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Structure and metamorphism of the Chakdara area NW of Swat river, Pakistan

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ABSTRACT: *Two major faults, the Kohistan and Kishora thrust, divide the study area into three tectonic terranes, the Indian shelf, Garai melange, and Kohistan arc. Stratigraphy, deformation, and metamorphism within each of these terranes developed independently until they were juxtaposed during Eocene-Oligocene collision. An important aspect of this study is the documentation of youngest deformation phases related with Himalayan orogen.*

Three deformation phases (D_1,D_2,D_3) are recorded in the Indian shelf and the melange matrix, each characterized by distinct fabrics and folding. S_1 occurs as relict intrafolial in the S_2 fabric as well as in the porphyroblasts and pressure shadows, in the Indian shelf rocks. F_1 are locally preserved and are found associated with movement on the Kishora thrust. S_2 is defined by the orientation of platy or elongated minerals and axial planes of F_2 folds. F_2 folds are strongly developed and strike NNE and SSW. These are associated with southeastward movement on the Kishora thrust. S_3 developed as minor crenulation cleavage when S_2 was folded during later deformation D_3. F_3 strikes NNW and NS. It may probably be associated with the Kohistan thrust during the development of the Indus syntaxis. These deformation phases took place under conditions of amphibolite facies in the Indian shelf and greenschist facies in the melange matrix.

The melange blocks and the Kohistan rocks record different deformation events. Apparently they preserve pre-emplacement structures. Two deformation phases are recorded. During D_1, S_1 and F_1 developed. S_1 occurs as relicts in the S_2 foliation. D_1 occurred independently in the melange blocks and Kohistan arc. During D_2, the S_1 foliation was folded. D_2 in the blocks is associated with the Kishora thrust while that in the Kohistan rocks is consistent with the D_2 of the melange matrix and the Indian shelf. D_1 and D_2 took place under conditions of greenschist facies in the melange blocks and of amphibolite facies in the Kohistan arc.

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 (Fig. 1). The area is composed of complex Precambrian to Mesozoic basement & shelf metasedimentary rocks, which vary from quartzofeldspathic gneisses, through pelitic-psammitic to calcareous-graphitic schists (Martin et al., 1962; Calkins et al., 1975; Kazmi et al., 1984). Intrusive granitoid bodies ranging in age from Precambrian (?) to Tertiary are common. These rocks were affected by polyphase metamorphism and deformation throughout the Himalaya (Treloar et al., 1989; DiPietro and Lawrence, 1991). In the south, the area is bounded by a series of north dipping thrust faults of the Hill Ranges, equivalent to the Main Boundary Thrust (MBT) of lesser Himalayas (Yeats and Lawrence, 1984; Fig. 1).

This paper describes geology north of Swat river near Chakdara with emphasis on (1) stratigraphy of the shelf and platform sediments of the Indian plate, (2) structures of the suture zone in the area, (3) the rocks of the Kohistan arc adjacent to the suture zone, and (4) details of the structural, metamorphic, and deformation history of the area through analysis of mesoscopic and petrofabric elements.

REGIONAL TECTONIC SETTING

Structurally, the Swat area is composed of three tectonostratigraphic terranes (Kazmi et al., 1986; Lawrence et al., 1989). From

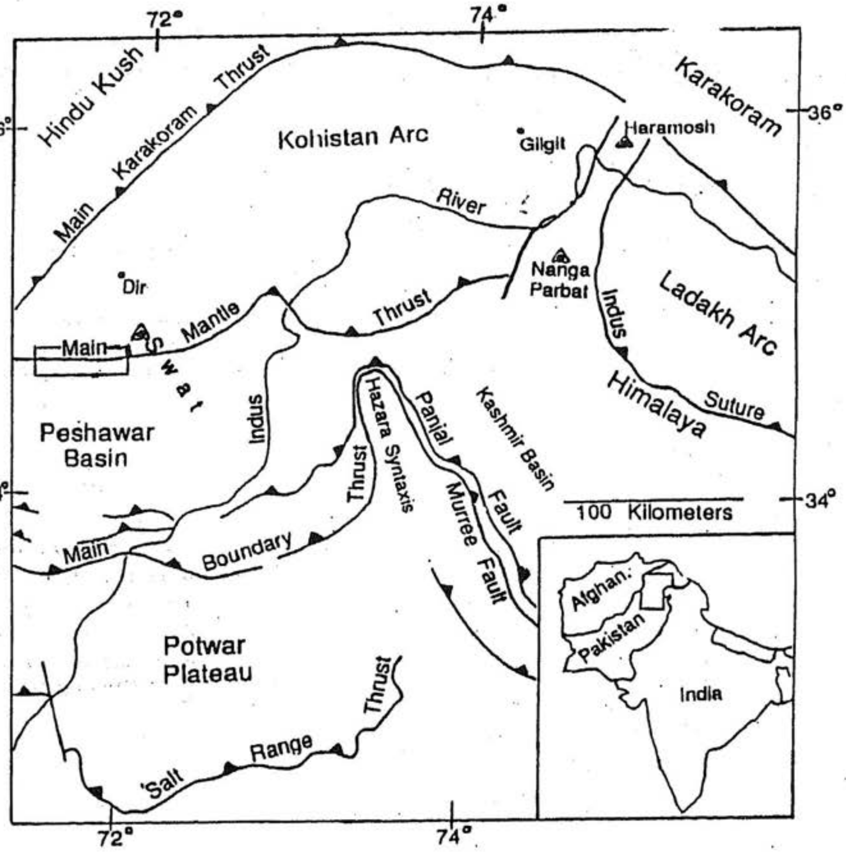


Fig. 1. Tectonic map of northern Pakistan. Box surrounding the location of the geological map (Fig. 2) modified from DiPietro (1990).

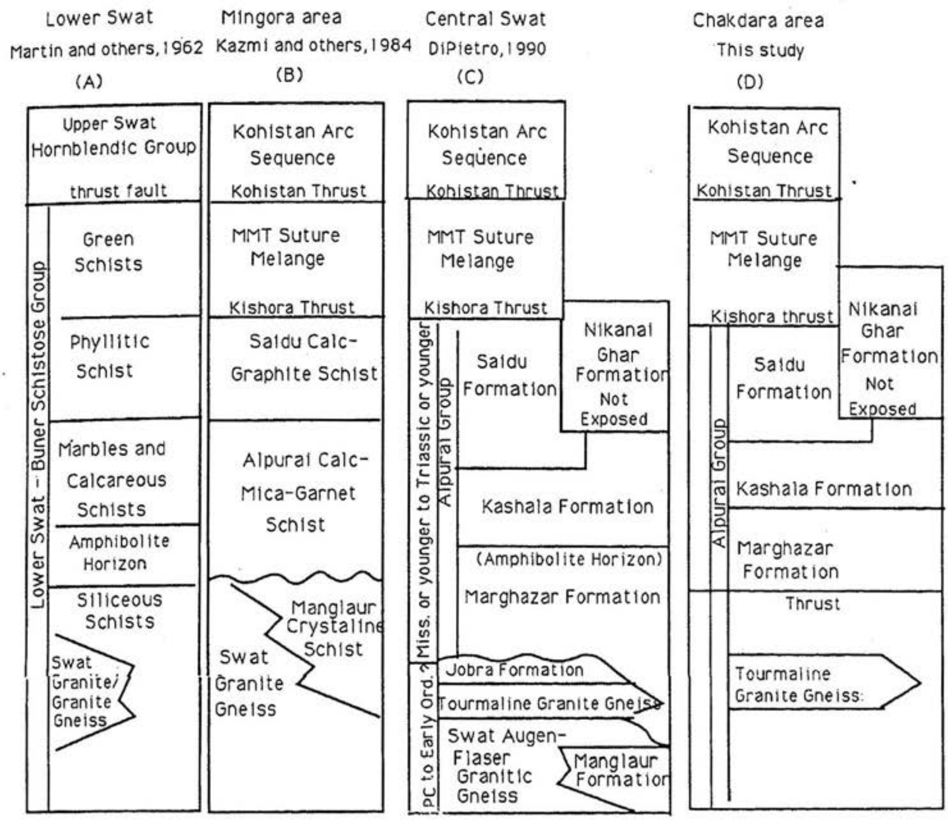
south to north, these are: (1) the shelf and platform sediments of the Indo-Pakistan plate; (2) the Indus suture melange group; and (3) the Kohistan arc sequence.

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-Triasic breakup. Stratigraphic columns from Swat area are presented in Table 1.

The Indus melange group has been subdivided into three fault bounded melange units (Kazmi et al., 1984) as (a) Mingora ophiolitic melange, composed of tectonized blocks and clasts of serpentine, talc dolomite, greenstone metabasalts, greenschist metapyroclastics, metagabbro, metasediments and metacherts; (b) Charbagh green schist melange, containing green schist metapyroclastics, with minor tectonized layers and wedges of metasedimentary rocks; (c) Shangla blueschist melange characterized by blocks of glaucophane crossite bearing blueschist (Shams, 1972; Jan, 1985), metavolcanics, phyllitic schists, serpentinite, metadolerite, metagreywacke, and metachert (Kazmi et al., 1986; Lawrence et al., 1989).

The Kohistan sequence represents an ancient andesitic island arc. In Swat adjacent to the MMT, it is composed of the Kamila amphibolite belt (Jan, 1977b). The lower part of the belt encloses lensoid bodies of mafic-ultramafic rocks (mainly harzburgites, dunites, diopsidites, and garnet spinel diopsidites) surrounded by more or less amphibolitized and (or) garnetiferous noritic gneiss. These are called the North Mingora complex in Swat valley and the Jijal Pattan complex in the Indus valley (Jan, 1977a,b; Jan and Howie, 1981).

TABLE 1. COMPARATIVE STRUCTURAL/STRATIGRAPHIC COLUMNS FROM LOWER SWAT, MODIFIED FROM DIPIETRO (1990)



LOCAL STRATIGRAPHY

The study area is composed of the MMT zone and the Indian plate sediments (Fig. 2). The Indian plate sequence comprises Alpurai group and the Saidu schist which are overthrust by the Indus melange group. The Alpurai group is represented by the Marghazar, Kashala and the Saidu formations. The Marghazar formation 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 granites of the Chakdara pluton is in contact with the Kashala formation of the Alpurai group. The contact relationship is not clear, whether it is an unconformity, a fault, or a greatly sheared unconformity.

The Indus melange group is the western extension of the Mingora ophiolitic melange and occur as an oceanic unit in the form of slivers and thrust sheets of talc-carbonate and serpentinite in association with metavolcanics and metasediments between the other tectonized blocks (schist, phyllites). The Indus melange group is overthrust by the Kohistan arc amphibolites.

CONDITIONS OF METAMORPHISM

The thin section study reveals that the metamorphism of the blocks and matrix rocks of the melange took place under conditions of the greenschist facies. In Indian plate rocks in the south and the Kohistan arc rocks in the north, metamorphism took place under amphibolite facies conditions. Metamorphic mineralogy is presented in Table 2. Generalized P-T estimates based on the present mineral assemblages, including some

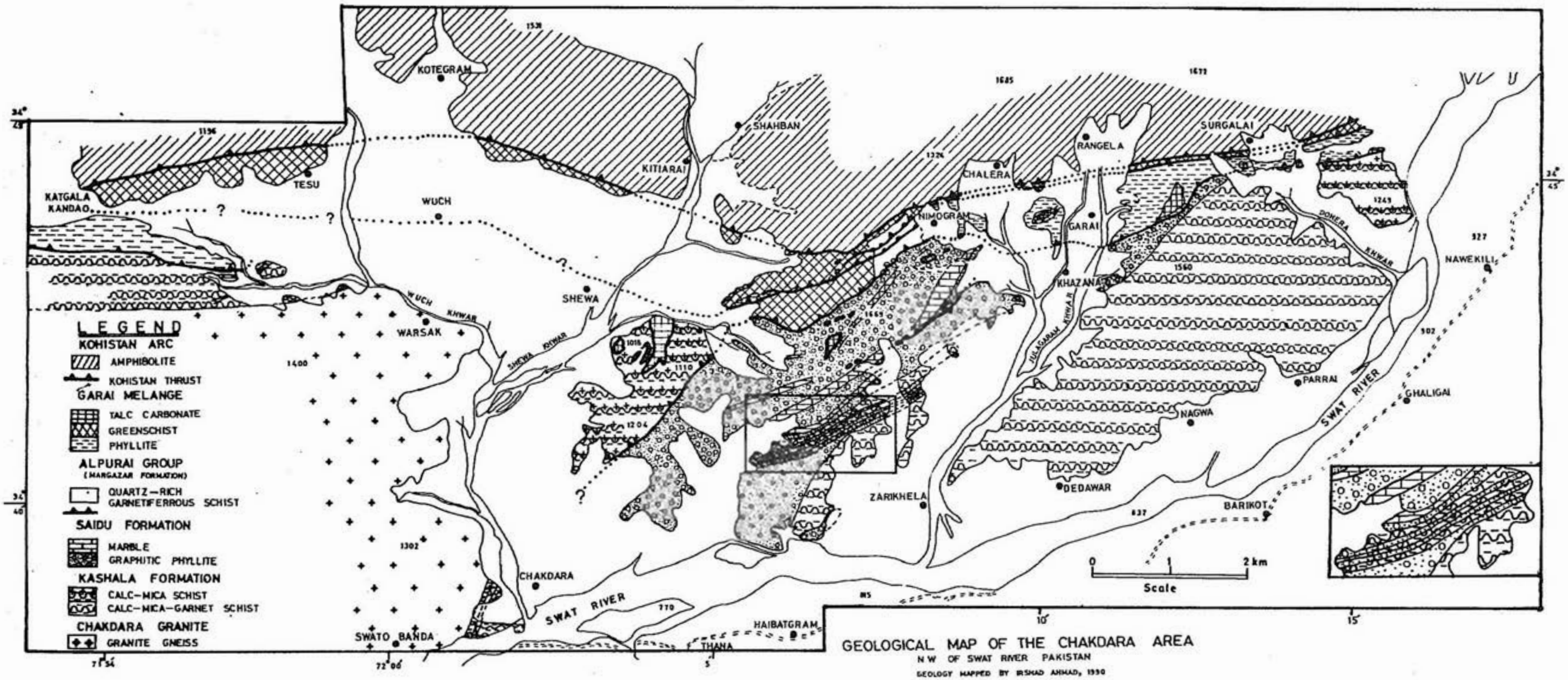


Fig. 2. Geological map of the Chakdara area.

non-equilibrium assemblages, from the three terranes are presented in Figure 3.

Melange blocks and Matrix

The mineral assemblage dolomite + chromite + magnetite + talc + quartz + albite + magnesite + fuchsite of the talc-carbonate rock, antigorite + chlorite + calcite of the serpentinite rock and albite + quartz + chlorite + muscovite + calcite + epidote + opaque ± biotite and ± sphene of the matrix rock (phyllite) indicate conditions of at least greenschist facies (Miyashiro, 1973).

The mineralogy of the serpentinite along the Kohistan thrust gives some constraint on the temperature. Antigorite is bladed and typically schistose. In general antigorite is the high temperature serpentine mineral compared to lizardite and chrysotile (Wenner and Taylor, 1974; Evans, 1977). It develops at temperatures between 250-550°C. 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).

The absence of high P-T minerals such as lawsonite and sodic amphibole in the greenschist indicate that the pressure attained

TABLE 2. METAMORPHIC MINERALOGY OF THE ROCKS OF THE CHAKDARA AREA

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

EXPLANATION

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

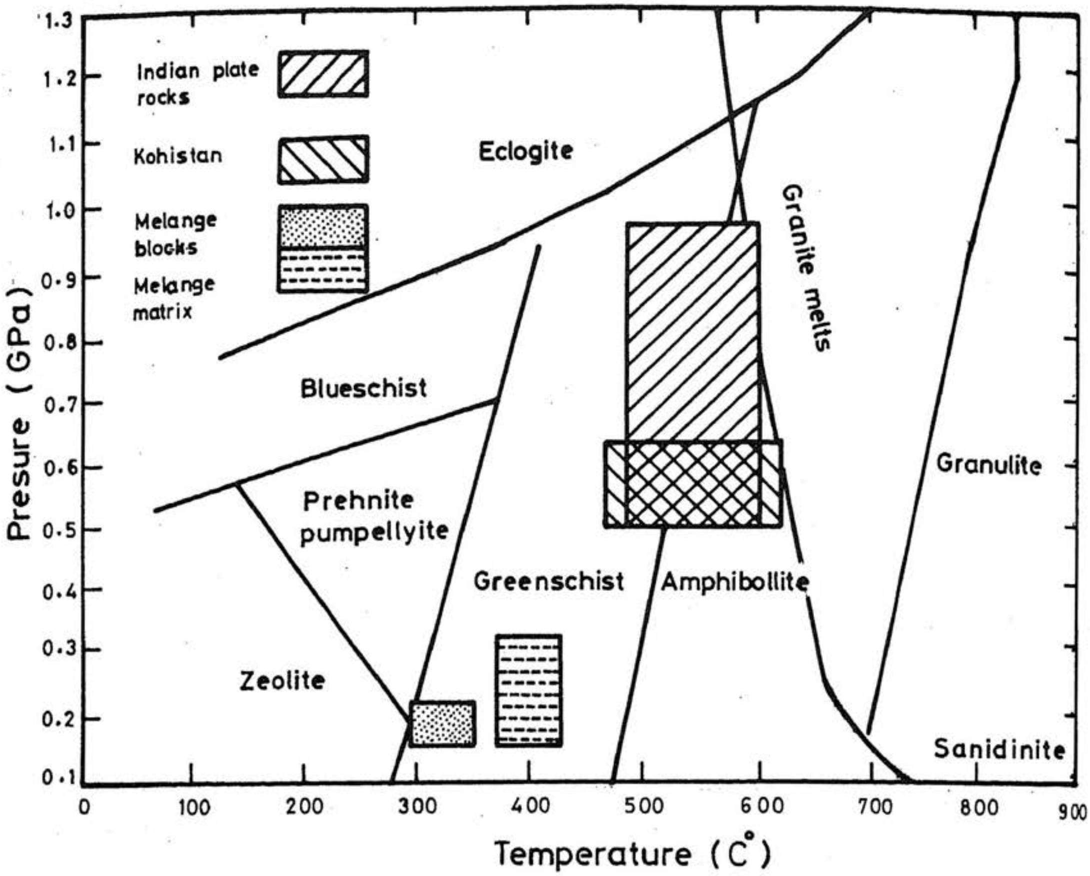


Fig. 3. Generalized P-T estimates for the study area.

were low probably < 3 kb. Some clues to the temperature of metamorphism of the melange matrix can be found in the texture and mineralogy of the matrix. Thermal modelling of the subduction zone environment and analyses of the textures and mineral assemblages of the matrix rocks by Cloos (1983,1985) has shown that temperature >200°C are necessary to coarsen pelitic sediments and obtain phyllitic and schistose rocks. Temperatures above 200°C are indicated by 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 pressure <3 kb can be suggested for the matrix rocks.

Indian shelf sediments

The metasedimentary rocks are divided into two groups, (1) calcpelitic (calc-mica schist and calc-mica-garnet schist), and (2) psammopelitic (quartz rich-garnetiferous schist and graphitic phyllite).

The calcpelitic rocks contain the mineral assemblage calcite + muscovite + paragonite + albite + zoisite + epidote + garnet + alumino-tschermakite + magnetite + ilminite ± chlorite ± biotite and ± graphite. Garnet and alumino-tschermakite are absent in the calc-mica schist. No microprobe analyses have been done for the calc-mica schist rock. The presence of paragonite is not confirmed. The absence of alumino-tschermakite and garnet in the calc mica-schist however may be due to lack of aluminous minerals or this

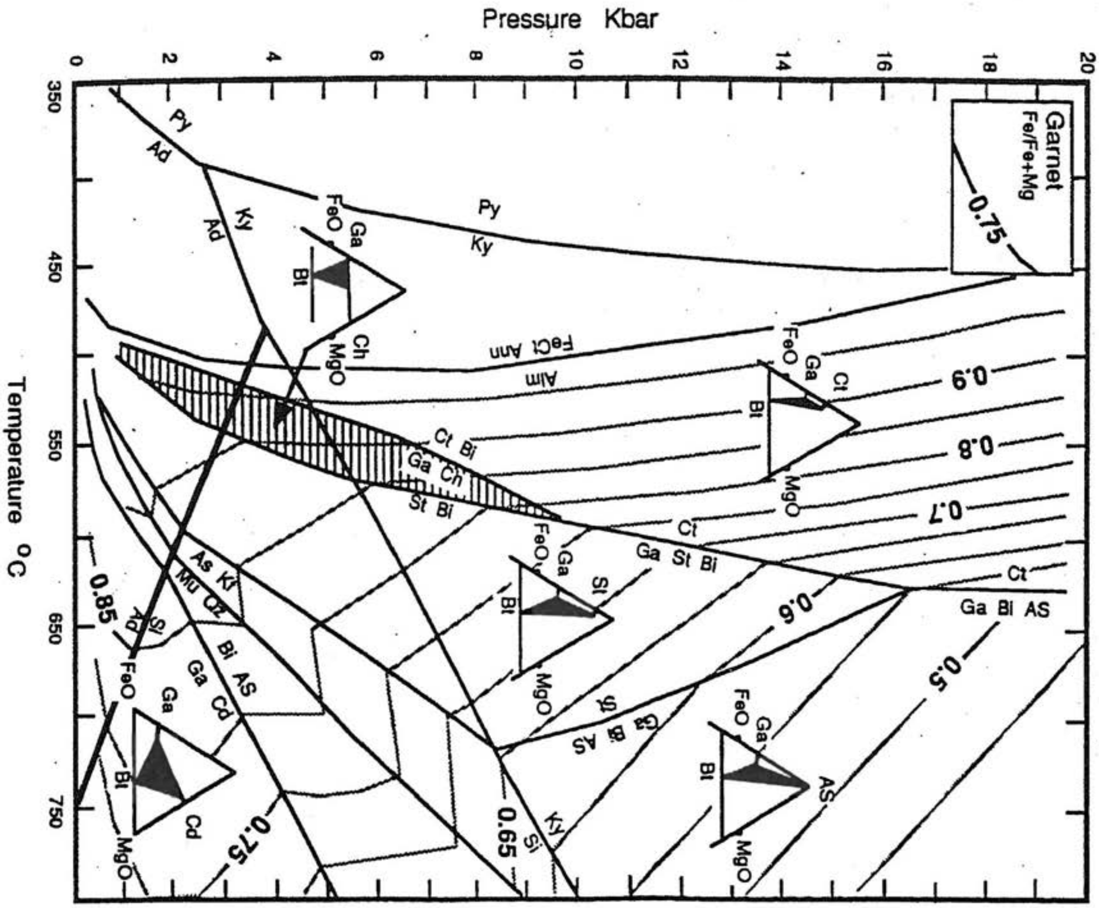


Fig. 4. P-T diagram after Spear and Cheney (1989). Horizontal lines represent the present mineral assemblage.

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 amphibolite facies of Miyashiro (1973) or to the greenschist-amphibolite transition facies of Turner (1981).

The presence of zoisite and garnet can be used as a geothermometer. The high-temperature stability limit of the zoisite + quartz assemblage was experimentally determined by Newton (1966a) to be about 670°C at 6kb in the presence of aqueous fluid.

Garnet in the graphitic phyllite changes composition from pyrope-rich rims to almandine-rich cores with a core to rim increase in the CaO and MnO contents (Table 3). Sturt (1962) and Atherton (1968) reported similar changes from the Barovian region of the Scotish Highlands. Plotting the mineral assemblage on the P-T diagram of Spear and Cheney (1989), the temperatures ranges from 480 to 570°C (Fig. 4). The pressure ranges from 1 to <10 kb. The upper limit of the pressure is consistent with, pressure in the south of the Swat river (DiPietro, 1990).

TABLE 3. MINERAL COMPOSITIONS OF INDIAN PLATE ROCKS

Garnet composition (sample IR-61)

	Pyrope rich		<–Almandine rich –>			Cations on 24 oxygen basis					
SiO_2	39.44	39.99	37.08	36.82	37.67						
TiO_2	0.35	0.31	0.09	0.08	0.06	Si	5.99	6.01	6.00	6.01	5.99
Al_2O_3	22.23	22.52	21.41	21.31	21.56	Ti	0.04	0.04	0.01	0.01	0.007
Fe_2O_3	0.00	0.00	0.00	0.00	0.00	Al	3.98	3.99	4.08	4.09	4.04
MgO	6.86	6.90	2.02	1.85	1.78	Fe^{2+}	1.99	1.99	4.09	4.01	4.31
CaO	14.13	14.11	7.36	7.13	6.99	Mg	1.55	1.54	0.48	0.45	0.42
MnO	0.72	0.69	0.15	0.16	0.13	Ca	2.30	2.27	1.27	1.24	1.19
FeO	15.71	16.10	30.05	30.05	32.42	Mn	0.09	0.09	0.02	0.02	0.018
Total	99.44	100.62	98.16	97.40	100.61						

Amphibole composition (sample IR-6)

				Cations on 23 oxygen basis			
SiO_2	41.68	41.47	41.35	Si	6.03	6.02	6.02
TiO_2	0.58	0.53	0.42	Ti	0.06	0.06	0.05
Al_2O_3	18.80	19.03	19.14	Al	3.21	3.25	3.28
MgO	7.94	7.80	7.85	Fe^{2+}	1.41	1.43	1.47
CaO	10.84	10.77	10.98	Fe^{3+}	0.57	0.53	0.46
MnO	0.05	0.09	0.09	Mg	1.71	1.68	1.70
FeO	16.36	16.20	15.89	Ca	1.68	1.67	1.71
Na_2O	2.07	2.16	2.09	Mn	0.006	0.01	0.01
K_2O	0.51	0.51	0.56	Na	0.58	0.61	0.59
Total	98.83	98.56	98.37	K	0.09	0.09	0.10

Muscovite and paragonite compositions (sample IR-7)

	Muscovite		Paragonite	Cations on 22 oxygen basis			
SiO_2	46.31	46.54	44.02	Si	6.25	6.29	5.76
TiO_2	0.38	0.27	0.08	Ti	0.04	0.03	0.01
Al_2O_3	34.10	33.80	40.51	Al	5.43	5.38	6.26
MgO	0.91	1.17	0.04	Fe^{+2}	0.15	0.14	0.04
CaO	0.02	0.02	1.87	Mg	0.18	0.23	0.01
MnO	0.006	0.00	0.00	Ca	0.003	0.003	0.26
FeO	1.39	1.32	0.38	Mn	0.001	0.00	0.00
Na_2O	1.19	1.19	5.40	Na	0.31	0.31	1.37
K_2O	8.96	8.72	0.75	K	1.54	1.50	0.13
Total	93.26	93.03	93.05				

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.
FeO expressed as total Fe. Alumino-tschermakite is determined using Leake (1978) nomenclature of amphibole.

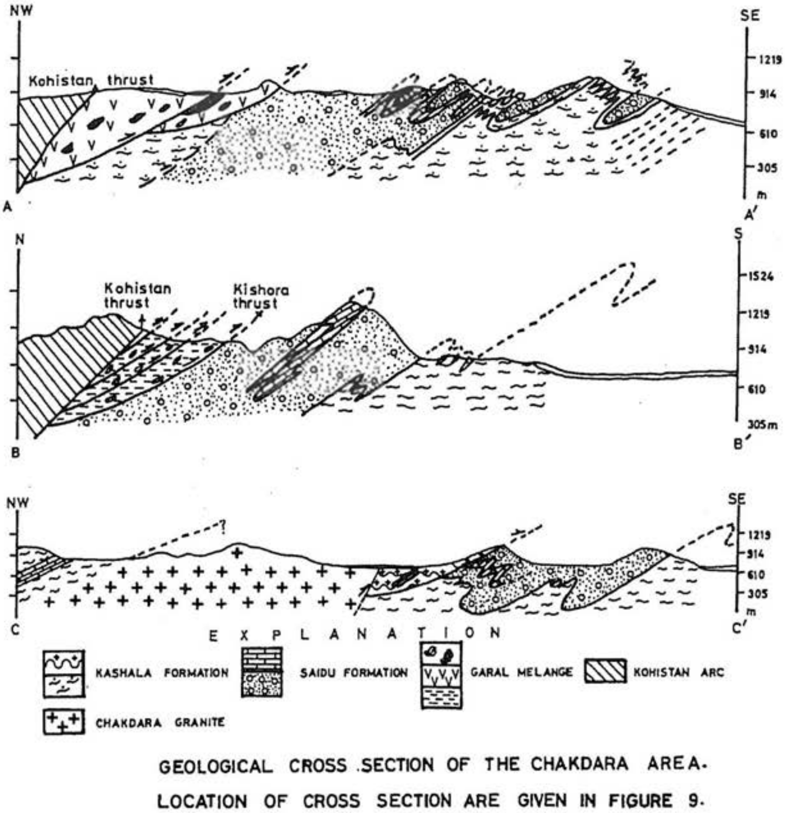


Fig. 5. Geological cross section of the Chakdara area. Location of the cross sections are given in Fig. 7.

The existence of the muscovite and paragonite assemblage is dependent on the grade of metamorphism. At 2000 bars muscovite and paragonite are stable upto 715°C and 660°C, respectively (Eugster, 1956). Therefore, temperature in the study area must have been below 660°C. Pressure for alumino-tschermakite is estimated to be $\geq$5kb on the basis of the ^{iv}Al and Ti plot of Rasse (1974; plot not presented; see 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 i.e Barrovian type (Miyashiro, 1973).

Assuming a temperature of 580°C for the epidote amphibolite facies and Barrovian type of metamorphism, a pressure of about 5.5 kb can be estimated (Turner, 1981, Fig. 11-14), which corresponds to a depth of <20 km (see Winkler, 1979).

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 during Eocene-Oligocene collision. Accordingly we 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 that extend beyond the study area, the Kohistan and Kishora thrust (Kazmi et al., 1986), dominate the structure of the study area. They bound the Garai melange on the north and south respectively, and separate the three terranes (Fig. 2).

The Kohistan thrust dip angle varies between 55-65° to the northwest and strikes approximately WSW. The map trace of the

TABLE 4. OBSERVED STRUCTURAL ELEMENTS OF GARAI MELANGE, INDIAN SHELF SEDIMENTS, AND KOHISTAN ROCKS OF THE CHAKDARA AREA.

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

	Amphibolite
D_1	S_1 = Dominant foliation
D_2	S_2 = Minor deformation

MELANGE BLOCKS

	Greenschist	Talc-carbonate and Limestone
D_1	S= 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

fault is mostly straight with a few deflections due to topography. A large brecciated zone with serpentine lenses can be observed along the contact with the greenstone. The Kishora thrust is also northwest-dipping and WSW striking and is traced at the northernmost location of Indian shelf sediments. It dips less steeply than the Kohistan thrust (Fig. 5). Numerous small blocks of melange material are found beneath the thrust (see below). In the study area the Kishora thrust brings up the melange over the Saidu and Kashala formations (Fig. 2). In the west of the study area, the Kishora thrust disappears under an

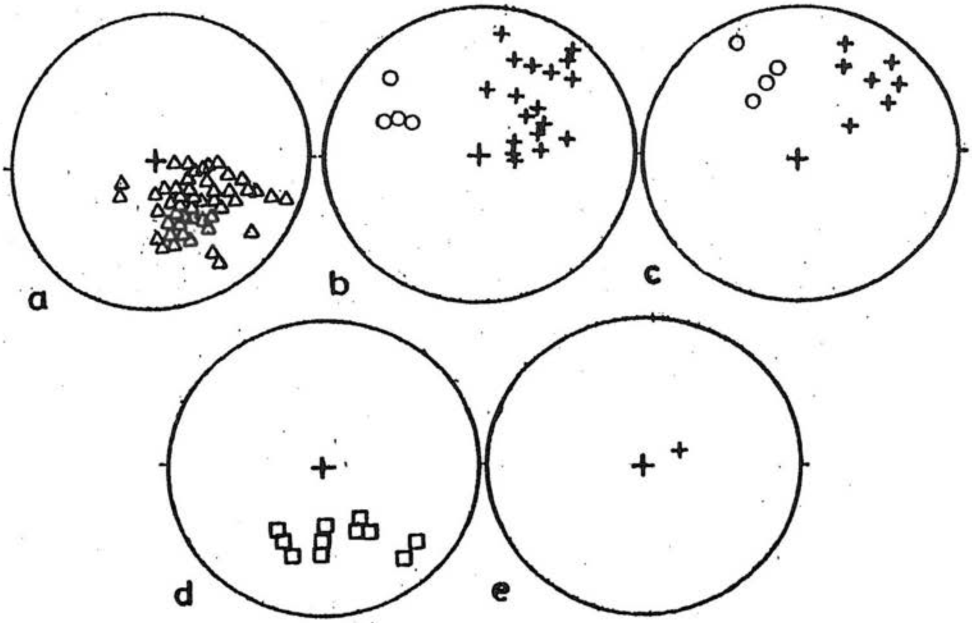


Fig. 6. Lower hemisphere equal area projection of data from Chakdara area. (a) open triangles = pole to all measured foliation in the Indian shelf and melange terranes. (b) Crosses = F_2 folds and open circle s = F_3 folds, all measured fold axis of the Indian shelf and melange terranes. (c) All measured lineations of the Indian shelf and melange, (d) Diamonds = poles to all measured foliations Kohistan arc. (e) Cross, F_2 folds, Kohistan arc.

extensive alluvium.

The upper portion of the Indian shelf sediments contain 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 were involved in the process (movement on Kohistan thrust) that created the melange. The small imbricate faults are considered also to be formed as part of this process.

Metamorphic Structures

Rocks of the study area record a history of polyphase deformation. Three phases of deformations are observed, on the basis of microscopic features and analysis of the folds and fabric elements related to different deformational phases.

The microscopic features are summarized in Table 4. For details see discussion and conclusions.

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 pattern was noted across the Kishora thrust so the Garai melange and Indian shelf data are presented together. The small amount of the Kohistan data are plotted separately (Fig. 6). The structural layout of the area is represented in Figures 5 and 7.

Folds and their relation to thrust system

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 (Fig. 8). No macroscopic and mesoscopic folds were observed. In most places it appears that F_2 folds have overprinted the F_1 folds completely. F_2 folds are

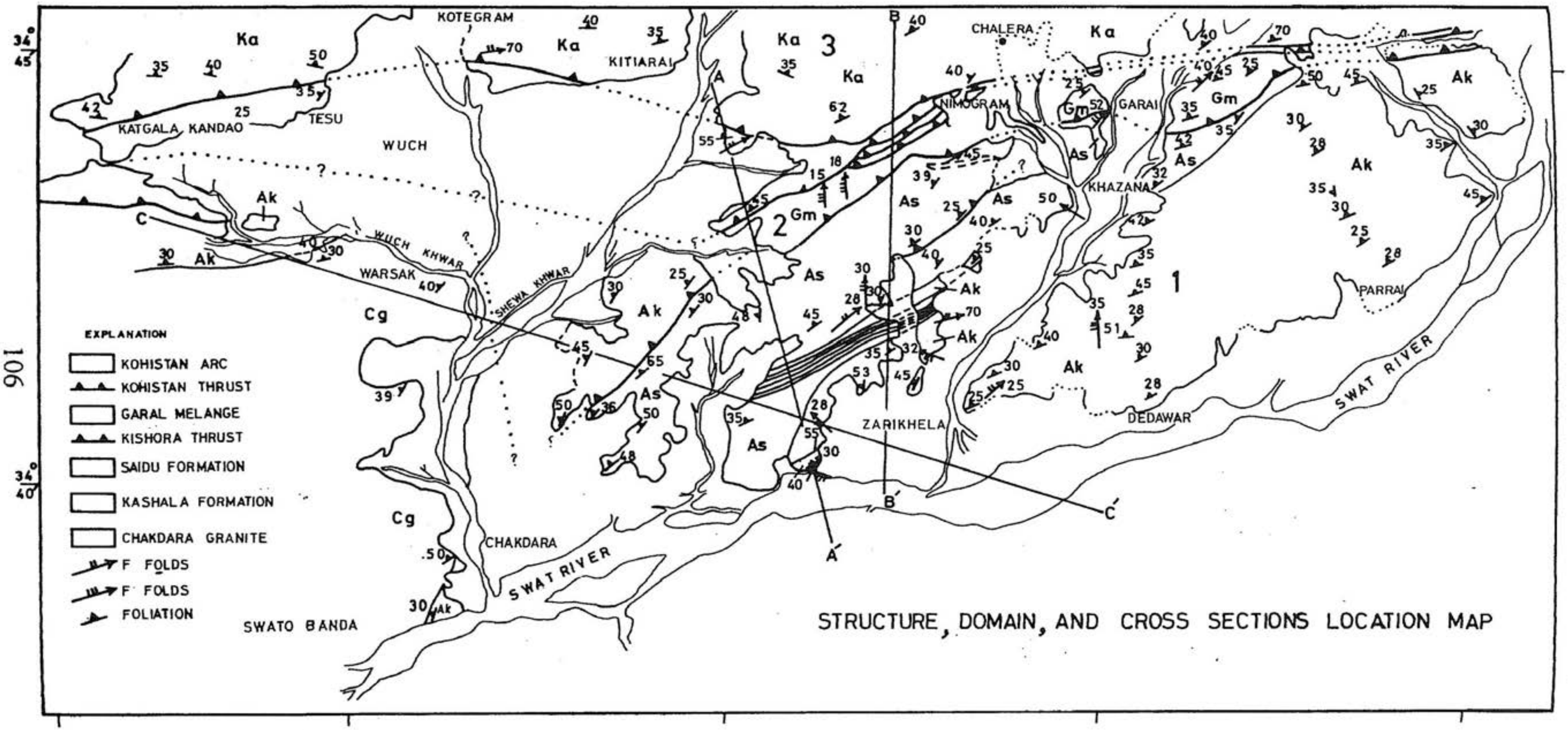


Fig. 7. Structural and cross sections location map.

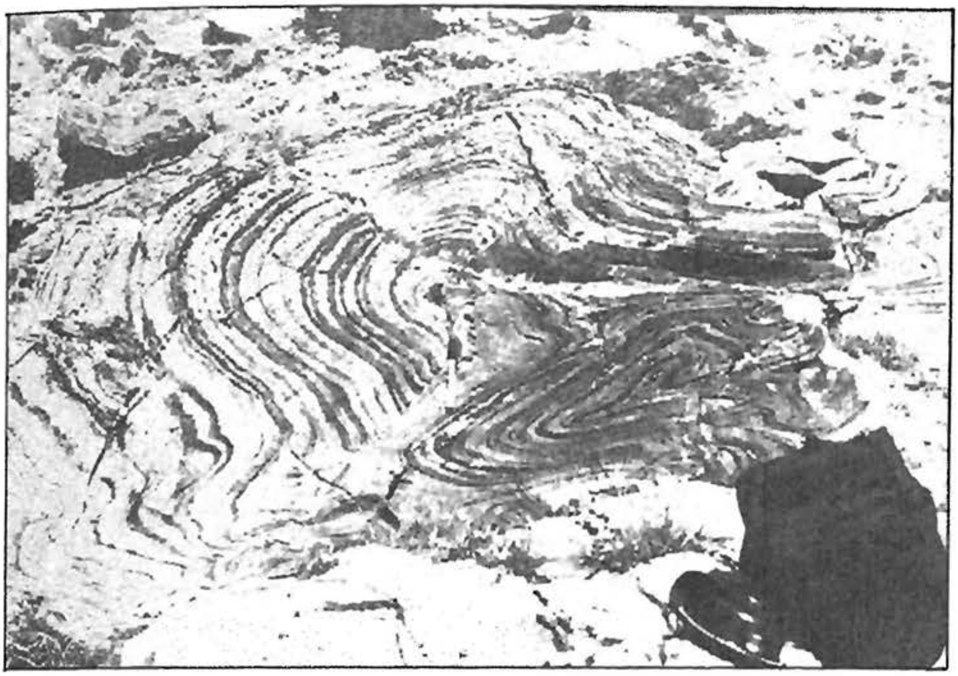


Fig. 8. Laminated dark gray marble showing D_2/D_1 interface pattern. F_2 folds superimposed on a dome, or a sheath like F_1 folds. View to northeast.

Fig. 9. Calc-mica-garnet schist showing F_2 folds and predominant S_2 foliation. See also thickned hinge areas and attenuated limbs after (Ramsay, 1967) View to north northeast.

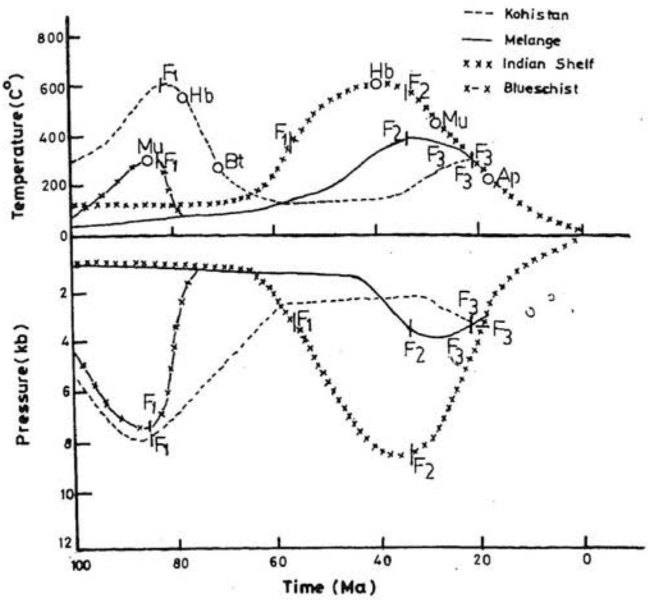


Fig. 10. Summary of the deformation events and metamorphism of the present study and part of the lower Swat area. F_1, F_2, F_3 represent the present deformation events. Hornblende (Hb), biotite (Bt). muscovite (mu) $^{40}Ar/^{39}/Ar$ dates and temperatures are from Baig (1990). Apatite (Ap) fission track age and cooling temperatures are from Zeitler (1985).

strongly developed in all three domains. They strike NNE and SSW. These are tight isoclinal folds. In Figure 6a the foliation orientation is generally axial planar to F_2 folds. In Figure 6b and 6c most of the fold axes and lineation 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 Kasahla and the Saidu formations and the Saidu formation occurs in the syncline of these large F_2 folds. They show thickened hinge regions and attenuated limbs (Fig. 5); 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 (Fig. 9). The general east-west orientation and south-westward vergence of these folds argues for NNW-SSE shortening. This would imply probably a south or south-eastward thrust direction. We consider that 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 of all three terranes, except in the melange blocks were formed during the movement on the Kohistan thrust.

F_3 folds strike NNW and SSE. They are common in domain 1 and 2. These are small scale upright folds and are oblique to the main foliation. Stereonet plot of these fold axes and related lineation are presented in Figure 6b and 6c. F_3 folds of domain 1 and 2 are later crenulation structures that do not appear in domain 3, probably because of the micaceous minerals in those rocks. F_3 folds 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 10. 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, 1985).

Three deformation phases (D_1, D_2, D_3) are

TABLE 5. RELATION OF DEFORMATION PHASES BETWEEN TECTONIC TERRANES OF THE STUDY AREA

	KOHISTAN	GARAI MELANGE BLOCKS	GARAI MELANGE MATRIX	INDIAN SHELF
	D1------	----D1		
KISHORA THRUST		----D2----	----D1----	----D1
MOVEMENT ON KOHISTAN THRUST	D2------------------------------------	------------------------------------	-------D2------- -----	--D2
			D3-------------	------D3

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, pressure shadows against garnet, and as inclusion trails in the garnet and amphibole porphyroblasts in the calc-mica-garnet schist 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, tschermakite, 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 destroyed, and S_3 formed. This event took place at lower grade than D_2, as no 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 shows somewhat different events between the blocks and the matrix. Apparently the blocks preserve pre-emplacement structures (probably behaved passively), 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 $>200°C$, and the pressure was probably >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 the growth of the greenschist facies minerals including 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 D_2. 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 provide evidence of P-T uplift paths and conditions, during emplacement of various blocks into the melange. Vein minerals common in the talc-carbonate include fuchsite, calcite, and quartzo-feldspathic material 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. We 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. We 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 the juxtaposition of the Kohistan terrane. F_3 folds of the melange and shelf terranes and later crenulation structures that do not appear in the Kohistan are 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.

Relation to structural development of neighbouring areas

Southeast of the Swat river, the Kishora thrust is reported to be everywhere in contact with the Saidu formation (Kazmi et al., 1986; Lawrence et al., 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 of the Kashala formation (Fig. 7). 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 et al., 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. The fold axes plunge gently toward the NNW and SSE. Small scale F_3 folds are tight with variably dipping axial surfaces. Large scale F_3 folds are upright and open, trending to north-south, and plunging south or southeast. F_4 are folds upright and variably tight to open and trend east-west. DiPietro (1990) 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 was 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 history 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 (see 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 suggest 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 documents the timing of the earliest fabric development in the region. S_1 and S_2 in the Swat region probably relate to early phase of prograde Himalayan deformation (Lawrence et al., 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 and 63 Ma which he relates to S_1 and S_2 development respectively. No fabric from this time is recognized as preserved in the study area north of the Swat river.

Lawrence et al., 1989 and L. Snee (in Palmer-Rosenberg, 1985) obtained $^{40}Ar/^{39}Ar$ ages of 39.9 $\pm$ 0.2, 39.8 $\pm$ 0.3 and 37.1 $\pm$ 0.7 Ma from hornblende in the Marghazar formation near Jowar and ages 30.6 $\pm$ 0.4 and 29.5 $\pm$ 0.3 Ma from muscovite in the Kashala formation near Saidu. These ages are similar to the younger K-Ar and $^{40}Ar/^{39}Ar$ obtained by Treloar et al (1989a) in this area. Polygonized and recrystallized hornblende in the hinge areas of F_3 crenulation folds in the Marghazar formation indicates 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 $\pm$ 0.2 Ma to 35 $\pm$ 0.15 Ma. This date hints of a late Cretaceous metamorphic event, rest 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 $\pm$ 0.13 Ma and muscovite has a plateau date of 28 $\pm$ 0.2 Ma. Potassium feldspar has an argon loss spectrum with a maximum date of 45 $\pm$ 0.2 Ma and minimum date 22 $\pm$ 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 foliation 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.

We 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 occurred between 28 and 32 Ma.

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