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Structural analysis south of the Malakand and adjoining areas, northern Pakistan

IRSHAD AHMAD[1] & NOOR JEHAN[2]
[1]NCE in Geology, University of Peshawar.
[2]Department of Environmental Sciences, University of Peshawar.

ABSTRACT: *Two major faults, the Kishora thrust and a back thrust, dominate the structure of the study area. The Kishora thrust divide the study area into two tectonic terranes, the Indus melanges including Dargai ultramafic complex, and the Indian shelf terrane, whereas the back thrust brings higher grade almandine zone rocks in contact with low grade chlorite zone rocks near Bar Bazdara and Zormandai village. An important aspect of this study is the relationship of the structures of Swat with the Peshawar basin. The structures and stratigraphy in Swat extends into the Peshawar basin.*

Four deformation phases (D_1, D_2, D_3, D_4) are recorded in the Indian shelf rocks from north to south, each characterized by distinct fabrics and folding. In Domains 1 and 2, D_1 formed S_1. The earliest recognizable fabric S_1 occurs as relict intrafolial in the S_2 fabric, pressure shadows and porphyroblasts. No macroscopic folding event related to S_1 fabric has been recognized. During D_2, F_2 folds (large and small scale) were formed. F_1 and F_2 are coaxial and coplanar with isoclinal, recumbent axial surfaces and fold axes that plunge gently toward the NNW are associated with movement on the Kishora thrust. The dominant S_2 foliation developed following the interkinematic phase. S_2 is associated with transposition of S_1 and rotation of porphyroblasts. S_2 is defined by calcite, muscovite, plagioclase, quartz, and garnet. The post S_2 phase is dominated by fractures and brittle shearing in the schists and annealing recrystallization in the granite gneiss and marbles. During D_3 crenulation of S_2, garnet growth, and the formation of the S_3 occurred. F_3 folds are upright and open and plunge gently, but variably towards north or less commonly the south or southeast. F_4 is related to the change of forces from westward to southward in the lower Swat when Kohistan was thrust southward to its present position. The superposition of the E-W trending F_4 folds on the generally N-S trending F_3 folds resulted in a dome and basin structure near Mora Kandao.

In the south, Domain 3 preserves the last two deformation phases. During D_3 deformation S_1 developed. During D_4, S_1 was transposed and also involved with the growth of the magnetite porphyroblasts. F_3 and F_4 folds are best preserved. The large-scale F_4 folds are mainly E-W, but at Rustam and Budal they are deflected into a broad arc near the Ambela complex. This is related to the back thrust in that the Ambela complex acts as buttress that deflects the later folds towards north.

Matrix schist records three deformation phases. During the D_2 deformation a transposed foliation produced. During D_3 the early S_1 was folded. During D_4 the S_2 was folded to produce local S_3 space crenulation cleavage.

The Dargai ultramafic complex has been emplaced along the Kishora thrust with the ophiolitic melange.

INTRODUCTION

A belt of metamorphosed continental rocks belonging to the Indian plate extends across the Pakistani Himalaya to the immediate south of the Indus Suture or Main Mantle Thrust (MMT). These rocks crop out extensively in the mountains surrounding the eastern Peshawar Basin and the Himalayan foothills of Swat district to the north (Fig. 1). This area is composed of complexly deformed Paleozoic to Mesozoic shelf and platform metasedimentary rocks, including pelitic, psammitic, calcareous and graphitic lithologies (Martin et al., 1962; Palmer-Rosenberg, 1985; Kazmi et al., 1984, 1986; Pogue & Hussain, 1986; Pogue et al., 1992; DiPietro et al., 1993; DiPietro et al., 2000). The style of deformation and metamorphism varies considerably across this belt.

The study area, lying south of Malakand between longitude 71^0 55′ and 72^0 20′ E and latitude 34^0 15′ and 34^0 40′ N, is important for the study of collisional structures because of its proximity to the Indus Suture. Previous work in this area was of a reconnaissance nature and only small scale maps resulted. In Swat, north of the study area, amphibolite facies Precambrian to Mesozoic schist, marble, amphibolite and granitic gneiss crop out in a series of structural domes that is overturned toward the west (DiPietro & Lawrence, 1991; DiPietro et al., 1993; Fig. 1). The geology of these rocks was first described by Martin et al. (1962). They emphasized a coherent stratigraphy that could be followed southward into low grade Precambrian and platform rocks of the Peshawar basin without structural disruption. Later field investigations, most notably those of King (1964), Stauffer (1967), Tahirkheli (1979), Kazmi et al. (1984, 1986), Palmer-Rosenberg (1985), DiPietro (1990), Pogue et al. (1992a) and Ahmad & Lawrence (1992) have refined and extended the stratigraphy of Martin et al. (1962), but none has noted the existence of a major fault between high-grade rocks in Swat and low-grade rocks in the Peshawar basin.

A few workers (Coward et al., 1988; Treloar et al., 1989) have shown a series of faults on sketch maps of Swat and surrounding areas, but present no evidence whatever for their existence.

The metamorphic stratigraphy in Swat can be followed westward possibly into Afghanistan, but these areas have not been mapped in detail (Lawrence et al., 1989). In this area, an ultramafic complex, locally called the Dargai klippe, represents a southward extension of the MMT structurally above the metamorphic sequence. DiPietro et al. (1997, 1999) observed that the stratigraphy in the Dargai area extends westward into the Mohmand agency and eastward into the Jowar area but there are problems with stratigraphic correlation and with the concept that the Dargai ultramafic complex is a klippe. These problems require further analysis.

The deformational sequence in central Swat is one of WSW-vergent folds followed by south-vergent folds. This fold sequence may be a direct geologic expression of Indian plate movement (DiPietro & Lawrence, 1991). The WSW-vergent folds are interpreted to have developed during oblique subduction of the Indian plate beneath the Indus suture melange. The later south-vergent folds developed following counterclockwise rotation of the Indian plate, during final southward obduction of Kohistan (DiPietro & Lawrence, 1991). In the Peshawar basin, the deformational sequence is one of southwest-vergent folds followed by southeast-vergent folds. How this fold sequence correlates with that in Swat requires further analysis. This paper describes in detail the structural history of the area through analysis of mesoscopic and petrofabric elements.

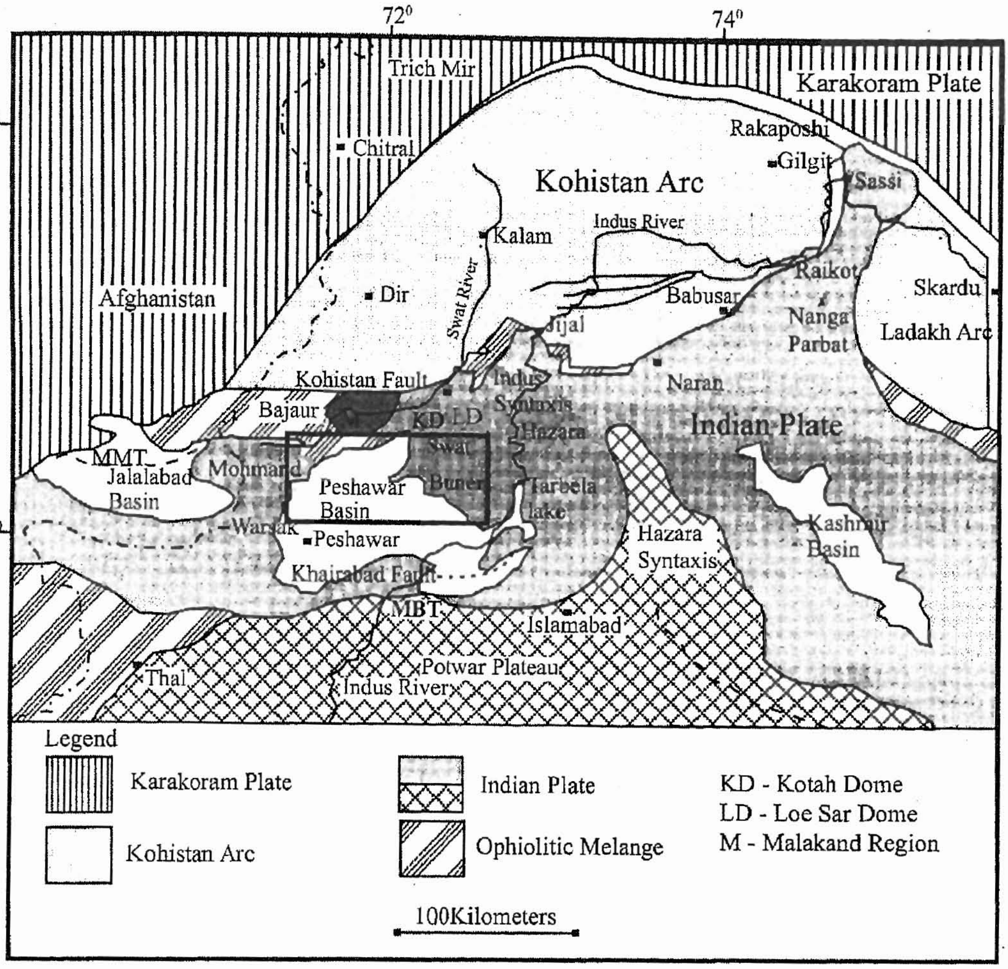
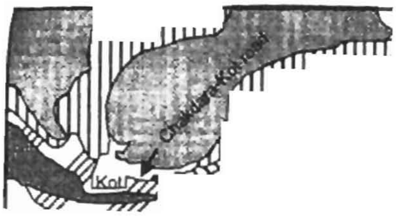


Fig. 1. Tectonic map of the western Himalayan syntaxis in northwestern Pakistan. Inset shows the location of the study area. (Modified after DiPietro et al., 2000).

GEOLOGICAL SETTING

The platform sediments of the Indian plate are pelitic, calcareous, graphitic, and psammitic in nature and were deposited on the northern margin of Gondwanaland before and after the Permo-Triassic breakup of Gondwana. These rocks range in age from Precambrian to Mesozoic. The older parts of the section have been intruded by early Paleozoic granitic plutons (Le Fort et al., 1980; Ashraf & Chaudhry, 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 et al. (1962). Kazmi et al. (1984) subdivided the lower Swat-Buner schistose group of Martin et al. (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 crystaline schist (Manglaur) probably of


Kol

the Dargai ultramafics is called the Dargai fault, and (2) the fault that bounds the base of the Malakand area metasediments and gneisses (Malakand block) is the Malakand fault. Both are low angle faults. The Malakand block is considered as a klippe with a different stratigraphy than the rest of Swat. The Malakand block is thrust over the Saidu along the Malakand fault. The Saidu overlies the Indus melange on an unnamed fault. The melange overrode the rest of Swat on the Dargai fault.

To interpret these as separate faults there are certain problems. First, the stratigraphy of the Malakand block north of Dargai is similar to the established Swat units. The Malakand fault runs along the contact between the Marghazar and Kashala formations with no field expression. Thus I do not recognize any fault here. Second, the map pattern of the ophiolite melange shows a synclinal structure. Third, the sharp edge effect of both the gravity and magnetic data indicate that the Dargai ultramafics do not extend north of the map boundary (Malincanico, 1982). Fourth, the Dargai and unnamed faults do not continue in the NE around the Malakand pass. Finally, the steep foliation and the lithologic contact between Dargai and Malakand are incompatible with the subhorizontal attitude of the faults (Fig. 3).

Another major fault also occurs in the southeast between the Marghazar and the Kashala formations. It is southeast dipping and WSW striking. It is a post-metamorphic normal fault where a large brittle breccia can be observed in the marble on the contact between the Marghazar and Kashala (Fig. 4). This fault extends from the Nikanai Ghar in the north to Jamal Garhi in the southeast where it cuts a fold limb in the calc-schist unit of the Marghazar formation (Fig. 4).

MESOSCOPIC STRUCTURES

Folds

North of the study area in lower Swat, the rocks have been found to have undergone multiple deformations with at least four periods of folding during a single Paleogene metamorphism (DiPietro & Lawrence, 1991). The earliest folds are composite W-SW-vergent, syn-metamorphic F_1/F_2 folds associated with the formation of the regional foliation. Late-metamorphic, N-S-trending open upright F_3 folds are associated with local foliation development, and E-W trending open F_4 folds are associated with retrograde metamorphism. These interfere with each other to produce dome/basin structures.

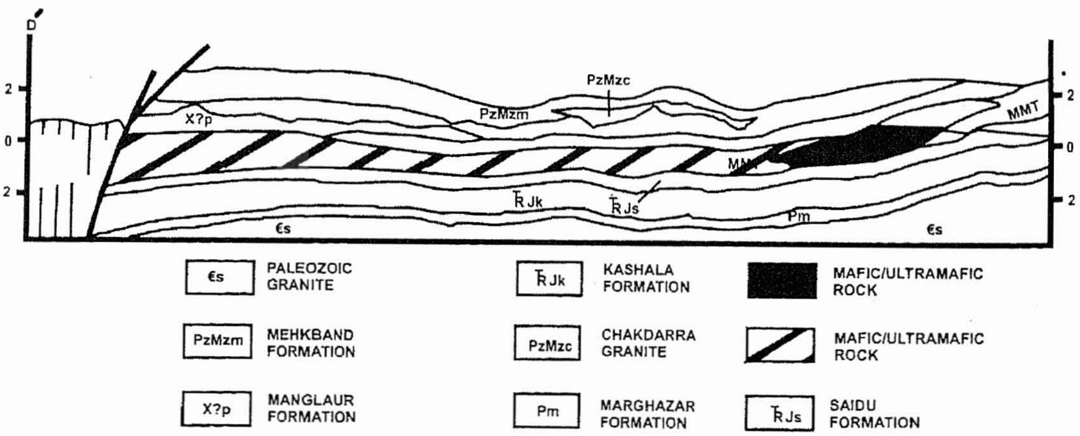


Fig. 3. Geological cross section across the Dargai Ultramafics. (after DiPietro et.al. 1999).

Fig. 4. Fault between Marghazar (lower) and Kashala (upper left) formations cutting a fold limb near Jamal Garhi.

In the study area, Domain 1 preserves all the four superposed small-scale folds (F_1 through F_4). F_1 and F_2 are coaxial and coplanar with isoclinal, recumbent axial surfaces and fold axes that plunge gently toward the NNW (Fig. 5). Where they are superposed F1 folds deform bedding but not foliation whereas F_2 deform a bedding parallel foliation. The similar geometry and orientation suggests that F_1 and F_2 developed at about the same time during progressive deformation (Fig. 6). F_3 and F_4 are the same as described above. They determine the map pattern of the area.

In the south in Domain 2 and 3 the earlier folds F_1 and F_2 are not preserved. Only the large scale F_3 and F_4 are well-developed. Large F_3 folds are upright folds. Small-scale F_3 folds are closed to tight with variably dipping axial surfaces whereas large-scale F_3 axes plunge gently, but variably towards north or, less commonly, the south or southeast (Fig. 7).

Large F_4 folds are best developed in Domain 3 near Thakht-i-Bahai and Mian Khan where they have broadly folded the Marghazar, Kashala and the Saidu formations. F_4 folds are open and E-W trending (Fig. 8). The F_4 folds are asymmetric. They have a different vergence in the different Domains. In Domain 1 and 3 they are south vergent whereas they are north vergent in Domain 2. These large-scale F_4 folds are mainly E-W, but near Rustam they trend NE and near Budal they trend WNW. Thus they appear deflected into a broad arc near the Ambela complex. North of Domain 2, F_4 folds gently deflect the northerly trending structures. South of the Domain 2, they are most obvious folds present and become south vergent (Fig. 8). The superposition of the east-west trending F_4 folds on the generally north-south trending earlier F_3 folds has created the dome and basin structure in the Mora area (Fig. 2).

RELATION OF THE FOLDS TO THE REGIONAL THRUST SYSTEM: A BACK THRUST?

Cross sections (Fig. 9) illustrate the structural relationship of the study area. The fold sequence implies an early period of E-W compression prior to the development of south verging structures. The small-scale F_1 and F_2 folds represent a progressive F_1/F_2 deformation that is associated with a single set of west-southwest-vergent large-scale folds (F_2). The large scale F_3 folds may have developed in intense localized shear strain related to ophiolite emplacement on the Kishora thrust. F_4 folds are upright and open with east-west axial trends. They may correlate with early doming of the lower Swat sequence and with strike slip displacement in the northern part of the MMT, north of lower Swat (DiPietro & Lawrence, 1991).

The reverse vergence of the F_4 folds in Domain 2 may be better explained by a back thrust. Back thrust is interpreted from the structural profile AA' across Rustam to Mora area (Fig. 9). The fault appears on the north edge of Domain 2 on the map. This fault is also supported by the abrupt change in the metamorphic grade. Rocks north of the village of Bar Bazdara and Zormandai are in epidote amphibolite facies whereas those immediately in the south are lower greenschist. In addition, the sheared contact between the Marghazar and Ambela supports this hypothesis. In most places the contact relationship is intrusive, but on the NW margin of the Ambela complex the base of the Marghazar is strongly sheared. I interpret this to be related to the back thrust.

F_4 folds are deflected into a north convex arc from Rustam to Budal (Fig. 2). This is probably related to the back thrust in that the Ambela complex acts as a buttress that deflects the later folds towards north. In effect, the high grade metamorphics are underthrusting the Ambela complex.

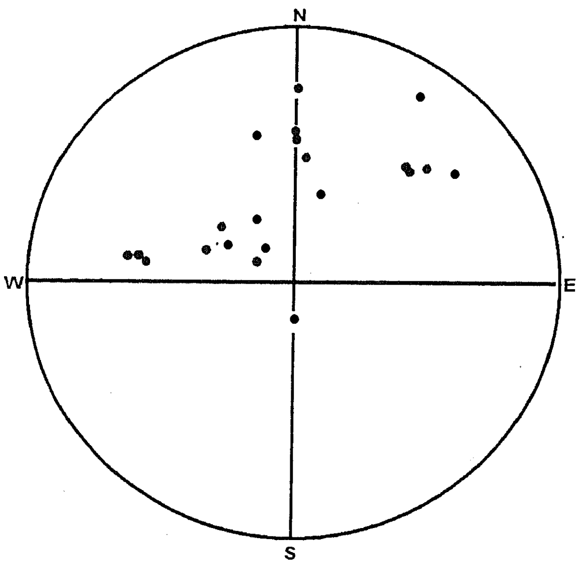


Fig. 5. Lower-hemisphere equal area projection of fold axis data south of Malakand and adjoining areas.

Fig. 8. Large-scale F_4 folds in Marghazar formation near Takht-i-Bahai (Fig. 2). Graphitic schist (right side) with intercalation of greenschist (left side) and quartzite in the middle part. View towards east.

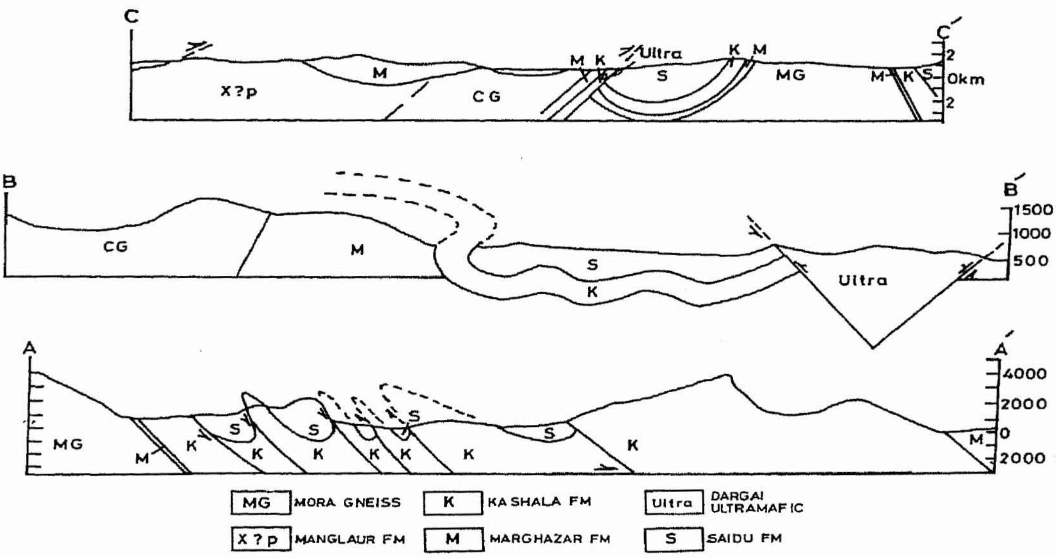


Fig. 9. Geological cross sections of the study area. Location of the cross sections is given in Fig. 18.

METAMORPHIC STRUCTURES

Rocks of the study area record a polyphase deformation history. The area is divided into three domains. The deformation phases in each domain are described independently and the relationship is outlined in the Table 1. The latest deformation phases that occurred everywhere have been given the same designation, D_4. As a result, in the south only two deformations occurred and D_1 and D_2 have not been used. This section will summarize the microscopic features and analysis of the fabric elements related to different deformation phases.

MICROSCOPIC FEATURES

The data presented here are based on criteria obtained from thin sections cut normal to foliation and both normal and parallel to the dominant lineation. Observed structural elements are given in Table 2.

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 recrystallizations. The greenschist and plagiogranite show only one phase of deformation where a single foliation is the only structure developed. The talc-carbonate and limestone blocks show evidence of recrystallization and at least show two phases of deformation. During the first phase D_2 the S_1 foliation was developed where the calcite and talc crystals have grown. During the later phase D_3 the first foliation, S_1, has been folded. The S_1 occurs as relict in the later S_2 foliation (Fig. 10). In the limestone blocks late quartz veins are folded into buckle folds due to variable competency of quartz and calcite (Ramsay & Huber, 1987).

TABLE 2. OBSERVED STRUCTURAL FEATURES OF THE OPHIOLITIC MELANGE BLOCKS AND MATRIX AND THE INDIAN SHELF SEDIMENTS SOUTH OF MALAKAND AND ADJOINING AREAS

Melange blocks	Greenschist	Calcareous schist, talc-schist, talc-actinolite schist, plagio-granite
D_2	S_2 = Dominant Foliation	S_2 = Dominant Foliation
Melange Matrix	Graphitic schist	
D_2	S_1 = Relic muscovite fold hinges	
D_3	S_2 = Dominant Foliation	
D_4	S_3 = Crenulation cleavage	
Indian shelf sediments Domain 1 &2	calc-mica-garnet schist, graphitic schist, calc-mica schist, qtz -mica schist, amphibolite, phyllite, marbles	
D_2	S_1 = Relic muscovite fold hinges	
D_3	S_2 = Dominant Foliation	
D_4	S_3 = Crenulation cleavage	
Domain 3	Quartzo-feldspathic schist, biotite chlorite schist, greenschist, marbles, crinoid bearing calcareous schist	
D_3	S_1 = Relic muscovite fold hinges	
D_4	S_2 = Dominant Foliation	

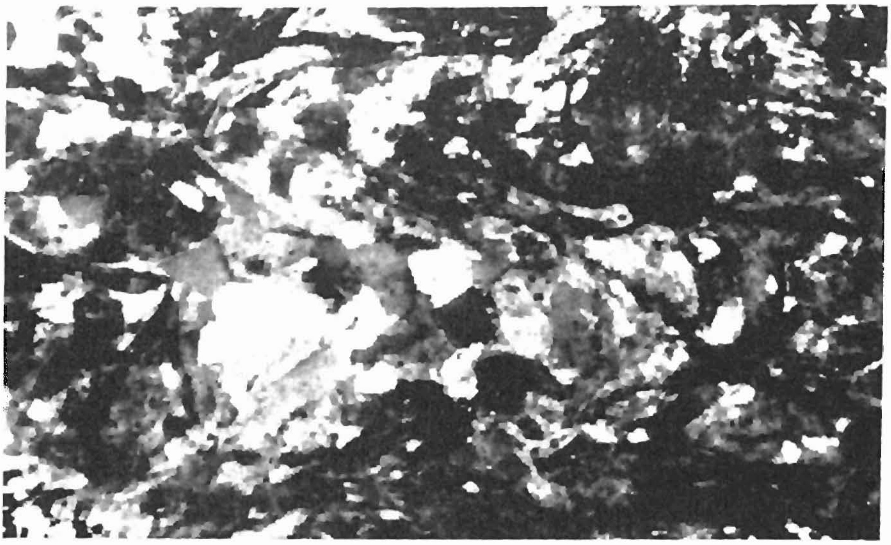


Fig. 10. Small intrafolial folds representing relic S_1. Axial planes to these microfolds describe the S_2 foliation. Marble block containing CO_3, muscovite, quartz and plagioclase. Crossed polars, field of view 1.8 mm long.

Dargai ultramafics

The Dargai ultramafics and mafics (peridotite, dunite, harzbergite, basalt and gabbros) do not show much evidence of recrystallization. Alteration is much more common where olivine has altered to serpentine, but pseudomorphs of olivine are common. Along shear zones some grains do show deformed boundaries. Near the contact with the metasediments these ultramafics are well-foliated. Fine to coarse layers are common in the ultramafics. This layering may be the result of metamorphic differentiation.

Microscopic features of the Matrix

The matrix is complexly deformed. On outcrop scale the deformation phases are hard to be separated. However, the microscopic features indicate the following sequence of events:

(1) S_1 occurs as relict intrafolial folds F_1 and F_2 have not been observed.

(2) A main S_2 phase with development of feldspar porphyroblasts and F_3 folds.

(3) An F_4 phase with development of crenulation cleavage, S_3.

S_1 phase: S_1 is mostly transposed. It occurs as intrafolial folds within the S_2 foliation or as foliation relicts in the hinges of the F_2 folds (Fig. 11). F_1 folds have not been observed.

S_2 phase: The S_2 phase recognized in the graphitic phyllite is recorded by locally developed asymmetric kink folds, F_2, which forms 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.

F_3 phase: The F_3 phase has crenulated the S_2 fabric, where the axes of F_3 folds represent the major lineation in these rocks (Fig. 12). Crenulation cleavage, S_3, has locally developed.

Microscopic features of the Indian shelf sediments

The Indian shelf sediments are also complexly deformed and show three main phases of deformation in Domain 1 and 2. Domain 3 in the south shows only two phases of deformation where the early deformation phases are not preserved. Domain 1 covers the extreme north whereas the Domain 2 is the transition zone between 1 and 3. The rock types in Domain 1 and 2 include calc-mica-garnet schist, graphitic schist, calc-mica schist, quartz-mica schist, and dibase dikes and sills. The microstructures observed in Domain 1 and 2 are as follows:

(1) An early S_1 phase of foliation and garnet development. S_1 and F_1 locally preserved.
(2) A main S_2 phase of foliation development with associated high grade recrystallization and development of garnet and hornblende porphyroblasts.
(3) Post S_2 phase.
(4) Post S_2 annealing phase.
(5) An F_3 phase with the development of crenulation folds, lineation and porphyroblast growth.
(6) A retrograde phase in which garnet is altered to chlorite and amphibole to biotite.

S_1 development: In thin section, the S_1 foliation is preserved in the micaceous rocks as inclusion trails within porphyroblasts, pressure shadow areas created by the deflection of the dominant S_2 foliation around the porphyroblasts, and as relict intrafolial microfolds in isolated microlithons within the dominant foliation except psammitic schist. The limbs of these microfolds are either truncated or are continuous with the dominant foliation. Biotite is the highest grade index mineral that defines the S_1 foliation suggesting that the S_1 fabric developed at biotite grade or less.

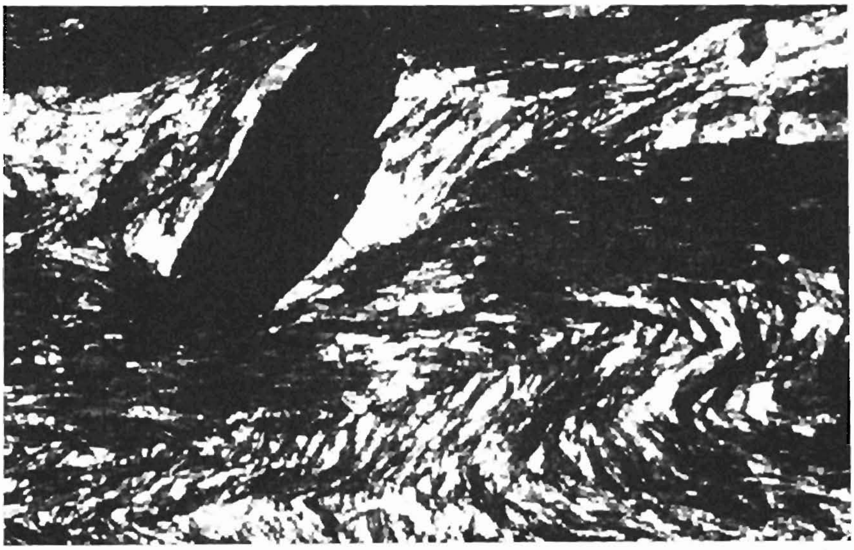


Fig. 11. Relict S_1 as intrafolial folds in dominant S_2 foliatio. Rotation of magnetite grain can also be seen. Graphitic phyllite containing also quartz, muscovite and graphitic dust. Crossed polars, field of view 1.8 mm long.

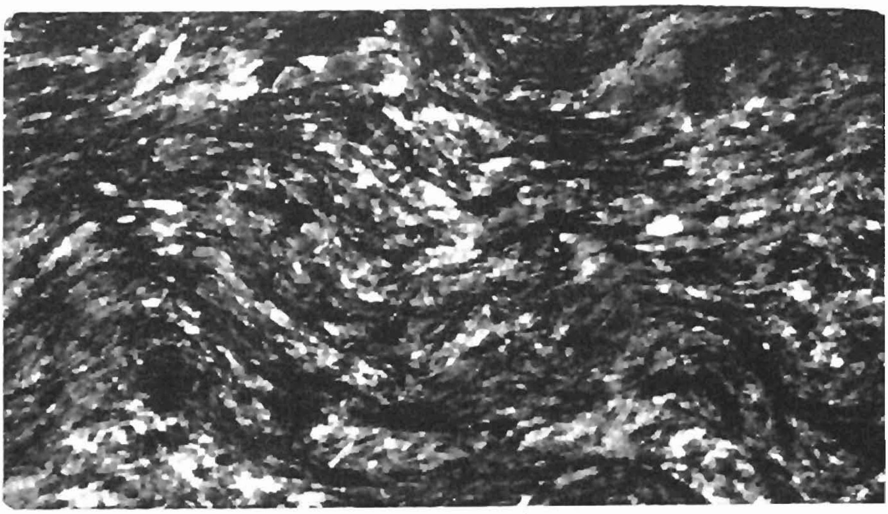


Fig. 12. F_3 phase defined by crenulation of S_2, which shows local crenulation cleavages S_3. graphitic phyllite containing quartz and muscovite. Crossed polars, field of view 1.8 mm in length.

Inter-kinematic phase: The straight to slightly curved inclusion trails shown in Fig. 13, suggest that the relict S_1 fabric was not crenulated or was weakly crenulated at the time that the biotite and plagioclase porphyroblast grew. Other porphroblasts with straight to crenulated S_1 inclusions trails are hornblende and garnet. Widespread porphyroblast growth, between the late stages of S_1 foliation development and the early stages of S_2 foliation development, defines an inter-kinematic phase that separates the deformation associated with S_1 from the deformation associated with the dominant S_2 fabric in the micaceous rocks.

In psammitic schists that lack a relict S_1 foliation, some garnet porphyroblasts contain randomly oriented inclusions in their cores. This suggests that these garnets crystallized early during the development of the dominant foliation (Vernon, 1976). They may record porphyroblast growth during the inter-kinematic phase in rocks which had not yet developed a foliation.

S_2 phase: Evidence for a strong component of rotational shear strain during the main phase of foliation development is preserved, at the scale of the thin section, in micaceous rocks with inter-kinematic garnet porphyroblasts. These porphyroblasts contain inclusion trails that are not aligned from one garnet to the next within a single thin section. The mis-orientation suggests that the garnets were rotated after they formed. Other inter-kinematic garnet porphyroblasts appear to have been broken, crushed, and recrystallized during development of the regional foliation. Whether garnets were rolled or crushed appears to be partly a function of the competency contrast between the porphyroblast and matrix. Garnet porphyroblasts were rolled in rocks with a fine-grained micaceous or calcite-rich matrix, but were crushed and recrystallized in rocks

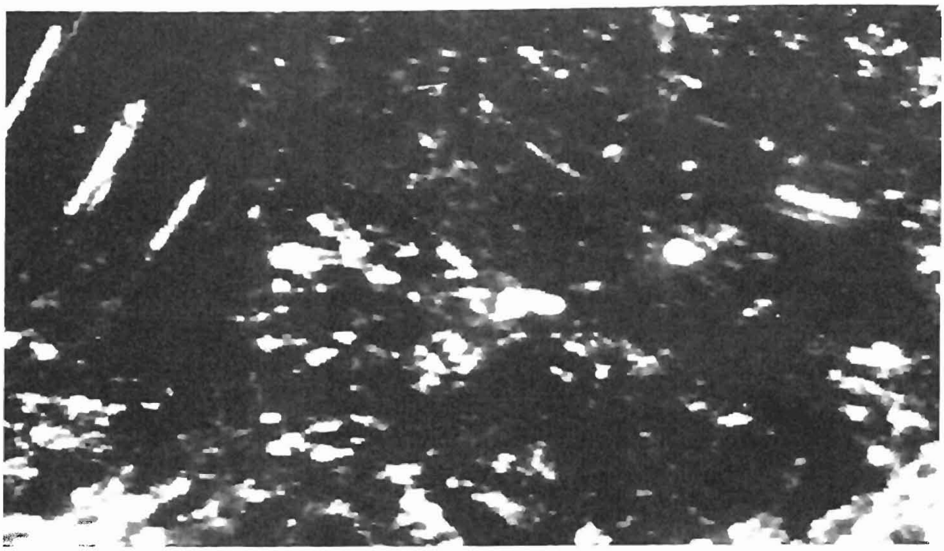


Fig. 14. Overgrowth of garnet porphyroblast. The inclusion trails on the right are straight which indicate that this side of the garnet porphyroblast is early to the S_2 foliation. In the middle the inclusion trail are slightly curved which indicate that this part is syntectonic to the S_2 foliation, and in the left corner the inclusions are at high angle to the external foliation which show that it is part of the garnet grew later and was rolled. This garnet, which formed with a flat or elongated shape in the graphitic schist, has overgrown to the final subidioblastic shape. Crossed polars, field of view 1.8 mm in length.

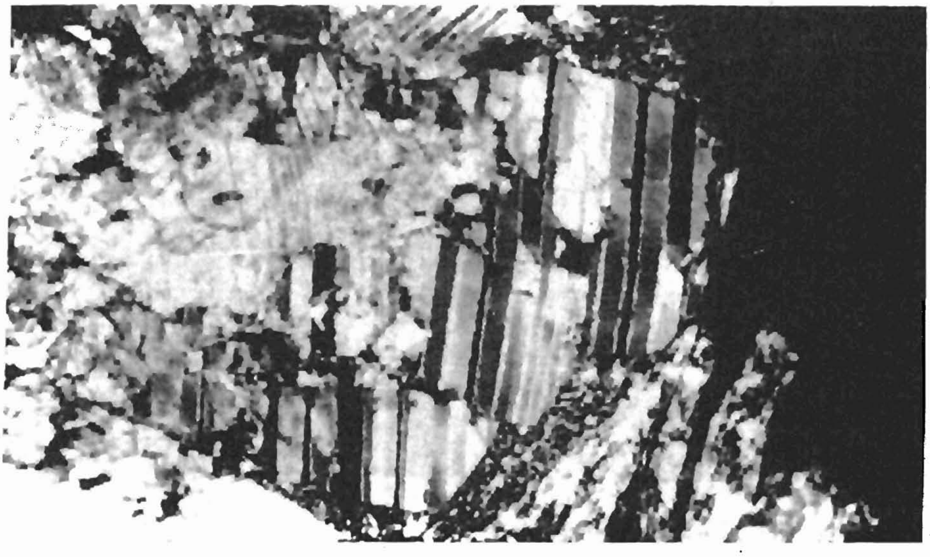


Fig. 15. Brecciated calcite porphyroblast, which was deformed during the emplacemnt of late calcite vein in calc-mica garnet schist. Crossed polars, field of view 1.8 mm in length.

In thin sections, recrystallized tails and pressure shadows are typically symmetric around preserved augen in the plane normal to foliation. This also suggests a flattening deformation (Choukroune, 1987).

F_3 phase: F_3 is well-developed in the north. In the calc-mica-garnet schist and the graphitic schist the F_3 phase involved in the crenulation of the S_2 fabric and the overgrowth of the garnet porphyroblasts. The garnet porphyroblasts are lying in the hinges of the F_2 folds. This suggests that the garnet grade recrystallization was continued during the F_3 deformation.

Retrograde phase: The retrograde phase in the calc-mica-garnet schist and the graphitic phyllite is represented by the alteration of the garnet into chlorite and biotite into chlorite.

Microscopic features of the Domain 3

Domain 3 covers the most southern part of the study area. The rock types include quartzo-feldspathic schist, biotite-chlorite schist, greenschist, calc-mica schist, dolomitic marble, and graphitic phyllite. The structures observed are as follows:

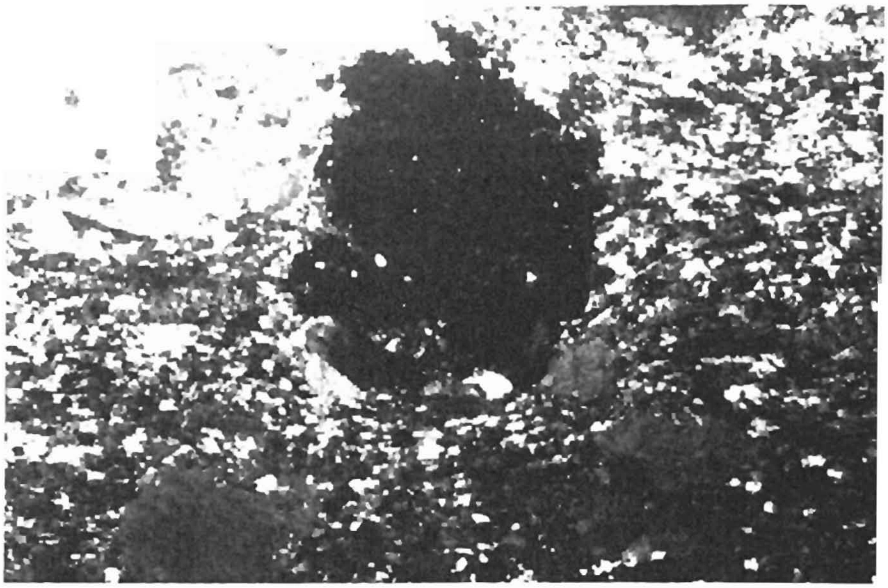
(1) Very locally, S_0, transposed bedding is preserved.
(2) An early S_1 phase of foliation
(3) A main S_2 phase of foliation development

S_0: Bedding S_0 is observed only on the outcrop scale near Takht-i-Bahai in the quartzo-feldspathic schist. In the thin section the S_0 is totally transposed.

S_1: The S_1 foliation is preserved as inclusion trails within porphyroblasts, pressure shadow areas created by the deflection of the dominant S_2 foliation around the porphyroblasts, and as relict intrafolial microfolds (Fig. 16).

S_2: The S_2 foliation is strongly developed and is defined by the orientation of platy or elongated minerals (actinolite, chlorite, biotite) and axial planes of preserved F_3 folds. Growth of magnetite and ilminite porphyroblasts is recorded with the S_2 foliation. The internal fabric in the magnetite is oblique or at an angle to the external foliation. There is also deflection of the external foliation against the porphyroblasts. This suggests that they were formed during and shortly after this phase (Fig. 17). Alteration of chlorite to actinolite is also recorded.

Fig. 16. Small intrafolial folds in greenschist from Takht-i-Bahai, containing chlorite, actinolite and plagioclase. Plane light, field of view 1.8 mm in length.



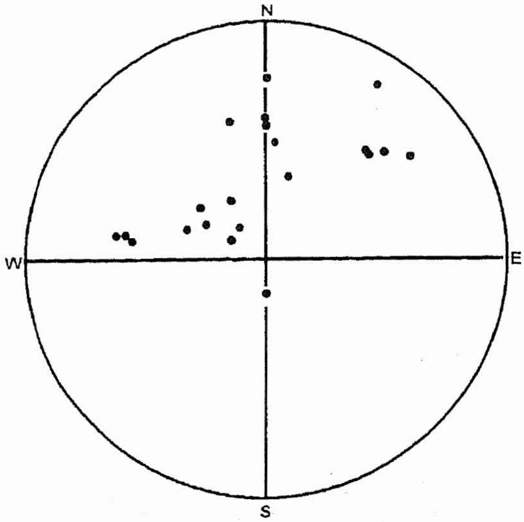
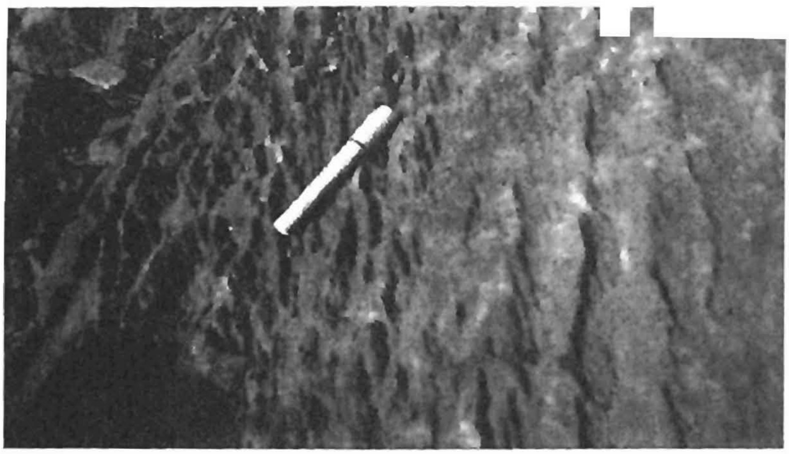


Fig. 19. Lower-hemisphere equal area projection of foliation data south of Malkand and adjoining areas.

Fig. 20. Crenulation cleavage marked by the growth of later mica. Cal-mica garnet schist containing calcite, plagioclase and quartz. Crossed polars, field of view 1.8 mm in length. Define the lineation on the S surface. It is sometime penetrative where it can be observed in the thin sections too.

Lineations

Three types of lineations are observed. They are mineral lineation, boudinage, and, microscopic crenulation folds. The most prominent lineations are the crenulation lineation and the mineral lineation. The crenulation lineation is very clear in hand-specimen and is a penetrative lineation. The mineral lineation is a non-penetrative one where mica flakes define the lineation on the S surface. It is penetrative in some rocks where it can be observed in the thin sections.



thrust is folded north of Chakdarra and near Dargai.

Timing of deformation

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 et al., 1989; DiPietro & Lawrence, 1991) but could conceivably be separate earlier events. Baig (1990) has dated fabrics in the Panjpir which he interprets to be equivalent to the early fabrics of the metamorphic rocks further north. His $^{40}Ar/^{39}Ar$ ages are> 83-85 Ma, which he relates to S1 development, and around 63 Ma, which he relates to the development of S_2. This deformation event may be related with brittle faulting in the Attock-Cherat range during Late Cretaceous (Yeats & Hussain, 1987), probable collision of the Indus suture melange with the Indian plate, and with the initiation or continuation of metamorphism within Indian plate rocks. No fabric from this time is recognized as preserved in the study area.

In the north, the Indian plate rocks reached peak metamorphic temperatures and subsequently cooled through the ≈ 525°C $^{40}Ar/^{39}Ar$ closing temperatures of hornblende between 51 and 32 Ma and through the ≈ 350°C $^{40}Ar/^{39}Ar$ closing temperature of muscovite between about 31 and 24 Ma (Maluski & Matte, 1984; L. Snee in Palmer-Rosenberg, 1985; Treloar et al., 1989b; Treloar & Rex, 1990; Baig, 1990). The cause of metamorphism may have been the rapid burial of Indian plate rocks as they were subducted beneath the Indus Suture melange. DiPietro and Lawrence (1991) presented evidence that the Indus suture was emplaced before the attainment of peak temperature in the Indian plate rock sequence. Additional evidence for early emplacement is the dominantly ductile and annealed fabrics along the entire length of the Main Mantle Thrust.

Lawrence et al. (1985) and Palmer-Rosenberg (1985) obtained $^{40}Ar/^{39}Ar$ ages of 39.9 ± 0.2, 38.8 ± 0.3 Ma from hornblende In the Marghazar formation near Jawar and ages of 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 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 & Lawrence, 1991). 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). Peak metamorphic conditions were attained during a period of static recrystallization following Indus Suture collision and development of the F_1/F_2 folds (DiPietro & Lawrence, 1991). Calculated temperatures in Swat, North of the latitude of Jawar, average between 600-700°C and 9-11 kbar (DiPietro, 1991).

Muscovite, biotite and alkali feldspar $^{40}Ar/^{39}Ar$ data from the Swat block (L. 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 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). Muscovite, biotite and alkali feldspars dates from a sheared sample of Swat granite gneiss by Baig (1990) has preferred biotite date of 32 ± 0.13 Ma and muscovite has a plateau date 28 ± 0.2 Ma. Potassium has an Argon loss spectrum with a maximum date of 45 ± 0.2 Ma and minimum date 22 $\pm$ 0.1 Ma. He interpreted these dates to indicate that the fabric S_1, S_2, S_3, S_4 in the area south of the Swat River formed before 45 Ma. However, the younger foliation in the Swat area only involves minor new mica growth that is reflected by the younger dates between 28 and 32 Ma. At least F_4 in the Mingora area is probably this young.

We have correlated S_1, S_2, and S_3 from the study area with S_2, S_3, and S_4 from the area to the north in Swat. If this is correct the F_2, F_3 and F_4 deformation phases in the study area may have occurred between 45 and 32 Ma.

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