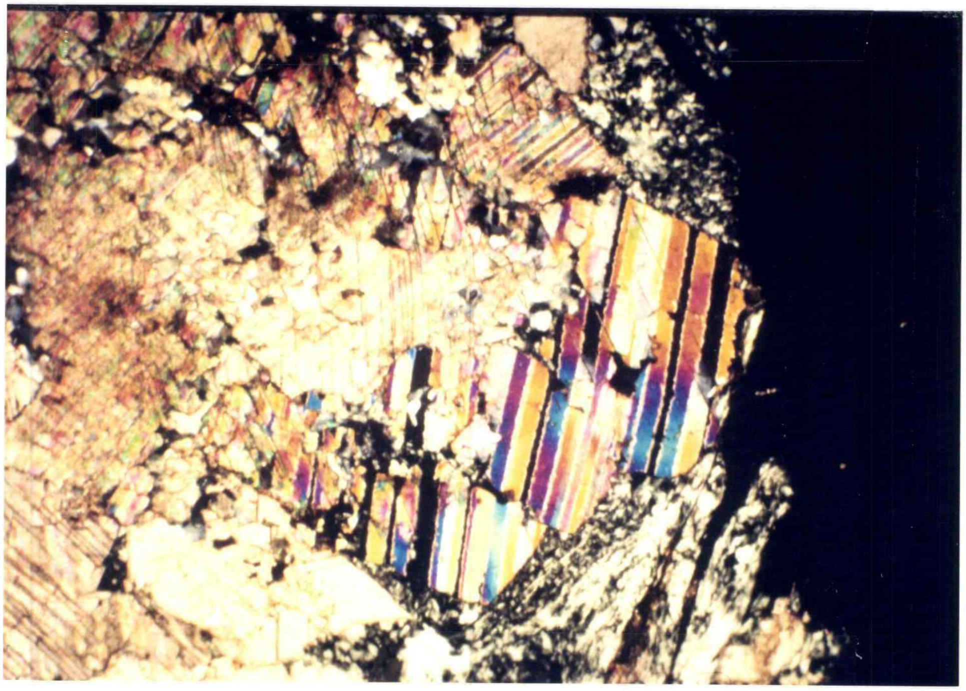

Figure 17. Brecciated calcite porphyroblast which was deformed during the emplacement of late calcite vein. Calc-mica- garnet schist IR-8 (Plate 2). Crossed polars, field of view 4 mm.

folded. During F_3, S_2, was crenulated and involve a new crenulation cleavage and lineation. This was followed by a retrograde phase.

Microscopic features of the Kohistan arc

Microscopic features observed in the Kohistan arc amphibolites are as follows.

(1) An early phase of foliation, S_1, development and growth of amphibole and albite porphyroblasts.

(2) A retrograde phase in which amphibole altered to chlorite.

S_1 development

In the amphibolite, S_1 is defined by the excellent alignment of hornblende and partial alignment of albite, quartz, and epidote group minerals. In some samples lineation has also been observed which is defined by later developed micas. Growth of hornblende and plagioclase was early, because some large crystals have healed fractures which are at a high angle to the enclosing foliation. These large feldspar grains are very cloudy and untwinned so that it is difficult to confirm that they are now albite. The external foliation truncates on the margins of hornblende and albite porphyroblast. In one sample (IR-48) a quartzo-feldspathic layer or vein has buckled due different competency of the quartz + feldspar and amphibole.

Retrograde phase

Retrograde recrystallization in the amphibolite is recorded by the alteration of hornblende to chlorite and rarely to biotite and the replacement of plagioclase with albite.

Structural analysis of fold and fabric elements

For the purpose of structural analysis, the area was divided into three domains bounded by the Kohistan and Kishora thrusts. Little difference in structural patterns was noted across the Kishora thrust so the Garai melange and Indian shelf data are presented together. The small amount of Kohistan data is plotted separately. The structural layout of the area is presented in Plate 3 and Figure 9.

Folds

Three phases of folds are recognized in the melange and shelf sediments south of the Kohistan thrust. The earliest F_1 folds are preserved only locally on the microscopic scale in the calc-mica schist unit of the Kashala formation. One outcrop shows interference patterns that may result from F_1 and F_2 folds (Figure 18). No macroscopic or mesoscopic folds were observed. In most places it appears that F_2 folds have overprinted the F_1 folds completely.

F_2 folds are strongly developed in all three domains. They strike NNE and SSW. These are tight isoclinal folds. In Figure 19a the foliation orientation is generally axial planar to F_2 folds. In

Figure 18. Laminated dark gray marble showing D_2/D_1 interference pattern. F_2 folds superimposed on a dome , or sheath like F_1 folds. View to northeast.

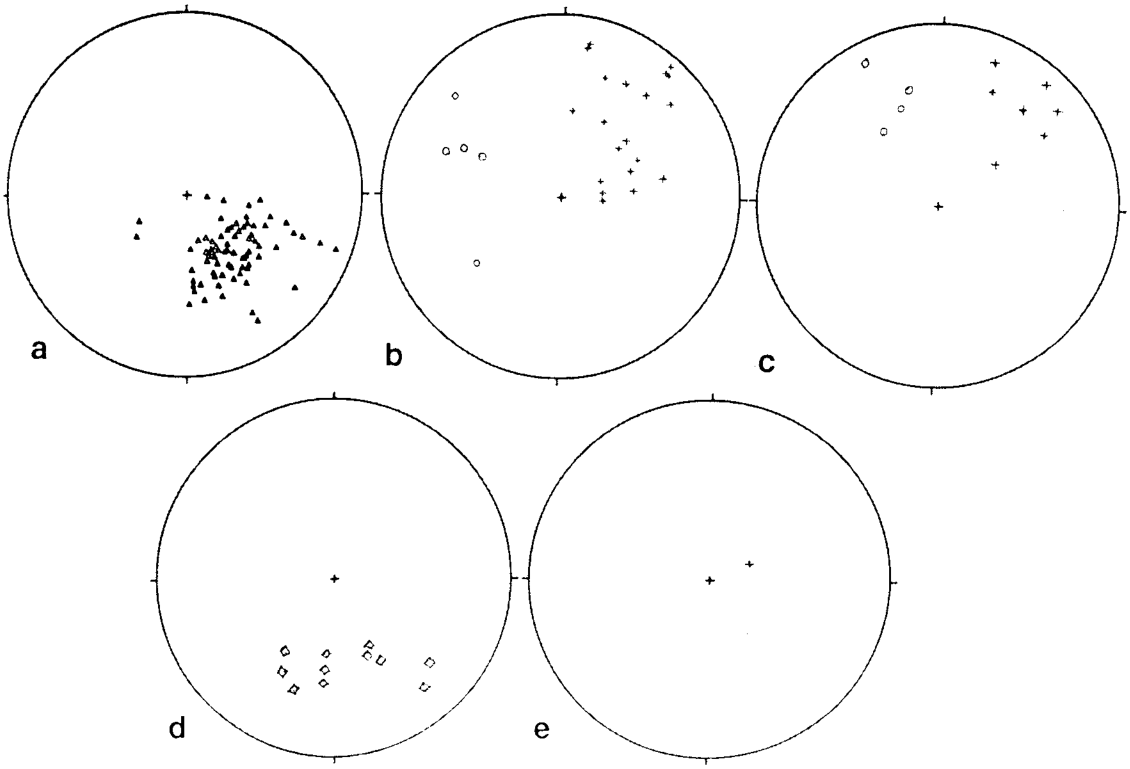

Figure 19. Lower-hemisphere equal area projection of data from Chakdara area. (a) Open triangles, poles to all measured foliation in the Indian shelf and melange terranes. (b) Crosses F_2 folds and open circles F_3 folds, all measured fold axis of the Indian shelf and melange terranes. (c) All measured lineations of the Indian shelf and melange. (d) Diamonds, poles to all measured foliation Kohistan arc. (e) Cross, F_2 folds Kohistan arc.

Figure 19 b and c most of the fold axes and lineations are seen to be developed during this event. Both small and large scale folds are observed. The small scale folds are parasitic to the large scale regional folds. On the large scale, F_2 has folded the Kashala and Saidu formations and the Saidu formation occurs in synclines of these large F_2 folds. They show thickened hinge regions and attenuated limbs (Figure 8); most can be classified as class 1C or 2 according to Ramsay (1967). Similar geometry can be observed in small scale F_2 folds in the calc-mica-garnet unit of the Alpurai group (Figure 20).

F_3 folds strike NNW and SSE. They are common in domains one and two These are small scale upright folds and are oblique to the main foliation (Figure 21). Stereonet plots of these fold axes and related lineations are presented in Figure 19) b and c.

Lineations

Three types of lineations are observed. They are mineral lineation, microscopic crenulation folds, and boudinage. The most prominent lineations are the crenulation lineation and the mineral lineation. The crenulation lineation is very clear in handspecimens and is a penetrative lineation. The mineral lineation is usually a nonpenetrative one with mica flakes defining it on the S surface. It is sometimes penetrative in which case it can be observed in the thin sections too. When plotted together they show NE and NW trends (Figure 19). The lineation trending NE may be related to the later F_2 folds where as those trending NW may be related to the F_3 fold generation. Although difficult to observe, the intersection of

Figure 20. Calc-mica-garnet schist showing F_2 folds and predominant S_2 foliation. See also thickened hinge areas and attenuated limbs after (Ramsay, 1967). View to north northeast.

Figure 21. Phyllite matrix rock showing predominant foliation S_2 and asymmetric kink folds, F_3, with axial surfaces S_3.

inclusions in porphyroblasts of rotated garnet with S_2 also records F_2.

Boudinage lineation is mostly observed in the phyllites where later quartz and calcite veins are boudinaged and elongated (Figure 22).

Cleavages

The most distinct cleavage observed is the crenulation cleavage. This cleavage can be divided into two types (a) zonal crenulation cleavage and (b) sigmoidal (asymmetric) zonal crenulation cleavage after (Gray, 1977; Plat and Visser, 1980). These cleavages are mostly found in the graphitic phyllite, phyllite, and rarely in the calcareous units. The crenulation cleavage also strikes in the NE direction, and probably developed during the F_3 phase (Figure 23).

Relation of the folds to the regional thrust system

F_2 folds are common in all the three domains which are bounded to the south by the Kishora thrust and Kohistan to the north. Structural profiles (Figure 9) illustrate the structural relationship between the later Kohistan and the earlier Kishora thrust faults. I consider that the F_1 of the shelf and the melange matrix and the F_2 of the melange blocks were formed during the emplacement of the Kishora thrust. F_2 folds of all three terranes, except in melange blocks, were formed during the movement on the Kohistan thrust. The general east-west orientation and southwestward vergence of

Figure 22. A quartz vien which is boudinaged. The boudins are elongated during later deformation phases which define the boudinage lineation.

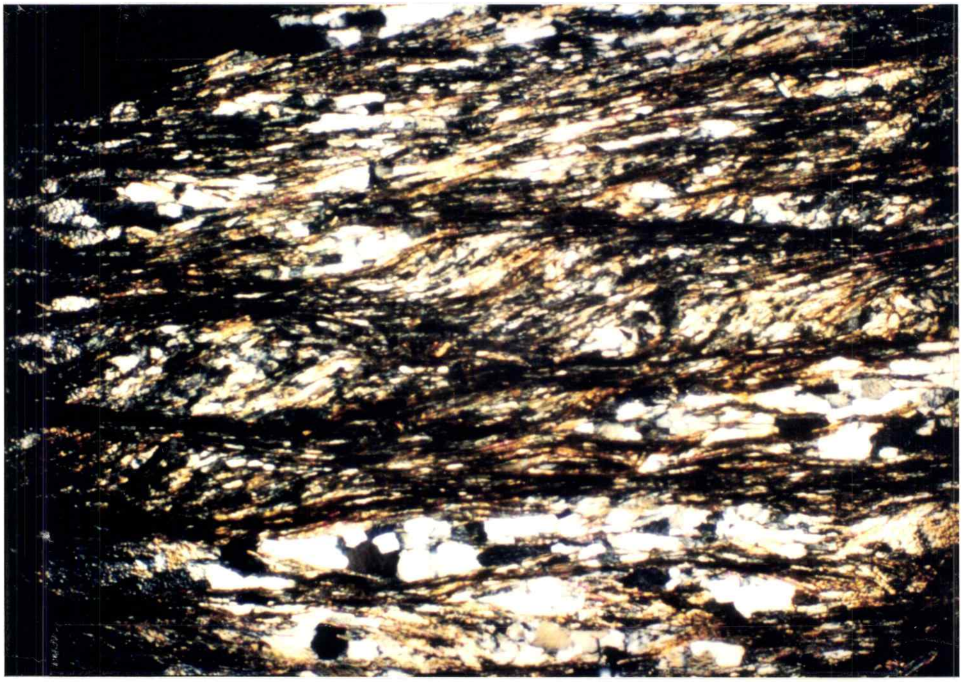

Figure 23. Sigmoidal asymmetric cleavages in phyllite. IR-18 (Plate 2), crossed polars, field of view 5 mm.

these folds argues for NNW-SSE shortening. This would imply probably a south or southeastward thrust direction.

F_3 folds of domain one and two (Plate 3) are later crenulation structures that do not appear in domain three, probably because of the micaceous minerals in those rocks. F_3 fold development is also related to the Kohistan thrust (see below).

DISCUSSION AND CONCLUSIONS

Structure and metamorphism of the study area

A summary of the deformation events and metamorphism in the three terranes is presented in Figure 24. Multiple deformation phases occur in each terrane, but only the latest phases appear to be directly related to each other. Juxtaposition of the terranes during the overthrusting of southern Swat by the Kohistan arc at roughly 30 Ma may explain the cooling-age discontinuity observed across the Main Mantle Thrust (Zeitler, 1982).

Three deformation phases (D_1, D_2, D_3) are recorded in the Indian shelf sediments, during which fabrics S_1, S_2, and S_3 developed in association with folds F_1, F_2, and F_3. The only remaining record of D_1 is S_1, which is preserved locally in the S_2 fabric, in pressure shadows against garnet, and as inclusion trails in the garnet and amphibole porphyroblasts in the calc-mica-garnet schists and graphitic phyllites. Inclusion trails are straight or rotated within garnets and are oblique to the external S_2 fabric. No macroscopic folding event related to S_1 fabric has been recognized. This event probably occurred under greenschist facies metamorphism. During D_2, S_1 was transformed and S_2 was formed. S_2 usually obliterates S_1. S_2 is defined by preferred orientation of calcite, muscovite, paragonite, albite, quartz, pargasite, and epidote. Garnet and amphibole porphyroblasts grew during and just after the formation of S_2. The grade of metamorphism is epidote amphibolite facies. During D_3, S_2 was crenulated, S_1 and garnet were nearly

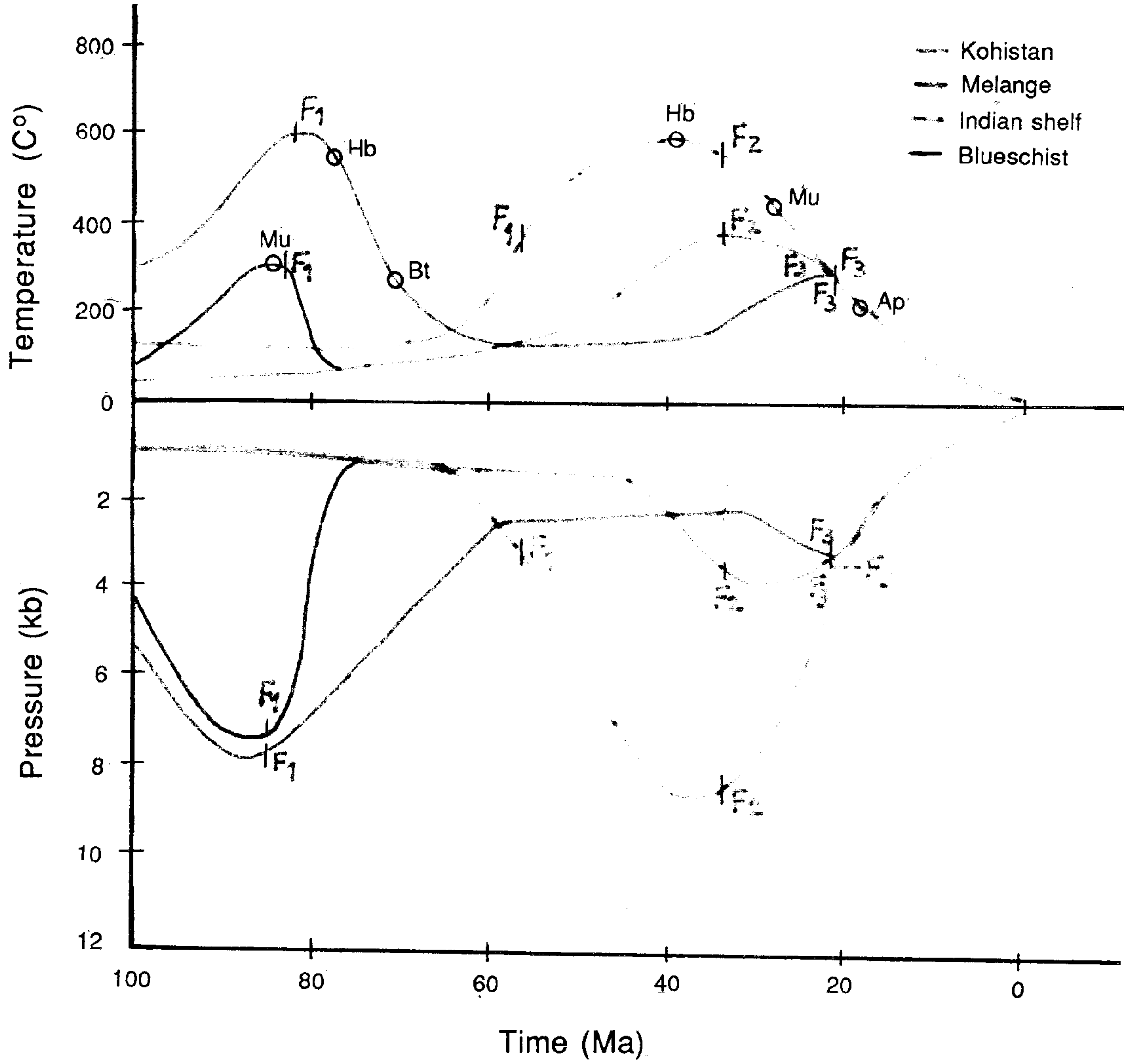

Figure 24. Summary of the deformation events and metamorphism of the present study and part of the lower Swat area. F_1, F_2, and F_3, represent the present deformation events. Hornblende (Hb), biotite (Bt), and muscovite (Mu) Ar^{40}/Ar^{39} dates and cooling temperatures are from Zeitler (1985), Maluski and Matte (1984), Baig (1990). Apatite (Ap) fission track age and cooling temperatures are from Zeitler (1985).

destroyed, and S_3 formed. This event took place at lower grade than D_2, as no new amphibolite facies minerals developed. The principal new crystallization during D_3 is minor mica growth in the crenulation cleavage. Thus D_3 reflects declining metamorphic conditions. This event was followed by substantial retrograde recrystallization in which garnet altered to chlorite, amphibole to biotite and biotite to chlorite, but no new fabric developed.

The Garai melange records somewhat different events between the blocks and the matrix. Apparently the blocks preserve mainly pre-emplacement structures, while the matrix fabric mainly reflects deformation as part of emplacement in the suture zone. Greenschist facies metamorphism of the blocks formed serpentine minerals from original ultramafic materials. The blocks record two deformations and metamorphism reached its highest temperatures during D_1 and phased out by the end of D_2. Low P/T minerals chlorite, albite, and epidote developed during D_1 and early D_2. The temperature of metamorphism was > 200^o C, and the pressure was probably less than 3 kb. S_1 of the blocks formed during D_1 and was folded during D_2. The melange matrix, on the other hand, records three deformations, mainly in the phyllite, the first of which appears to be the same as the younger deformation of the blocks. D_1 of the matrix produced a locally preserved foliation during growth of the greenschist facies minerals chlorite, albite, and muscovite. During D_2 the early S_1 was transposed and often obliterated. The main foliation of the matrix is S_2. Metasomatism was important in the ultramafic rocks of the matrix during D2. Previously present serpentine minerals were extensively replaced by talc, dolomite and magnesite as water and carbon dioxide were added to form talc-carbonate rocks. During D_3, S_2 was folded. The vein mineral assemblages in both the block and matrix rocks provides evidence of P/T uplift paths and conditions during emplacement of the various blocks into the melange. Vein minerals common in the talc-carbonate include fuchsite, carbonates, and quartzo-feldspathic composition confirming greenschist facies metamorphic conditions.

The Kohistan arc rocks suffered two deformation phases. During D_1, S_1 and F_1 developed under amphibolite facies conditions. This deformation appears to have occurred before the Kohistan arc was associated with the other rocks of the area. It was followed by retrograde recrystallization of albite and chlorite and minor deformation D_2.

The inferred relationship of folding events between terranes and to the terrane bounding thrust faults is shown in (Table 5). I suggest that the F_1 folds of the shelf and melange matrix and the F_2 folds of the melange blocks were formed during the juxtaposition of these two terranes by motion on the Kishora thrust. I infer that the F_2 folds of all three terranes, except in the melange blocks, were formed by the movement on the Kohistan thrust during juxtaposition of the Kohistan terrane. F_3 folds of the melange and shelf terranes are later crenulation structures that do not appear in Kohistan, probably because of the lack of micaceous minerals in those rocks. F_1 folds in the Kohistan terrane and melange blocks probably formed before the terranes came together.

	KOHISTAN	GARAI MELANGE Blocks	Matrix	INDIAN SHELF
	D1----┤	├----D1		
Kishora thrust		├---- D2 -----	-----D1-----	-----D1
Movement on Kohistan Thrust	D2-----	-------------	----- D2 -----	----- D2
			D3-----	-----D3

Table 5. Relation of deformation phases between tectonic terranes of the study area.

Relation to structural development of neighboring areas

Southeast of the Swat River, the Kishora thrust is reported to be everywhere in contact with the Saidu formation (Kazmi and others, 1986; Lawrence and others, 1989; DiPietro, 1990). Based on this criterion DiPietro (1990) concluded that the Kishora thrust overrode the lower Swat area along a flat thrust at the top of the Alpurai group, presumably during the earliest deformation. In the study area the Kishora thrust is in contact with both the Saidu and Kashala formations. A major bend in the thrust coincides with the contact with the Kashla formation (Plate I). Therefore, in support of DiPietro's suggestion, the geometry of the Kishora thrust in the study area may be a ramp that connects to the major flat to the southeast.

In the Mingora area and south (Lawrence and others, 1989; DiPietro, 1990), and in the Alpurai and Ajmar areas (Baig, 1990), the Swat block records four fabrics. DiPietro (1990) reported that the earliest superposed small scale folds (F_1 and F_2), are co-axial and co-planar with isoclinal, recumbent axial surfaces and fold axes plunge gently toward the NNW and SSE. Small scale F_3 folds are closed to tight with variably dipping axial surfaces. Large scale F_3 folds are upright and open, trend to north-south, and plunge south or southeast. F_4 folds are upright and variably tight to open and trend east-west. He related the F_1/F_2 and F_3 to movement on the Kishora thrust. F_4 was related to the change of forces from westward to southward in the lower Swat when the Kohistan thrust developed. The three early fabrics reflect north-south to northwest-southeast oriented structures. All four relate to prograde Himalayan deformation and metamorphism, but S_1 is preserved only intrafolially. Baig (1990) reported an S_1 in the Panjpir area that is preserved as an intact fabric. Thus older fabrics are better preserved to the south; metamorphic intensity continued longer to the north. Indeed, no structures similar to the first three fabrics seen to the south are present in the study area. The only remnant of these early events is probably the locally preserved, transposed S_1 fabric north of the Swat River. F_2 folds of the study area are the best preserved indicators of the relation of structures across the Swat River. Their general east-west trend and SSE vergence correlate to DiPietro's F_4 (DiPietro, 1990). F_3 of the study area may correlate with the development of the Indus syntaxis (NS trending), the last tectonic event reported by Baig (1990).

Across the Swat River there is a major tectonic contrast. Many of the structures present to the southeast are not present north of the river, probably because metamorphic reconstruction of the rocks after these events was more complete. This suggests that a large thrust fault is concealed beneath alluvium along the river. Motion on such a fault may have brought the areas north and south of the river together.

Timing of deformation events

At present no isotopic dates clearly document the timing of the earliest fabric development in the region. S_1 and S_2 in the Swat region probably relate to early phases of prograde Himalayan deformation (Lawrence and others, 1989; DiPietro, 1990) but conceivably could be separate earlier events. Baig (1990) has dated fabrics in the Panjpir which he interprets to be equivalent to these early fabrics of the metamorphic rocks farther north. His $^{40}Ar/^{39}Ar$ ages are >83-85 Ma, which he relates to S_1 development, and around 63 Ma, which he relates to the development of S_2. No fabric from this time is recognized as preserved in the study area north of the Swat River.

Lawrence and others (1985) and L. Snee (in Palmer-Rosenberg, 1985) obtained $^{40}Ar/^{39}Ar$ ages of 39.9 ± 0.2, 39.8 ± 0.3 and 37.1 ± 0.7 Ma from hornblende in the Marghazar formation near Jowar and ages 30.6 ± 0.4 and 29.5 ± 0.3 Ma from muscovite in the Kashala formation near Saidu. These ages are similar to the younger K-Ar and $^{40}Ar/^{39}Ar$ ages obtained by Treloar and others (1989a) in this area. Polygonized and recrystallized hornblende in the hinge areas of F_3 crenulation folds in the Marghazar formation indictes that hornblende recrystallized during or after DiPietro's F_3 phase (DiPietro, 1990). Therefore, 38 Ma is the minimum age for the F_1/F_2 and F_3 deformation phases south of the Swat River (DiPietro, 1990).

Muscovite, biotite, and alkali feldspar $^{40}Ar/^{39}Ar$ data from the Swat block (Snee in Rosenberg, 1985) record thermal cooling through 300° C. Two maximum dates on muscovite from the Jowar area south of the suture zone are between 30 and 29 Ma. The third muscovite date from near the suture zone yielded an argon loss spectra from 80 ± 0.2 Ma to 35 ± 0.15 Ma. This date hints of a Late Cretaceous metamorphic event, reset at about 35 Ma, during Himalayan shearing (Baig, 1990). Recently, additional muscovites, biotites, and alkali feldspars have been dated from a sheared sample of Swat granite gneiss (Baig, 1990). Biotite has a preferred date of 32 ± 0.13 Ma and muscovite has a plateau date of 28 ± 0.2 Ma. Potassium feldspar has an argon loss spectrum with a maximum date of 45 ± 0.2 Ma and minimum date 22 ± 0.1 Ma. Baig (1990) interprets these data to indicate that S_1, S_2, S_3, and S_4 in the area south of the Swat River formed before 45 Ma. However, the younger foliations in the area only involve minor new mica growth, clearly reflected in the numerous younger dates between 28 and 32 Ma. At least F_4 in the Mingora area is probably this young.

I have correlated S_2 from the study area north of the Swat River with S_4 from the area to the south. If this is correct, F_2 and F_3 deformation phases in the study area probably occured between 28 and 32 Ma.

Timing of melange development

The association of chert, metabasic rocks, and ultramafic rocks in the Garai melange complies with current definitions of the ophiolite suite (Gansser, 1974; Coleman, 1978; Dewey and Bird, 1971; Moores and Vine, 1971). I consider this melange to be an extension of the Mingora ophiolitic melange southeast of the study area of the MMT zone.

The MMT is considered a major crustal-scale thrust carrying the Kohistan island arc sequence along the hanging wall (Tahirkheli, 1979; Jan and Bard, 1982; Coward and others, 1982). The Kohistan island arc terrane sutured to the Asian plate in the Late Cretaceous and predates the collision of the Indo-Pakistan plate with the Kohistan island arc terrane in the Eocene (Coward and others, 1986,1987; Treloar and others, 1989). Thrust bounded wedges of granulites (Jijal complex) and blueschist crop out along the MMT in southern Kohistan. The granulites of the Jijal complex have a Sm-Nd isochron of 103 Ma (Thirwall in Coward and others, 1986), indicating that they formed prior to the collision at the base of the Kohistan arc. The blueschist near Shangla has $^{39}Ar/^{40}Ar$ age of 80 $\pm$ 5 Ma (Maluski and Matte, 1984). Similar results from the blueschist in Ladakh indicate that northward subduction beneath and southward thrusting of the Kohistan arc was active during the Late Cretaceous (Searle, 1986). Kazmi and others (1984) interpreted the Shangla blueschist melange to have developed above a subduction zone, north of the Neotethys and oceanward of the Kohistan arc, that operated during Jurassic-Cretaceous ocean closure. The Mingora melange on the other hand was interpreted a block obducted onto the Indo-Pakistan subcontinent similar to Lasbela, Muslimbagh, Waziristan, Logar, Dargai, Spontang, and Jungbawa blocks (Asrarullah and others, 1979; Abas and Ahmad, 1979; Dejong and Subhani, 1979; Gansser, 1980; Thakur, 1981). These melanges were interpreted to have been generated at a midocean ridge in the Neotethys and emplaced on the northern margin of the Indian subcontinent some time between late Cretaceous and early Eocene. Recently Baig (1990) reported a fuchsite yielding a plateau date of 82 $\pm$ 0.22 Ma from fuchsite bearing schist in the Mingora ophiolitic melange. This also suggests a Cretaceous time for the development of the Mingora ophiolitic melange similar to the Shangla blueschist melange. As the Garai melange is a extension of the Mingora ophiolitic melange, the same age constraint can be applied.

Emerald mineralization

Emerald mineralization is associated with the Garai melange. This is a new addition to the previously reported emerald bearing ophiolitic melanges in the Mingora, Malakand, and Mohmand areas (Kazmi and Snee, 1989). The ultramafic rocks of the ophiolitic suites are considered to be the source of the chromium, which colors the beryl to make emeralds (Snee and others, 1989; Hammarstrom, 1989). The Mingora emerald deposits are extensively studied (Kazmi and others, 1984,1986; Lawrence and others, 1989; Snee and others, 1989). These authors associated the emerald mineralization with four occurences (1) faults and fractures, (2) limonite zones, (3) calcite nodules and veinlets, and (4) quartz stockworks. The emeralds are considered to have formed after the major deformation was complete. The mineralization is structurally controlled, and emeralds were formed during shearing and the last stage of alteration of the Mingora ophiolitic melange. Emeralds in the first two cases mainly occur in the groundmass of the talc + chlorite + dolomite schist with no significant quartz-calcite veins or stockworks in the vicinity. Emerald mineralization in calcite-quartz fissure fillings and stockworks probably formed later during a more hydrous phase when the mineralizing fluids contained relatively larger amount of silica, carbon dioxide, beryllium and boron. Emerald mineralization was preceded by limonization and was followed by the deposition of calcite.

During the present study the mineralization zone was not accessible. However, the talc-carbonate blocks in the other parts of the study area are rich in calcite, quartz, and fuchsite-bearing veins. Limonite staining northwest of the Garai village (Plate 1) is common in weathered talc-carbonate rocks. Thus, it is most probable that the emerald mineralization in the study area is associated with faults and fractures and limonite zones. Further investigation of the study area may result in locating new mineralized zones.

REFERENCES

Abbas, S.G., and Z. Ahmad, 1979, The Muslimbagh Ophiolites, in A. Farah and K.A. Dejong, eds., Geodynamic of Pakistan: Geological Survey of Pakistan, Quetta, p. 243-250.

Ahmad, I., 1986, Geology of Jowar area, Karakar pass, Swat district, N.W.F.P., Pakistan: Unpublished M.phil. thesis University of Peshawar, Pakistan, 144p.

Ahmad, I., P.S. Rosenberg, R.D. Lawrence, A.A.K. Ghauri., and M. Majid,1988, The new stratigraphic model for the rocks of Karakar pass section, south of the Main Mantle Thrust, Swat, district N.W.F.P. Pakistan: Geological Bulletin University of Peshawar, v. 20, p. 189-198.

Ahmad, Z., and M.N. Chaudry, 1976, Geology of Babusar area, Diamir district, Gilgit, Pakistan: Geological Bulletin Punjab University, Pakistan, no. 12, p. 67-68.

Apted, M., and J.G. Liou, 1983, Phase relations among greenschist, epidote amphibolite, and amphibolite in a basaltic system: American Journal of Science, v. 283A, p. 328-354.

Ashraf, M., M.N. Chaudry, and S.S. Hussain, 1980, General geology and economic significance of the Lahor granite and rocks of the southern ophiolite belt in Allai Kohistan area: Geological Bulletin University of Peshawar, Pakistan, v. 13, p. 207-213.

Asrarullah, Z. Ahmad, and S.G. Abbas, 1979, Ophiolites in Pakistan: an introduction, in A. Farah and K.A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 181-192.

Atherton, M.P., 1968, The variation in garnet, biotite, and chlorite composition in medium grade pelitic rocks from the Dalradian, Scotland, with particular reference to the zonation in garnet: Contribution to Mineralogy and Petrology, v. 18, p. 347-371.

Baig, M.S., 1990, Structure and Geochronology of pre-Himalayan and Himalayan orogenic events in NW Himalaya, with special reference to the Besham area: Unpublished Ph.D. thesis, Oregon State University, Corvallis, Oregon, 397 p.

Bard, J.P., H. Maluski, and F. Proust, 1980, The Kohistan sequence; crust and mantle of an obducted island arc: Geological Bulletin University of Peshawar, v. 13, p. 87-94.

Bard, J.P., 1983, Metamorphic evolution of an obducted island arc; Example of the Kohistan sequence (Pakistan) in the Himalayan collided range: Geological Bulletin University of Peshawar, v. 16, p. 105-184.

Barton, M.D., 1986, Phase equilibria and thermodynamic properties of minerals in the BeO-Al_2O_3-SiO_2-H_2O (BASH) system with petrologic applications: American mineralogist, v. 71, p. 277-300.

Berkland, J.O., 1972, Paleogene "frozen" subduction zone in the Coast Range of the northern California: 24th International Geological Congress, Montreal, Sec. 3, p. 99-105.

Butt, K.A., M.N. Chaudry, and M. Ashraf, 1980, An interpretation of petrogenetic assemblage west of western Himalayan syntaxis in Dir district and adjoining areas in northern Pakistan: Geological Bulletin University of Peshawar, Pakistan, v. 13, p. 79-86.

Butt, K.A., 1981, Hydrothermal phenomena associated with Lahor pegmatoid/granite complex, Kohistan: Geological Bulletin University of Peshawar, Pakistan, v. 14, p. 85-93.

Butt, K.A., 1983, Petrology and geochemical evolution of Lahor pegmatoid/granite complex, northern Pakistan, and genesis of associated Pb-Zn-Mo and U mineralization in granites: In Granites of the Himalaya and Karakorum and Hindukush (F.A. Shams, eds.) Institute of Geology, Punjab University, Lahore, p. 309-326.

Calkins, J.A., T.W. Offield, S.K.M. Abdullah, and S.T. Ali,1975, Geologyof the southern Himalayas in Hazara: U.S. Geological Professional Paper 716-C, 29 p.

Cloos, M., 1983, Comparative study of melange matrix and metashales from the Franciscan subduction complexwith the basal Great Valley sequence, California: Journalof Geology, v. 91, p. 291-306.

Cloos, M., 1985, Thermal evolution of convergent plate margins: thermal modeling and reevaluation of isotopic Ar-ages for blueschists in the Franciscan Complex of California: Tectonics, v. 4, p. 421-433.

Coleman, R.G., 1977, Ophiolites: Ancient oceanic lithosphere?: Springer-Verlag New York, 229p.

Cowan, D.S., 1977, Origin of blueschist-bearing chaotic rocks in the Franciscan complex; San Simeon. California: Geological Society of American Bulletin, v. 89, p. 1415-1423.

Coward, M.P., M.Q. Jan, D. Rex, J. Tarney, and B.F. Windley, 1982, Geotectonic framework of the Himalaya N. Pakistan: Journal Geological Society of London, v. 139, p. 299-308.

Coward, M.P., and W.H. Butler, 1985, Thrust tectonics and the deep structures of the Pakistani Himalaya: Geology, v. 13, p. 417-420.

Coward, M.P., B.F.Windley, R.D. Broughton, I.W. Luff, M.G. Peterson, C.J. Pudsey, D.C. Rex, and M.A. Khan, 1986, Collision tectonics in the NW Himalaya: In Collision tectonics, (M.P. Coward and A.C. Ries, eds.) Geological Society Special Publication 19, Blackwell Scientific Publications, London, United Kingdom, p. 203-219.

Coward, M.P., R.W.H. Butler, M.A. Khan, and R.J. Knipe, 1987 The Tectonic history of Kohistan and its implications for Himalayan structure: Journal of Geological Society London, v. 144, p. 377-391.

Dejong, K.A., and A.M. Subhani, 1979, Note on the Bela ophiolites, with special reference to the Kanar area, in A. Farah and K.A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 263-270.

Desio, A., 1964, Tectonic relationship between the Karakorum Pamirand Hindukush: Report XXLL Sess. India International Geological Congress, New Dehli, v. 11.

Dewey, J.F., and J.M. Bard, 1971, Origin and replacement of the ophiolite suite: Apalachian ophiolites in Newfoundland: Journal of Geophysical Research, v. 76, p. 3179-3206.

DiPietro, J.A., 1990, Stratigraphy, structure, and metamorphism near Saidu Sharif, Lower Swat, Pakistan: Unpublished Ph.D. thesis, Oregon State University, Corvallis, Oregon, 182 p.

Evans, B.W., 1977, Metamorphism of alpine peridotites and serpentinites: Annual Review of Earth and Planetary Sciences, v. 5, p. 397-448.

Gansser, A., 1964, Geology of the Himalaya: Wiley Interscience, NewYork, New York, 289p.

Gansser, A., 1974, The ophiolite melange, a world wide problem on Tethyan examples: Ecolagae Geolgicae Helvetiae, v. 67, p. 469-507.

Gansser, A., 1980, The significance of Himalayan suture zone: Tectonophysics, v. 62, p. 37-52.

Ghazanfar, M., M.S. Baig, and M.N. Chaudry, 1983, Geology of Tithwal-Kel, Neelum valley, Azad Jammu and Kashmir: Kashmir Journal of Geology, Institute of Applied Geology, Azad Jammu and Kashmir, University Muzffarabad (A.K), Pakistan, v. 1, no.1, p. 1-10.

Gray, D.R., 1977, Morphological classification of crenulation cleavage: Journal of Geology, v. 85, p. 229-235.

Hammarstrom, J.M., 1989, Mineral chemistry of emeralds and associated minerals from Pakistan and Afghanistan: an electron microprobe study: In A.H. Kazmi and L.W. Snee,editors, Emeralds of Pakistan: Geology, Gemology and Genesis; Van Nostrand Reinhold, New York, p. 125-150.

Honegger, K.V., W. Dietrich, A. Frank, M. Gansser, M. Thoeni, and Trommsdorff, 1982, Magmatism and Metamorphism in the

Ladakh Himalaya (the Indus Tsangpo zone): Earth Planetary Science Letters, v. 60, p. 253-292.

Hsu, K.J., 1971, Franciscan melanges as a model for eogeosynclinal sedimentation and underthrusting tectonics: Journal of Geophysical Research, v. 75/5, p. 1162-1170.

Jan, M.Q., and R.D.C. Kempe, 1973, The petrology of the basic and intermediate rocks of upper Swat, Pakistan: Geological Magazine, v. 110, p. 285-300.

Jan, M.Q., 1977a, The mineralogy, geochemistry, and petrology of Swat Kohistan, NW Pakistan: Unpublished Ph.D. thesis University of London, 349p.

Jan, M.Q., 1977b, The Kohistan basic complex, a summary based on recent petrological research: Geological Bulletin University of Peshawar, Pakistan, v. 9-10 p. 36-42.

Jan, M.Q., 1979a, Petrography of the Jijal complex, Kohistan: Geological Bulletin University of Peshawar, v. 11, p. 51-64.

Jan, M.Q., 1979b, Petrography of the amphibolites of Swat and Kohistan: Geological Bulletin University of Peshawar, v. 11, p. 51-64.

Jan, M.Q., 1979c, Petrography of the quartz diorites to the south of Kalam, Swat: Geological Bulletin University of Peshawar, v. 11, p. 87-97.

Jan, M.Q., 1980, Petrology of the obducted mafic and ultramafic metamorphites from the southern part of the Kohistan island arc sequence: Geological Bulletin University of Peshawar, v. 13, p. 95-107.

Jan, M.Q., 1980a, Chemical changes accompanying the granulite to amphibolite transition in Swat, NW Pakistan: In Contemporary Geoscientific Researches in Himalaya, (S.P. Nautiyal vol.) Himachel Times Pres., Dera Dun, India, p. 149-152

Jan, M.Q., 1985, High-P rocks along the suture zone around Indo-Pakistan plate chemistry of blueschists from eastern Ladakh: Geological Bulletin University of Peshawar, v. 18, p. 1-40.

Jan, M.Q., and R.A. Howie, 1980b, Ortho and clinopyroxenes from the pyroxene granulite of Swat Kohistan, northern Pakistan: Mineralogical Magazine, v. 43, p. 715-26.

Jan, M.Q., and R.A. Howie, 1981a, The mineralogy and geochemistry of the metamorphosed basic and ultrabasic of the Jijal complex Kohistan, northwest Pakistan: Journal of Petrology, v. 22, p. 85-126.

Jan, M.Q., M. Kamal, and M.I. Khan, 1981b, Tectonic control over emerald mineralization in Swat: Geological Bulletin University of Peshawar, v. 14, p. 101-109.

Kazmer, C., 1986, The Main Mantle Thrust zone at Jawan pass area, Swat, Pakistan: Unpublished M.S. thesis, Univ. of Cincinatti, 79p.

Kazmer, C., S.S. Hussain, and R.D. Lawrence, 1983, The Kohistan Indian plate suture zone at Jawan pass, Swat, Pakistan: Geological Society of America, Abstract with Programs, v. 15, p. 609.

Kazmi, A.H., R.D. Lawrence, H. Dawood, L.W. Snee, and S.S. Hussain, 1984, Geology of the Indus suture zone in the Mingora-Shangla area of Swat: Geological Bulletin University of Peshawar, v. 17, p. 127-144.

Kazmi, A.H., R.D Lawrence, J. Anwar, L.W. Snee, and S.S. Hussain, 1986, Mingora emerald deposits (Pakistan): Suture associated gem mineralization: Economic Geology, v. 81, p. 2022-2028.

Landis, C.A., 1971, Graphitization of dispersed carbonaceous material in metamorphic rocks: Contribution to Mineralogy and Petrology, v. 30, p. 34-45.

Lawrence, R.D., C. Kazmer, and R.A.K. Tahirkheli, 1983, The Main Mantle Thrust: a complex zone, northern Pakistan: Geological Society of America, Abstract with Programs, v. 15, p. 624.

Lawrence, R.D., and P.S. Rosenberg, 1985, Nappe structure in a crustal scale duplex in Swat, Pakistan: Geological Society of America Abstract with Programs, v. 17, p. 640.

Lawrence, R.D., A.H. Kazmi, and L.W. Snee, 1989, Emerald deposits of Pakistan: in A.H. Kazmi and L.W. Snee editors, Emeralds of Pakistan: Geology, Gemology, and Genesis; Van Nostrand Reinhold, New York, New York, p. 13-38.

Leake, B.J., 1978, Nomenclature of amphiboles: Mineralogical Magzine, v. 42, p. 533-563.

LeBas, M.J., I. Mian, and D.C. Rex, 1987, Age and nature of carbonatite emplacement in north Pakistan: Geolgische Rundschau, v. 76/2, p. 317-323.

LeFort, P., F. Debon, and J. Sonet, 1980, The "Lesser Himalaya "corderite granite belt, typology and age of the pluton of Mansehra, Pakistan: Geological Bulletin University of Peshawar, v. 13, p. 51-62.

LeFort, P., F. Debon, and J. Sonet, 1983, The lower Paleozoic "Lesser Himalaya" granitic belt: Emphasis on the Simchar pluton of central Nepal, in Granites of Himalayas Karakorum and HinduKush, edited by F.A. Shams, Institute of Geology, University of Punjab, Lahore, Pakistan, p. 235-255.

Lillie, R.J., and R.D Lawrence, 1989, Structure of Himalayan Foreland Thrust Belt in Pakistan: 28th IGC Abstracts, v. 2 of 3, p. 2-300- 2-301.

Majid, M., and F.A. Paracha, 1980, Calc-alkaline magmatism at destructive plate margin in Kohistan northern Pakistan: Geological Bulletin of University of Peshawar, v. 13, p. 109-120.

Maluski, H., and P. Matte, 1984, Ages of alpine tectonometamorphic events the northwestern Himalaya (northern Pakistan) by Ar/Ar method: Tectonics, v. 3, p. 1-18.

Marshak S., and G. Mitra, 1988, Basic methods of structural geology: Prentice-Hall, Inc., Englewood Cliffs, NewJersey, 446 p.

Martin, N.R., S.F.A. Siddiqui, and B. King, 1962, A geological reconnanssaince of the region between the lower Swat and Indus River of Pakistan: Geological Bulletin Punjab University, v. 2, p. 1-14.

Maruyama, S., K. Suzuki, and J.G. Liou, 1983, Greenschist-amphibolite transition equilibria at low pressures: Journal of Petrology, v. 24, p. 583-604.

Mc Call, G.J.H., ed., 1983, Ophiolitic and related melanges: Benchmark Papers in Geology, v. 66, 443 p.

Miyashiro, Akiho, 1973, Metamorphism and metamorphic belts: New York, Harper and Row, 514 p.

Moore, E.M., 1981, Ancient suture zone within continents: Science, v. 213, p. 41-46.

Moore E.M., and F.J. Vine, 1971, The Troodos Massif, Cyprus, and other ophiolites as oceanic crust: Evaluation and implications: Royal Society London Philos, Trans., Ser, A., v. 268, p. 443-466.

Petterson, M.G., and B.F. Windley, 1985, Rb/Sr dating of the Kohistan arc batholith in the Trans-Himalaya of north Pakistan, and tectonic implications: Earth and Planetary Science Letters, v. 74, p. 45-57.

Platt, J.P., and R.L.M. Vissers, 1980, Extensional structures in anisotropic rocks: Journal of Structure Geology, v. 2, p. 397-410.

Pogue, K.R., and A. Hussain, 1988, Paleozoic stratigraphy of the Peshawar basin, Pakistan: Geological Society of America, Abstract with programs, 20, p. 266-267.

Pogue, K.R., Wardlaw, A. Harris, and A. Hussain, (In prep.), Paleozoic-Mesozoic Tethyan stratigraphy of the Peshawar basin, Pakistan: Correlations and Implications: Geological Society of American Bulletin.

Pogue, K.R., J.A. DiPietro, S. Hughes, R.D. Lawrence, and S.Rahim, (in Prep. a), Paleozoic rifting in northern Pakistan: Tectonics.

Powell, C.M.A., 1979, A speculative tectonic history of Pakistan and surrounding: some constraint from the Indian ocean: in A. Farah and K.A. Dejong, Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 524.

Raase, P., 1974, Al and Ti contents of hornblende, indicators of pressure and temperature of metamorphism: Contributions to Mineralogy and Petrology, v. 45, p. 231-236.

Ramsay, J.G., 1967, Folding and fracturing of rocks: New York, McGraw-Hill, 568 p.

Ramsay, J.G., and M.I. Huber, 1987, The techniques of modern structural geology, Vol. 2, folds and fractures: Academic press, London, p. 309-700.

Raymond, L.A., eds., 1984, Melanges: Their nature, origin, and significance: Geological Society of America, Special paper, 198, p. 169-170.

Rosenberg, P.S., 1985, Himalayan deformation and metamorphism of rocks south of the Main Mantle Thrust zone, Karakar pass area southern Swat, Pakistan: Unpublished M.S. thesis, Oregon State University Corvallis, Oregon, 68p.

Shackleton, R.M., 1951, The Kavirondo Rift Valley: Journal Geological society of London, v. 106, p. 345-392.

Searle, M.P., B.F. Windley, M.P. Coward, D.J.W. Cooper, A.J. Rex, D. Rex,Li. Tingdong, Xuchang, Xiao., M.Q. Jan, V.C. Thakur, and S. Kumar,1987, The closing of Tethys and the tectonics of Himalaya: Geological Society of American Bulletin, v. 98, p. 678-701.

Shams, F.A., 1972, Glaucophane bearing rocks from near Topsin, Swat, first record from Pakistan: Pakistan Journal of Science, v. 24, p. 343-345.

Shams, F.A., 1972, Glaucophane bearing rocks from near Topsin, Swat, first record from Pakistan: Pakistan Journal of Science, v. 24, p. 343-345.

Shams,F.A., 1980, Origin of the Shangla blueschist Swat Himalaya, Pakistan: Geological Bulletin University of Peshawar, v. 13, p. 67-70.

Shams, F.A., 1983, Granites of the northwestern Himalayas in Pakistan: in Granites of Himalayas Karakorum and Hindukush, edited by F.A.Shams Institute of Geology, Punjab University, Lahore, Pakistan, p. 341-354.

Shams, F.A., G.C. Jones, and R.D.C. Kempe, 1980, Blueschists from Topsin, Swat district, NW Pakistan: Mineralogical Magzine, v. 79, p. 1331-1350.

Silver, E.A., and E.C. Beutner, 1980, Penrose Conference report: Melanges: Geology, v. 8, p. 32-34.

Snee, L.W., E.E. Foord, B. Hill, and S.J. Carter, 1989, Regional chemical differences among emeralds and host rocks of Pakistan and Afghanistan: implications for the origin of emerald: in A.H. Kazmi and L.W. Snee, editors, Emeralds of Pakistan: Geology, Gemology, and Genesis, Von Nostrand Reinhold New York, p. 93-124.

Spear, F.S., and J.T. Cheney, 1989, A petrogenetic grid for pelitic schists in the system SiO_2-FeO-MgO-K_2O-H_2O: Contribution to Mineralogy and Petrology, v. 101, p. 149-164.

Sturt, B.A., 1962, The composition of garnets from pelitic schist in relation to the grade of regional metamorphism: Journal of Petrology, v. 3, p. 181-191.

Tahirkheli, R.A.K.,1979a, Geotectonic evolution of Kohistan: Geological Bulletin University of Peshawar, v. 11, p. 113-130.

Tahirkheli, R.A.K., 1979b, Geology of Kohistan and adjoining Eurasian Indo-Pakistan continents, Pakistan: Geological Bulletin University of Peshawar, v. 11, p. 1-30.

Tahirkheli, R.A.K., M. Mattauer, F. Proust, and P. Taponier, 1979, The India-Eurasia suture zone in northern Pakistan: Synthesis and interpretation of recent data at plate scale: in A. Farah and K.A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 125-130.

Thakur, V.C., 1981, Regional framework and geodynamic evolution of the Indus-Tsangpo suture zone in the Ladakh Himalayas: Trans. Royal Society Edinburgh, v. 72, p. 89-97.

Treloar, P.J., D.C. Rex, P.G. Gnise, M.P. Coward, Searle, B.F. Windley, M.G. Peterson, M.Q. Jan, and I.W. Luff, 1989, K-Ar and Ar-Ar Geochronology of the Himalayan collision in NW Pakistan: Constraints on the timing of suturing, deformation, metamorphism and uplift: Tectonics, 8/4 p. 881-909.

Turner, F.J., 1981, Metamorphic Petrology: Mineralogical Field and Tectonic Aspects (Second edition): New York McGraw-Hill, 524 p.

Verplanck, P.L., 1987, Petrology and structure of the eastern portion of the Nanga Parbat-Haramosh massif along the Indus River, northern Pakistan, with special attention to the gem-bearing pegmatites: Unpublished M.S. thesis, Oregon State University, Corvallis, Oregon, 138 p.

Wenner, D.B., and Jr. H.P. Taylor., 1974, Temperatures of serpentinization of ultramafic rocks based on O^{18}/O^{16} fractionation between coexisting serpentine and magnetite: Contributions to Mineralogy and Petrology, v. 32, p. 165-185.

Windley, B.F., 1983, Metamorphism and tectonics of the Himalaya: Journal Geological Society of London, v. 140, p. 849-865.

Winkler, H.G.F., 1979, Petrogenesis of Metamorphic rocks (fifth edition): New York, Springer-Verlag, 348 p.

Yeats, R.S., and R.D. Lawrence, 1984, Tectonics of the Himalayan thrust belt in northern Pakistan:in B.U.Haq and J.D. Milliman eds., Marine Geology and Oceanagraphy of Arabian Sea and Coastal Pakistan Van Nostrand Rienhold, New York, New York, p. 177-198.

Yeats,R.S., and A. Hussain, 1987, Timing of structural events in the Himalayan foothills of northwestern Pakistan: Geological Society of American Bulletin, v. 99, p. 161-176.