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# THE LOCATION OF THE MAIN CENTRAL THRUST IN THE NORTHWEST HIMALAYA OF PAKISTAN: TECTONIC IMPLICATIONS

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**Abstract**:- *A number of workers have proposed different positions for the Main Central Thrust in the northwest Himalaya of Pakistan. These positions have varied from considering the Panjal Thrust, the Oghi Shear Zone and even the Raikot Fault, as well as many other intervening locations in the area between the Main Mantle Thrust in the north and the Main Boundary Thrust in the south, as the Main Central Thrust. All these positions are enumerated and critically appraised in their context of the geology of the area. They are subsequently evaluated to see whether they follow the tectonic requirements of the Main Central Thrust as a Boundary Thrust that marks the contact between the Higher and Lesser Himalaya. It is subsequently argued that, except for the Batal Fault near Naran (in Upper Kaghan Valley) Luat Fault (in Neelum Valley) and the tectonic lineament near Malakand (in Lower Swat), no other position fulfils the required criteria specified for the definition of Main Central Thrust. These most likely positions of the Main Central Thrust, according to this review, were only located after extensive geological mapping of the terranes in Neelum and Kaghan Valleys and in the area of Besham and lower Swat.*

## INTRODUCTION

The delineation of the positions of the Main Central Thrust (MCT) in the northwest Himalaya of Pakistan and the adjoining Azad Kashmir are numerous. To date, twelve locations of the MCT have been discovered and at least partially mapped (for review, see Spencer, 1995). In this paper, we consider the factors responsible for this confusion and expand in greater detail on the various reasons for the rejections of many of these locations as being the equivalent of the MCT.

The Himalaya of Pakistan (also known as the Northwest Himalaya), constitute the northwestern and western extremity of the more than 2,800 Km (upto the Ahwaz block in Afghanistan) long Himalayan range. The transverse subdivision of Himalaya into Tethyan Himalaya, Higher Himalaya, Lesser Himalaya and Sub-Himalaya, which was first established in eastern and central Himalaya (India and Nepal) could not be fully extended to western Kashmir and adjoining Pakistan since these areas had remained largely unmapped or inaccessible until very recently.

In addition, these areas are affected by syntaxial formation (i.e., Nanga Parbat, Hazara-Kashmir and Besham Syntaxes) and the region becomes increasingly complicated in its tectonic setup. Sub-sequently, the main Himalayan subdivisions (Tethyan, Higher, Lesser and Sub Himalaya) are altered as they enter from eastern Kashmir into the western syntaxial region. In particular, they have undergone a marked change in their strike, coeval cover-basement metamorphism, extensive internal imbrication and late-stage strike-slip faulting that results in either the attenuation or even total elimination of some of the rock units. In the NW Himalayan region, the splitting and merging of even the major faults, as well as changes in their nature (e.g., normal or reverse to strike-slip or oblique-slip) appears common. Under such circumstances, the definition and delineation of boundary faults, such as the MCT, would not be an easy task, especially in areas that have only been traversed and/or not mapped in detail.

Whilst the Main Boundary Thrust (MBT) had been roughly identified in many parts of the Northwest Himalaya, little was known either about the location or the extension of the MCT in this region. The Higher Himalayan Crystallines were presumed to have been either attenuated, patchy, or completely terminated in Kashmir, west of the Simla Himalaya. The westward extension from India (eastern Kashmir) of the Main Central Thrust and of the Higher Himalaya into Western Kashmir and adjoining Pakistan has, therefore, continued to intrigue Himalayan Geologists for decades. Initial attempts showed various workers trying to connect the MCT from Kashmir with the Panjal Thrust, the Murree Thrust (or MBT) and even with the Main Mantle Thrust (MMT or Indus Suture). For example, Gansser (1964), Valdiya (1980) and Sinha (1981, 1989) regarded the Main. Boundary Thrust and Panjal Thrust as the correlative of the MCT in Kashmir and the NW Himalaya. This view, first published by Gansser (1964), has generally been accepted for the last two decades. Recently, detailed mapping of the NW Himalayas has been carried out by many foreign and Pakistani teams. It has now become apparent that the acceptance of the view, according to Gansser (1964), would lead to the combining together, in one block, of terranes consisting of entirely different tectono-stratigraphic, tectono-meta-morphic, tectono-magmatic and structural characteris-tics. Clearly, the MCT could not connect with the Panjal Thrust, as was first envisaged.

In order to prepare an acceptable tectonic model for the NW Himalaya, and correlate it with the rest of the Himalaya, systematic programmes of mapping in the Northwest Himalaya of Pakistan have now been comp-leted by many workers. Some of these programmes had an emphasis on the demarcation of MCT. In Kaghan Valley alone, for example, many teams have mapped the valley both separately and jointly (Ghazanfar et al., 1983; Ghazanfar and Chaudhry 1985, 1986, Chaudhry and Ghazanfar 1987, 1990, 1993; Chaudhry et al. 1994a, 1994b, Greco et al. 1989; Greco and Spencer 1993, Spencer et al. 1990, Spencer 1993, 1995). As such, the Main Central Thrust was first clearly located as a separate, distinguishable fault in the Kaghan and Neelum Valleys by Ghazanfar and Chaudhry (1986, 1990). It was subsequently extended across the entire NW Himalaya of Pakistan (Chaudhry et al. 1994a, 1994b).

Other parts of the NW Himalaya and Azad Kashmir have also been mapped by Greco (1989), Bossart et al. (1988), Fontan and Schouppe (1994), Madin et al. (1989), Papritz (1989), Rey (1989), Williams et al. (1989, 1991) and DiPietro (1991), to name a few significant contributions. Although most of these papers and thesis did not concentrate specifically on the location of the MCT, all provided various views on its position (or reasons as to why the MCT should not be brought into the subdivision terminology of the Hima-laya in Pakistan). Moreover, contrary to the expecta-tions that mapping in the NW Himalayas by a large number of workers would lead to a consensus on the position of MCT, and the subsequent demarcation of the boundary between the Higher and Lesser Himalaya, the problems have infact proliferated. Instead of just the one MCT that was proposed by Ghazanfar and Chaudhry (1986) during early mapping in Kaghan being extended to the adjacent regions, some eleven other, and mostly unrelated locations have been found, all of which have been called the "Main Central Thrust". This current situation has been summarised by Spencer (1995).

## POSITION OF THE MCT IN CENTRAL HIMALAYA

Crustal scale tectonic discontinuities (like the MCT), which demarcate tectonic zones in collisional mountain chains, are generally not simple and easily recognisable faults. Auden (1937) and Heim and Gansser (1939), while working in Garhwal and Kumaun, defined a major thrust between the sedimentary formations and moder-ately metamorphosed rocks. This thrust, that persistent-ly dips north at 15°-45°, was formalised as the Main Central Thrust. Sinha (1981, 1989) has followed Heim and Gansser (1939) in defining the Main Central Thrust in the central Himalaya. According to Spencer (1995), much confusion about whether the Main Central Thrust is actually one, two or even three thrust surfaces has been especially common in central Himalayas (Sinha 1989, Thakur, 1992). For example, Pati and Rao (1981) suggested that the Chail Thrust surface is the base of the Main Central Thrust whilst the Jutogh Thrust is the roof of the Main Central Thrust. By contrast, in places where both thrusts are present, the lower Chail Thrust has been called the Main Central Thrust, whereas where the Jutogh Thrust (which comes into contact with the sedimentary rocks), has also been called the Main Central Thrust.

Moreover, in an attempt to redefine the Main Central Thrust, Valdiya (1980) used other criteria such as the abrupt break in the grade of metamorphism and the change in the petrological composition (of the rocks of the Central Crystallines, or Higher Himalaya), to define a thrust plane that was subsequently called the Vaikrita Thrust (or MCT). This location was at an even higher stratigraphic level (i.e., at the base of the kyanite-sillimanite bearing rocks) than the one that was previously defined by earlier workers.

## CONTROVERSY REGARDING THE DEFINITION OF THE MCT

Although there is a general agreement that the MCT demarcates the boundary between the Higher Himalaya and the Lesser Himalaya, there is no general agree-ment on the definition or even a specific location of the Main Central Thrust. This is true even in its type locality in the central Himalaya. For example, three locations of the MCT, namely MCT-1 (Chail Thrust), MCT-2 (Jutogh Thrust) and MCT-3 (Vaikrita Thrust) have been propos-ed in India (see Thakur, 1992 for review). The confusion in the northwest Himalaya of Pakistan is more apparent where twelve locations of the MCT have been proposed. In order to define the MCT (and the subsequent inherent interpretation of a footwall Lesser Himalaya and hang-ing wall Higher Himalaya), it must be realised that the crustal scale discontinuities (such as the MCT) which demarcate tectonic zones in collisional mountain chains are generally not easily recognisable faults and of which there could be many possibilities. However, in this respect, the MCT in quite unique in having stratigraphic, metamorphic, chronological and structural (strain) criteria that can distinguish it from other major faults.

On the basis of the above criteria, most Himalayan workers now generally agree that the MCT is an intra-continental thrust that demarcates the boundary bet-ween the two distinct zones of the Lesser and the Higher Himalaya. This fault has also resulted in a consi-derably thickening of the continental crust. It is a north dipping low to high angle thrust associated with mylo-nitisation, a pervasive stretching lineation and strong foliation. It is also marked by inverse metamorphism and a sudden jump in metamorphic grade from green-schist to upper amphibolite facies with differing tectonic style on either side (Pecher 1977, Brunel 1986, Valdiya 1984; Ghazanfar and Chaudhry, 1986, Chaudhry and Ghazanfar 1990, and Chaudhry et al. 1994a, 1994b). It is on the basis of these characteristics that the Main Central Thrust was recognised and extended in India and Nepal. Similarly, for any extension into the North-west Himalaya of Pakistan, any proposed MCT must fulfil most, if not all of the above criteria.

## EXTENSION OF THE MCT INTO THE NORTHWEST HIMALAYA OF PAKISTAN

The Main Central Thrust can be demarcated as an almost continuous tectonic line from the Assam Himalaya in the east to the Punjab Himalaya in the west (Figure 1),

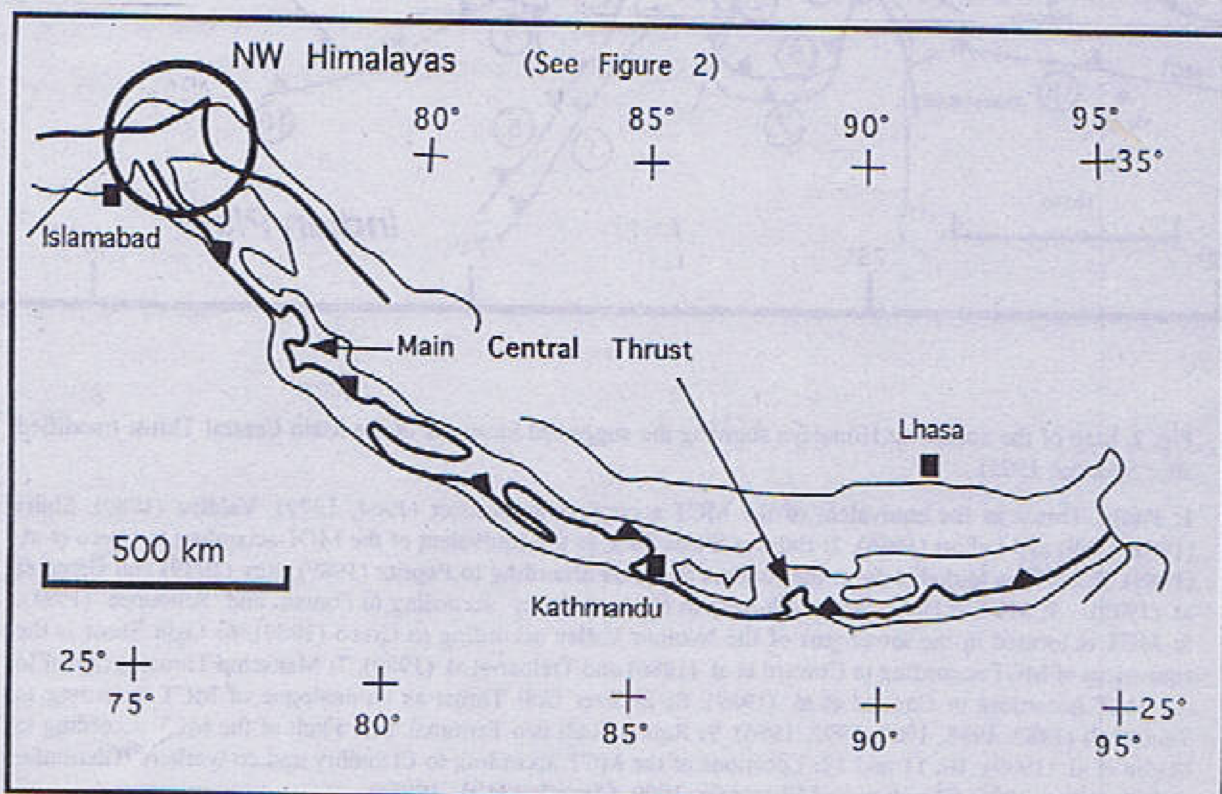



Fig. 1. Map of the Himalayas showing the known extent of the Main Central Thrust (map redrawn from Pecher, 1991). The location of the Main Central Thrust can be traced along most of the length of the Himalayan region (from Spencer, 1995).

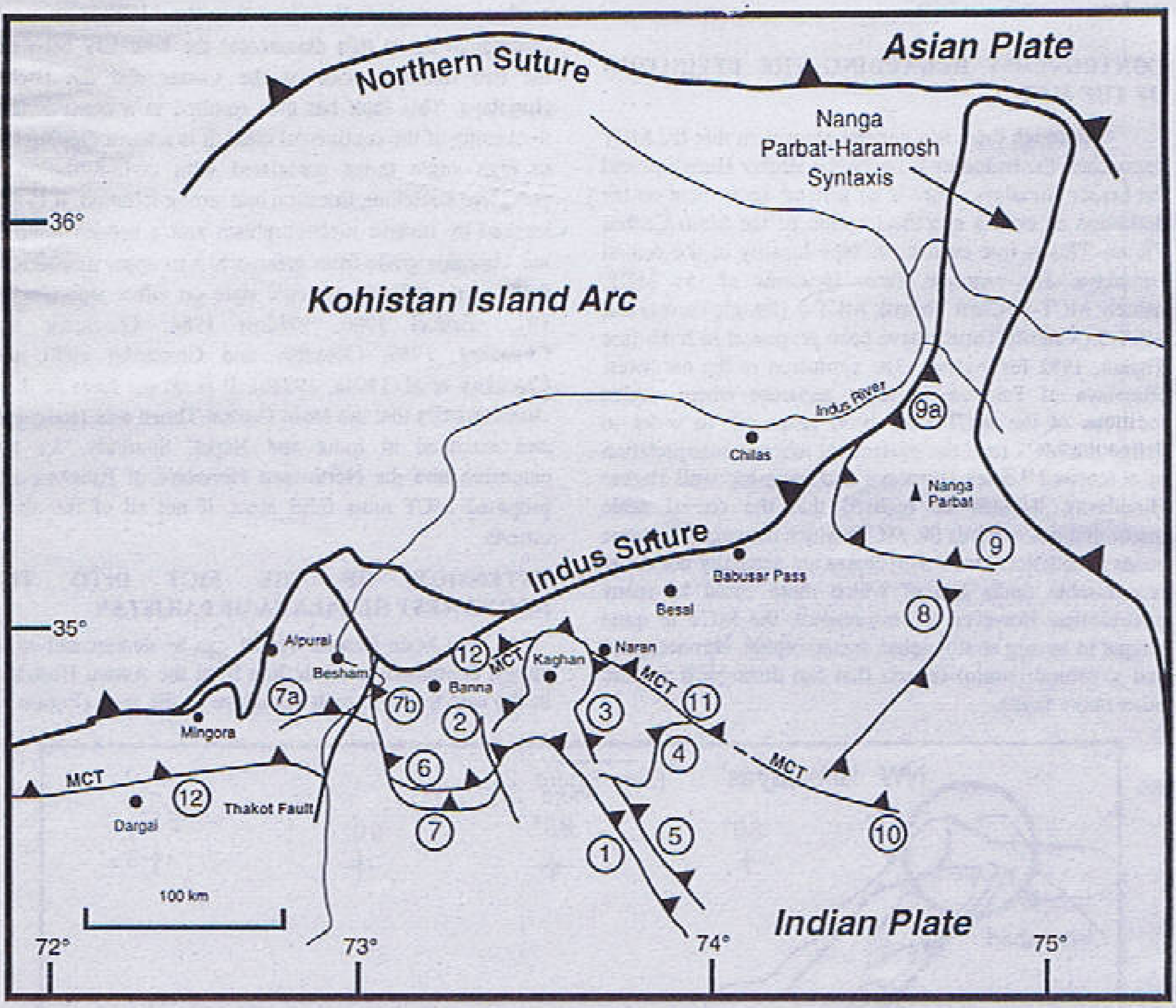



**Fig. 2.** Map of the northwest Himalaya showing the suggested locations of the Main Central Thrust (modified after Spencer, 1995).

**1:** Panjal Thrust as the equivalent of the MCT according to Gansser (1964, 1979), Valdiya (1980), Sinha (1981, 1989) and LeFort (1986). **2:** Balakot Shear Zone as the equivalent of the MCT according to Greco et al. (1989). **3:** MCT is folded to form the Kaghan Syntaxis according to Papritz (1989), Rey (1989) and Greco et al. (1989). **4:** MCT at Batal-Musa Gali-Luat in Neelum Valley according to Fontan and Schouppe (1994). **5:** MCT is located in the lower part of the Neelum Valley according to Greco (1989). **6:** Oghi Shear is the equivalent of MCT according to Coward et al. (1986) and Treloar et al. (1989). **7:** Mansehra Thrust is coeval to the MCT according to Coward et al. (1989). **8:** Shonter Gali Thrust as an analogue of MCT according to Tahirkheli (1987, 1988, 1989, 1992, 1996). **9:** Raikot Fault is a Terminal Tear Fault of the MCT according to Madin et al. (1989). **10, 11 and 12:** Locations of the MCT according to Chaudhry and co-workers (Ghazanfar and Chaudhry, 1986; Chaudhry and Ghazanfar, 1990; Chaudhry et al., 1994a).

with its locus typicus in the central Himalaya. Since the Higher Himalaya Crystalline Block, with the MCT at its base, could not be extended much beyond Simla Himalaya, the position of the MCT in Kashmir and the NW Himalaya of Pakistan remained uncertain. However, many different positions of the MCT have been proposed by various workers in Pakistan. They are evaluated in accordance with the definition of the MCT given above. The actual positions of the various locations of the MCT are found in Figure 2 (slightly modified after Spencer, 1995).

**Panjal Thrust as the Equivalent of the MCT**

Gansser (1964, 1979), Valdiya (1980), Sinha (1981, 1989) and Le Fort (1986) have advocated for the recognition of the Panjal Thrust as the correlative of the MCT (Thrust 1 in Figure 2). Thus, most of the published tectonic maps of Himalaya show the Panjal Thrust as the tectonic line connecting the MCT between Northwest Himalaya and the Panjal Thrust west from Kashmir. Beyond Kashmir, the Panjal Thrust is shown as the surficial trace of the MCT into Pakistan and is shown terminating at the apex of the Hazara-Kashmir Syntaxis.

Such an extension of the MCT in Neelum Valley of Kashmir and Kaghan Valley of Hazara, however, results in the fault running close to the south of the belt that is composed of greenschist facies rocks and through an area with a structural style characterised by a schuppen zone in a brittle deformation regime (the 'Foreland Fold and Thrust Belt'). To the north of this line, two tectonic domains with entirely different tectonostratigraphy, structural styles and metamorphic histories get grouped together. Its further extension westwards, as postulated by Calkins et al. (1975) and Gansser (1979), is shown in Figure 3 (thrust indicated as 'PF'). The section of this fault passing south of Peshawar Basin is also known as the Khairabad Fault. If this extension of the MCT is accepted, then it passes right through the middle of the well established and accepted 'Lesser Himalayan' tectonostratigraphy (Tahirkheli, 1992). The location of the MCT west of the Hazara-Kashmir Syntaxis does not conform to the actual stratigraphic position between epi- to meso-grade Jutogh-Salkhalas and kata- (higher) grade Himalayan Crystallines that are known from the type sections in central Himalaya. Tahirkheli (1992) has rightly pointed out that by considering the Panjal Thrust and the MBT as representing the surficial trace of the MCT in Kashmir and NW Himalaya, one departs from the basic norms of the megashear that it displays in the type sections in the eastern, central and western Himalaya.

**The Balakot Shear Zone is the Equivalent of MCT**

Greco et al. (1989) have suggested that west of the Hazara-Kashmir Syntaxis, the Balakot Shear Zone (Thrust 2 in Figure 2) forms a very important structural and metamorphic discontinuity. It separates the 'Salkhala Formation' from the so called overlying 'Higher Himalayan Crystallines'. This shear zone, on the western side of the Hazara-Kashmir Syntaxis, is a sub-vertical left-lateral strike-slip fault giving rise to strong deformation in what they call the Panjal Unit. The location of this shear zone (i.e. NNW-SSE on the eastern side of the Mansehra Fault) puts the fault well within the Tanawal Formation, the two mica cordierite granites of Le Fort et al. (1980) and a part of the Kashmir sequence of Chaudhry and Ghazanfar (1987). Not only are these two units generally recognized as 'Lesser Himalayan', but locating the MCT here would preclude the fault of its main character of differentiating tectonostratigraphic regimes. We note that whilst Greco et al. (1989) place this shear zone between two strikingly different tectonostratigraphic and tectono-metamorphic regimes at Batal (near Naran), by contrast they have deviated from this criteria further south in the region of the Hazara-Kashmir Syntaxis. We believe that the Higher Himalaya, with a well recognised stratigraphy, metamorphism and structural style, lies much further to the north and northeast of the MCT as located by Greco (1989).

**The Main Central Thrust is Folded to Form the Kaghan Syntaxis**

Papritz (1989), Rey (1989) and Greco et al. (1989) fold the Main Central Thrust north of Batal to form the Kaghan Syntaxis (Thrust 3 in Figure 2). According to these workers, a domal structure deforms the MCT into a half window. Other detailed field mapping (Chaudhry and Ghazanfar, 1987; Smith 1994) demarcates the MCT in an alternative position - instead of changing its strike (by 180°), deforming it around the Kaghan Syntaxis, they map it as striking east-west around Dheri (NE of Banna), close to Main Mantle Thrust (MMT) or the Indus Suture. In Nili Nadi (Bhimbal Valley), northwest of Naran, the Higher Himalaya thins dramatically between the MMT and the MCT. We believe that further west in Allai Kohistan (Banna), the Higher Himalaya pinches out completely. Subsequently, we interpret that in Allai Kohistan, sediments of possible "Tethyan" origin (Ghazanfar et al., 1996) expand and come directly into contact with the Mansehra Granite of the Lesser Himalaya, without exposure of the Higher Himalaya Block in between. The Higher Himalaya reappears again on the western side of the Thakot strike-slip fault and then can be traced through Lower Swat, Malakand (Chaudhry et al., 1994a) and further west towards the Ahwaz Block in Afghanistan.

If the interpretation of Papritz (1989), Rey (1989) and Greco et al. (1989) is followed with their location of the MCT, then the fault would run entirely within the Kaghan

Group of Chaudhry and Ghazanfar (1987). In Middle Kaghan Valley, this unit is composed predominantly of pelites, psammites and calc-pelites with subordinate marbles and a band of gypsum. This sequence probably extends below the Hazara Group of Chaudhry and Ghazanfar (1993) and also below the Dogra Slates of Kashmir Valley where it has been called the low grade Salkhalas. Thus, turning the MCT (from Batal) around the Kaghan Syntaxis is depriving the MCT of its role as a boundary thrust marking a lineament of significant pressure-temperature break and differing structural styles between the hanging wall and the foot wall. Moreover, there is a timing problem. The MCT is known to have formed early in the tectonic history of the Himalayan deformation yet the Balakot Shear Zone on the western side of the Hazara-Syntaxis formed relatively late in the Himalayan tectonic history. Linking these two faults of known different ages is a problem that was noted by Papritz (1989) and Rey (1989).

**The MCT Lies Between Batal-Musa Gali and Luat in Neelum Valley**

Fontan and Schouppe (1994) locate the MCT at the recognised locations of Batal (in accordance with Ghazanfar and Chaudhry, 1986, 1990; Greco et al., 1989) and Luat (in accordance with Chaudhry and Ghazanfar, 1990). However, in between these two areas, they demarcate the MCT as being folded around the Musa Gali area (Thrust 4 in Figure 2). A similar position was also indicated by Greco (1989). Thus, Fontan and Schouppe (1994) follow Ghazanfar and Chaudhry (1986) between Luat and Batal. However, further to the west, they follow Greco et al. (1989) folding the MCT around the Hazara-Kashmir Syntaxis and linking it with the Panjal Fault on the western limb of syntaxis.

**The MCT Strikes Across the Lower Part of Neelum Valley**

Greco et al. (1989) agree with Ghazanfar and Chaudhry (1986) in placing the MCT near Batal in Kaghan Valley. However, when extending this fault into Kashmir, they turn it towards Harla Baihk, north of Galihetar and Musa Gali Baihk in the lower Neelum Valley (Thrust 5 in Figure 2). Greco et al. (1989) note that the position of this thrust is based on structural, stratigraphic and metamorphic evidence. This fault runs parallel and close to the Panjal Fault in Kashmir (Thrust 1 in Figure 2). Greco et al. (1989) then turn their MCT south from Batal (near Naran) in Kaghan towards Nauseri in the lower Neelum Valley. This is in contrast to the eastward extension from Batal to Luat (in Middle Neelum Valley) which was suggested by Ghazanfar and Chaudhry (1986) and Chaudhry and Ghazanfar (1990). In Lower Neelum Valley (between Tithwal and Luat), Ghazanfar et al. (1983) mapped an extensive sequence of Tanawals with Mansehra type two mica cordierite bearing porphyritic Jura Granite. This sequence, however, is attenuated northwards as it reaches the Lower Kaghan Valley, over the ridge from the neighbouring Neelum Valley, only to open up again to the west of Hazara-Kashmir Syntaxis in the Mansehra area. The pelite-psammite unit of Mansehra, Oghi and Batgram is, we suggest, the same Tanawals as encountered in the Neelum Valley. There it is overlain by the Authmuqam slates, similar to the tectono-stratigraphic situation in Hazara (Chaudhry and Ghazanfar, 1993).

Based on the above description, we suggest that the extension of the MCT from Batal towards Nauseri in lower Neelum Valley is probably not justified. The main argument for this is because it places the entire low grade Tanawal sequence of Lower Neelum Valley, along with the overlying Authmuqam Slates (Dogra Slates), in the 'Higher Himalaya'. Moreover, such a tectonic position does not take into account the major pressure-temperature break at Luat, a further 100 km up north up the valley. There are other tectonic problems with the placement of the MCT parallel to the Panjal Fault near Nauseri in the Neelum Valley, according to Greco et al. (1989). They have effectively made the Kashmir Basin part of the Higher Himalaya, although it is stratigraphically correlatable to the Peshawar Basin to the west, which is of clear Lesser Himalayan affinity. Infact, it would be difficult to explain the sediments in this unmetamorphosed basin in juxtaposition with the high grade gneisses of the Higher Himalayan Basement unless there is an extensional contact between them. By contrast, if this location was to be accepted, it could be envisaged that the basin was somewhat akin to the Tethyan Himalaya, north of the Zanskar in Ladakh and not part of the Lesser Himalaya at all.

**The Oghi Shear Zone is the Equivalent of MCT**

The Oghi Thrust (Coward et al., 1986), or the Oghi Shear Zone (Treloar et al., 1989a) in the Mansehra area, has been regarded as an important tectonic discontinuity. Greco et al. (1989) regard this shear zone (Thrust 6 in Figure 2) as the equivalent of the Main Central Thrust. This shear zone, in fact, follows very closely the contact between the Mansehra Granite and the pelitic-psammitic Tanawal Formation (of Precambrian age) within the Mansehra area. This shear zone is well exposed on the Oghi-Jal Gali road. Is it really the MCT or its equivalent? Does it conform to the generally accepted definition of the MCT?

On the Oghi-Jal Gali Road, the Oghi Shear passes along the contact between the Susal Gali Granite gneiss and the Tanawal Formation. Displacement along this shear zone (in this section) is argued to be minor because the shear zone passes through hornfelses and does not even eliminate them. Moreover, the rocks on either side of this shear zone are in amphibolite facies (kyanite grade). Note that this metamorphic grade does not necessarily imply that these units should be classified as 'Higher Himalayan' because we follow Chaudhry (1964), Baig et al. (1988), Chaudhry et al. (1989) and Williams et al. (1990) in the interpretation of this localised metamor-phism as being pre-Himalayan. Therefore, we consider the granites and associated metamorphic rocks that crop out on either side of this shear zone to be part of the same Mansehra Block which is composed of Tanawals and intrusions of the porphyritic two mica-cordierite bearing Mansehra Granite. Finally, the structural style on either side of this shear zone is also the same. Therefore, we interpret this shear zone as being one that forms entirely within the Lesser Himalayas, and more specifically the porphyritic two mica cordierite granites and its associated metamorphic rocks.

### Mansehra Thrust is Coeval to the MCT

Coward et al. (1988) regard the Mansehra Thrust as coeval to the Main Central Thrust (Thrust 7 in Figure 2). Near the town of Mansehra, the thrust is shown at the contact of the biotite grade pelite- psammites and the Mansehra Granite. However, in this area, the massive Mansehra Granite, with its chiastolite-cordierite hornfels aureole preserved, is hardly sheared or faulted. Furthermore, this zone does not represent any significant break in either metamorphic grade or structural style. In fact, we believe that the presence of a Mansehra Thrust itself is highly doubtful because around Mansehra there is neither any evidence of shearing nor of any significant dislocation.

Coward et al. (1988) show that part of the Mansehra Thrust (or the MCT) changing strike from east-west to north-south close to the River Indus before being cut by the Indus Suture east of Besham (Thrust 7b in Figure 2). This section is very interesting. Here the Mansehra Thrust virtually runs along the Thakot Fault of Ashraf et al. (1980). This fault does not thrust the Mansehra area (that we regard as the Lesser Himalaya) over the Besham area (that we regard as the Higher Himalaya). By considering the Mansehra Thrust as the MCT, Coward et al. (1988) by definition must now consider the Mansehra block as the 'Higher Himalaya' and the overthrust (to the west) Besham block as the 'Lesser Himalaya'. At the same time Treloar et al. (1989) admit that the Mansehra block represents relatively lower pressure conditions compared to Upper Kaghan in the northeast. The lineament (Thrust 7A in Figure 2) west of the River Indus (Coward et al. 1988) does, however, comes close to the position of the MCT in an area as further located by Chaudhry et al. (1994a) (see below). Unfortunately, Coward et al. (1988) whilst showing this small segment of MCT on their maps do not discuss it.

### Shontar Gali Thrust is an Analogue of the Main Central Thrust

Tahirkheli (1987, 1988, 1989, 1992, 1996) suggests that the Shontargali Thrust (Thrust 8 in Figure 2) is an analogue of the Main Central Thrust. This thrust trends NE-SW from Baloshbar (between Ratta and Astor) and Kel Nala. Here he observed the Nanga Parbat Gneisses overriding the middle greenschist facies rocks, which locally rise to kyanite and sillimanite grades, of what he regards as 'Salkhala Formation'. If, as suggested by Tahirkheli, the MCT lies between the Salkhala Formation and the Nanga Parbat Gneiss in the north, it then becomes difficult to explain as to how a separate jump from greenschist to kyanite-sillimanite grades occurs within the Salkhala Formation to the south which he places in the Lesser Himalaya. The Shontar Gali area does show the presence of a local shear zone. However, there is no significant pressure-temperatue break across this shear zone. The rocks in both the hanging wall and footwall fall into the same metamorphic grade, have the same structural and a similar deformational style. The rocks in the area have undergone variable stages of retrogression. The so-called 'Salkhalas' in the area have the presence of kyanite and sillimanite, wherever the lithology is suitable. A study of mineral assemblages in different lithologies shows that these 'Salkhalas' fall into upper amphibolite facies.

The papers of Tahirkheli do not take into account the recent mapping carried out by Chaudhry and Ghazanfar (1987), Greco et al. (1989), Hubbard and Spencer (1990), Spencer (1993), Greco and Spencer (1993) and Hubbard et al. (1995) which shows a continuation of the geology of Upper Kaghan into the Nanga Parbat massif. The location of the MCT as suggested by Tahirkheli is, in fact, placed well within the Higher Himalaya Crystalline Slab. Spencer (1995) has carried out an interesting structural analysis of the Shontargali Thrust (MCT of Tahirkheli, 1987, 1988, 1989, 1992, 1996). According to Spencer (1995), the south-eastward dipping Main Central Thrust would, have to turn and strike from southeast to northwest to solve the accommodation of the uplift of the Nanga Parbat. Notwithstanding the problems of putting the eclogite facies rocks of the Upper Kaghan Valley into this tectonic scenario (part of the 'Lesser Himalayan', according to Tahirkheli), the strike of Shontargali Thrust would have to change from northeast-southwest to northwest-southeast. This would effectively make the thrust three sides of a domal structure which indeed would question its evolution as one of the Himalayan tectonic scars. Thus, we do not concur with Tahirkheli's (1996) Map: 'Tectonostratigraphic domains of northern collisional belts in Pakistan' and associated introduction which notes that "the recent discovery of a deep level thrust of megashear level.....has resolved the issue of the presence of the MCT in the northern collisional belt of Pakistan." Such a location quite clearly creates more questions than it does solve problems, especially when this thrust is joined into the Raikot Fault on the western side of the Nanga Parbat Syntaxis.

**Raikot Fault is the Main Central Thrust**

Madin et al. (1989) have suggested that the western edge of the Nanga Parbat Syntaxis (the 'Raikot Fault' of Lawrence and Ghauri (1984), 'Liachar Thrust' of Butler and Prior (1988)) as the terminal tear fault of the MCT (Thrust 9 in Figure 2). They argue that the MCT which is dipping to the northwest in the Central Himalayas eventually becomes a south-north strike-slip fault where the Main Central Thrust encounters the western edge of the Indian Plate Slab. This subsequently causes east-west compression against the Kohistan Arc to the west. Madin et al. (1989) argue that the crustal thickening was achieved by a ramp structure in the Indian basement. This implies that the Higher Himalaya terminates at Nanga Parbat and, therefore, the MCT must underlie the Nanga Parbat Syntaxis. Moreover, Madin et al. (1989) point out that no Indian Plate basement rocks are known to the west of the Nanga Parbat Syntaxis, implying that this location now approximately marks the edge of the pre-collisional Indian craton.

There are considerable problems with the interpretations of Madin et al. (1989). Considering the Raikot Fault as a terminal ramp of MCT cannot be accepted. In the first instance, the movement direction of the Higher Himalayan slab, according to the stretching lineations, is approximately north to south; the ramp on the western margin of Nanga Parbat Syntaxis, terminating the Higher Himalaya, indicates east-west compression. Madin et al. (1989) argued that the east - west compressive movements along the Raikot Fault are those of the Main Central Thrust. This would imply that the initial movement direction of the Main Central Thrust was north to south and that now it displaces similar rocks of the same age by east to west movements. They therefore suggest that it is the same structure producing both sets of movements in opposite directions at the same time, yet producing different structures associated with it. Clearly, there is some timing problems associated with this scenario.

Second, the suggestion that the Higher Himalaya terminates at Nanga Parbat does not stand the testimony of geology on the ground (Spencer, 1995). In Upper Kaghan, Chaudhry and Ghazanfar (1987), Hubbard and Spencer (1990), Pognante and Spencer (1991), Spencer et al. (1990, 1991), Greco and Spencer (1993), Tonarini et al. (1993) and Spencer (1993) have concluded that the amphibolite to eclogite facies rocks are those of the Higher Himalaya Crystalline, last known in the Zanskar region. In fact the Higher Himalaya does not terminate at Nanga Parbat but very much extends into the Swat region and further west towards the Ahwaz block in Afghanistan. Moreover, recent work by Treloar et al. (1989c) and Baig (1991) in the Besham area has established that the granites of 1800 Ma event located in the Besham Syntaxis do now correlate to the Indian Plate basement.

Third, crustal ramping as described by Madin et al. (1989) (Thrust 9a in Figure 2) shows that the ramp must have initiated at least at depths of 30 to 35 km to 'uplift' the amphibolite facies rocks of the Nanga Parbat Syntaxis (Spencer, 1995). Ramp-flat geometry (or thin-skinned tectonics) is suggested to be only appropriate for the external frontal portions of mountain belts (see Ramsay, 1988, for discussion). Making crustal ramps to such depths would not only be mechanically unwise but is incompatible with structural observations. The Nanga Parbat domal structures are not the kink-like structures that would be related to ramp-flat geometry. Moreover, these highly deformed rocks have strain values completely outside those predicted for the formation of folds related to ramping when conditions of ductile deformation are prevalent. Finally, Madin et al. (1989) themselves point out that they have not mapped a connection between the Raikot Fault and any of the known MCT positions from Kashmir and India. So, placing the MCT at the western margin of Nanga Parbat under no circumstances conforms with any of the known mapped geology.

**Locations of the MCT Proposed by Chaudhry et al. (1994)**

The Luat Fault in Neelum Valley and the Batal Fault in Kaghan, which was extended to Dheri (Thrust 10 and 11 in Figure 2) was proposed as the location of the MCT by Ghazanfar and Chaudhry (1986) and Chaudhry and Ghazanfar (1990). Subsequently, the MCT was mapped and extended by Chaudhry et al. (1994a, 1994b) from west of the river Indus through Pacha, Swat, Malakand and Bajaur close to Afghan border. Thus, this MCT (with the Higher Himalayan Crystalline block to the north and the Lesser Himalayas to the south) was mapped from Neelum Valley in Kashmir across almost the entire Northwest Himalaya of Pakistan (Thrust marked as 'MCT' in Figure 2).

In Neelum and Kaghan Valleys, the MCT was demarcated between Batal in Kaghan and Luat in Neelum

Valley. Between Luat and Batal, the fault strikes in a general SE-NW direction. Some distance west of Batal, the Higher Himalayan block starts wedging out and the MCT curves and runs almost east-west, attenuating the Higher Himalaya until in the Biari and Banna areas the Tethyan sedimentary cover directly overlies the Lesser Himalaya. Here, the Lesser Himalayan Mansehra Granite is, we believe, in direct contact with the Tethyan sediments upto the Thakot strike-strip fault. West of the Thakot Fault, the Higher Himalayan block (with the MCT at its base) reappears (Thrust 12 in Figure 2). From here onwards, the MCT runs south of Pacha and through Malakand further west towards the Ahwaz block in Afghanistan.

## CHARACTER OF THE MCT IN THE NORTHWEST HIMALAYA OF PAKISTAN

The MCT in the northwest Himalaya (Fig. 3) is generally a 0.5 to 1.5 km thick ductile shear zone which dips approximately north at 30-55°. It shows the development of a strong schistosity undergoing simple shear deformation. At the margins of the fault, the schistosity is oblique but is being rotated into the shear zone. Wherever the ductile shear zone has developed in the turbiditic sediments (Greco et al., 1989; Spencer, 1993), the bedding (and the graded bedding) is replaced by a strong

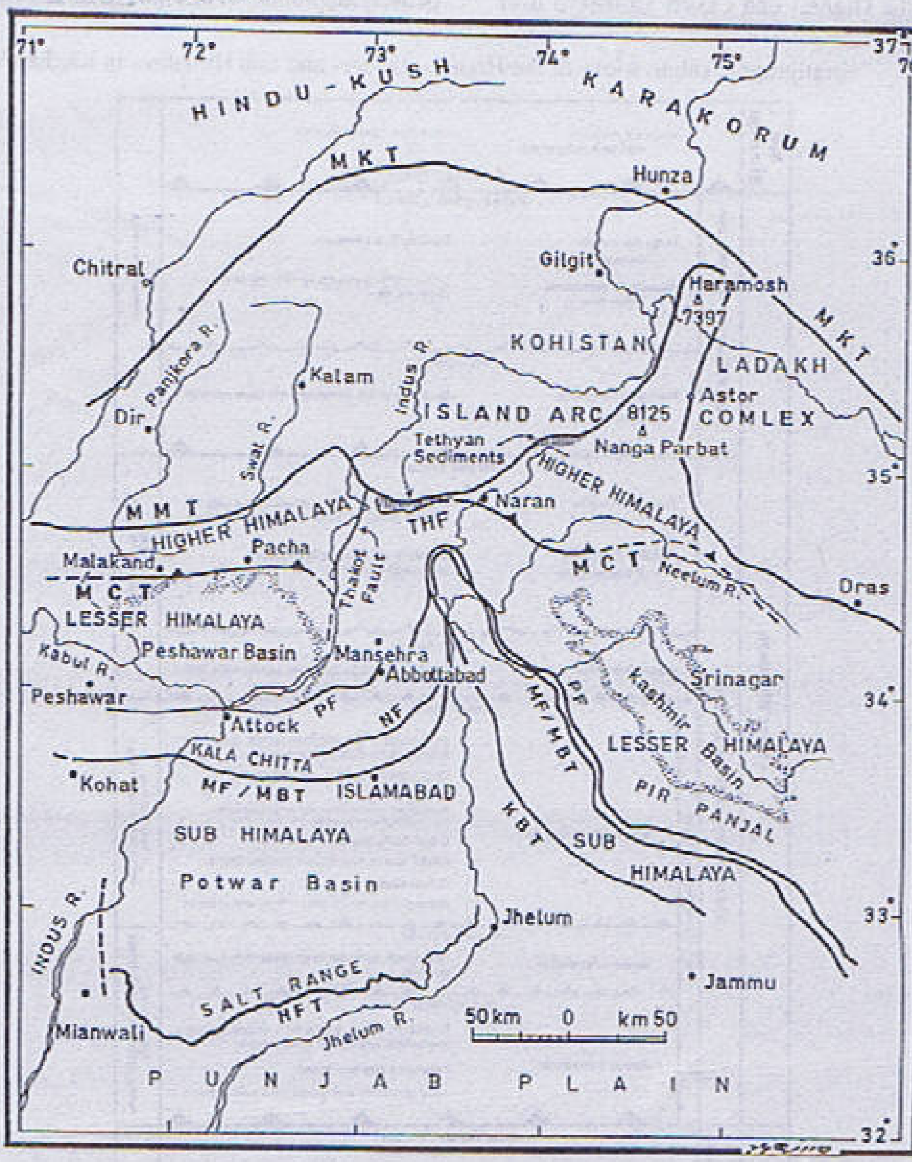



Fig. 3. Simplified location of the Main Central Thrust and the interpreted tectonic framework of the northwest Himalaya according to Chaudhry and coworkers. The position of this MCT in the Neelum/Kaghan Valleys and Lower Swat are suggested here to be the only locations that completely fulfils the stratigraphic, structural, metamorphic and tectonic requirements that allow this fault to be clearly demarcated as the MCT. There are still refinements of its positions to be made in some of the intervening areas.
**HFT** - Himalayan Frontal Thrust; **KBT** - Kashmir Boundary Thrust; **MCT** - Main Central Thrust; **MF/MBT** - Murree Fault/Main Boundary Thrust; **MMT** - Main Mantle Thrust; **MKT** - Main Karakoram Thrust; **NF** - Nathia Gali Fault; **PF** - Panjal Fault; **THF** - Trans Himadri Fault.

mylonitic fabric. As such, the original bedding and the major foliation have both been rotated into parallelism with the shear zone deformation. The thicker arenaceous beds, by contrast, are more folded and boudinaged. The mineral stretching lineation is strong and indicates a sense of shear perpendicular to the strike of the the shear zone. All kinematic indicators (shear sense criteria such as C-S fabrics, en-echelon tension gashes and slickensides) suggest a general 'top-to-the-south' sense of shear.

## Stratigraphy of the Higher- and Lesser Himalaya

There is a remarkable similarity and continuity of stratigraphy of both the Higher- and Lesser Himalaya over the entire Northwest Himalaya of Pakistan and adjoining Kashmir. The Higher Himalaya is composed of a lower 'Basement' and an upper 'Cover' (Greco et al., 1989; Spencer, 1993; Greco and Spencer, 1993; Chaudhry et al., 1994a). The lower Basement (known as Purbinar Group east of Thakot Fault and the Pacha Group to the west) is composed predominantly of granitoids, migmatites, pelites and psammites. Minor carbonates, calc-pelites and amphibolites are present. The upper Cover (Burawai Group in Upper Kaghan east of Thakot Fault and the Alpurai Group to the west in Lower Swat) is composed predominantly of marbles and calc-pelites with subordinate pelites, amphibolites and psammites. (Tables 1 and 2). The

**Table 1.** Stratigraphic subdivisions of the Higher-, Lesser- and Sub Himalaya in Kaghan Valley.

| Domain | Zone / Group | Formation | Lithology | Metamorphic grade |
|---|---|---|---|---|
| Sub Himalaya | | Murree Formation (Mid Eocene-Miocene) | Sandstone, Shale sequence | |
| | | *Main Boundary Thrust* | | |
| Lesser Himalaya | Lesser Himalayan Sedimentary Zone | Paras Formation (Paleocene/Eocene) | Foraminiferal limestone | Unmetamorphosed |
| | | Rosachcha Formation (Paleocene) | Calc-arenite, quartzite, lateritic/pisolitic claystone etc. | |
| | | *Unconformity* | | |
| | | Malkandi limestone (Trias/Jurassic) | Dark grey oolitic limestone with shale partings | |
| | | *Panjal Thrust* | | |
| | Lesser Himalayan Metamorphic Zone | Panjal Formation (Permian) | Panjal basic volcanics and associated Ling, Bhunja and shiroo bands of limestone/marble | Lower Greenschist Facies Chlorite Grade |
| | | Chushal Formation (Carboniferous) | Graphitic schist, limestone/marble, metaconglomerate | |
| | | *Unconformity* | | |
| | | Jared Formation | Agglomeratic slate, quartzite, quartz mica Schist | |
| | | *Jared Thrust* | | |
| | Kaghan Group (Late Proterozoic) | Mahandri Formation | Shari quartzites, metaconglomerate, quartz mica schists, calc-schist and pegmatites. | Middle Greenschist Facies Biotite Grade |
| | | | Doga schists, marbles, quartzites and metaconglomerates | |
| | | | Kamalban quartz mica schists, quartzites calc-schists and marble | |
| | | | Lohar Banda Marble | |
| | | | Phagal quartz mica schists and quartzites. | |
| | | | Kandla marble | |
| | | | Khannian quartzites, calc-schists and marbles | |
| | | *Khannian Thrust* | | |
| | | Julgran Formation | Pelites with subordinate graphitic schist, marble, gypsum | Middle-Upper Greenschist Facies Garnet Grade |
| | | *Rajwal Thrust* | | |
| | | Rajwal Formation | Rajwal quartzites, quartz mica schists/gneisses, pegmatites, aplites and granite gneiss | |
| | | | Paludaran graphitic schist | |
| | | | Basal quartzites and quartz mica schist/gneiss | |
| | | *Main Central Thrust* | | |
| Higher Himalaya | Burawai Group (Upper Proterozoic or U. Paleozoic/L. Mesozoic) | Higher Himalayan Cover | Garnetiferous calc-pelites, marbles, dolomites and pelites | Upper Amphibolite to Eclogite Facies Kyanite-Sillimanite Grade |
| | | | Amphibolites (eclogites) with intercalated marbles | |
| | | *Tectonised Unconformity* | | |
| | Purbi Nar Group (Proterozoic or L. Paleozoic) | Higher Himalayan Basement | Turbidites, migmatites with minor marble and pelite-psammite horizons | |
| | | | Granitoids | |

**Table 2.** Stratigraphic subdivisions of the Higher- and Lesser Himalaya, west of the Thakot Fault (Lower Swat Valley).

| | | | | |
|---|---|---|---|---|
| Lesser Himalaya | Lesser Himalayan Metamorphic Zone | **Bampokha Group** (Upper Paleozoic-Lower Mesozoic) | Predominantly marbles with minor graphitic schists and calc-pelites | Lower Greenschist Facies Chlorite-Biotite Grade |
| | | **Dargai Formation** (Eo-Cambrian or Paleozoic-Mesozoic) | Graphitic schist, phyllite, calc-pelites, marbles and rare metabasites | |
| | | *Main Central Thrust* | | |
| Higher Himalaya | Alpurai Group (Upper Proterozoic or U. Paleozoic/L. Mesozoic) | **Higher Himalayan Cover** | Thick sequence of calc-pelites and marbles<br>Thin pelite-psammites with amphibolites and intercalated marbles | Upper Amphibolite Facies Kyanite-Sillimanite Grade |
| | | *Tectonised Unconformity* | | |
| | Pacha Group (Proterozoic or L. Paleozoic) | **Higher Himalayan Basement** | Granitoids, pelite-psammites, migmatites with turbidites and associated minor marble horizons | |

whole block has undergone metamorphism in upper amphibolite facies, with minor relics of eclogite facies within this predominant metamorphic grade (Pognante and Spencer, 1991). Suitable lithologies have undergone minor anatexis and regional migmatites have developed in the Purbi Nar and Pacha Groups. This has also resulted in the generation and emplacement of the Himalayan-aged leucogranites (Smith et al., 1994).

The Lesser Himalaya, south of the MCT and east of the Thakot Fault, consists of a northern metamorphic and a southern sedimentary zone. According to Ghazanfar et al. (1992), the metamorphic zone is composed of a lower Kaghan Group and an upper Kashmir sequence (Table 1). The Kaghan Group (Upper Proterozoic) which probably underlies the Hazara Group (Hazara Slate and the Tanawal Formation) is composed predominantly of pelites, psammites, calc-pelites with minor marbles, graphitic schists and a band of gypsum. Some horizons may contain pegmatites, aplites and small bodies of Mansehra-type granite (Table 1). This group has undergone metamorphism in greenschist facies. The Kashmir sequence (Table 1) is composed of a lower metamorphic and an upper sedimentary zone. The metamorphic zone is of quartzite and quartz-mica schist at the base (Jared Formation) followed upwards by a graphitic schist (Agglomeratic Slate or Chushal Formation) and Panjal metabasites of Carboniferous-Triassic age. All these have undergone metamorphism in the lower greenschist facies (chlorite/biotite grades). The upper part of this sequence consists of a sedimentary zone that includes the lower Malkandi Limestone (Triassic/Jurassic) and an upper Palaeogene Limestone (Paras Formation), with an unconformity in between. This is represented by a partly residual formation known as the Rosachcha Formation (Table 1).

The Lesser Himalaya, south of MCT and west of the Thakot Fault in Swat and Malakand, is composed of the Dargai Formation and the Bampokha Group. The Dargai Formation is a graphitic, pelitic-psammitic flyschoid unit with rare calcareous beds (Table 2). It has often been correlated with the Hazara or Attock Slates of Upper Proterozoic age. The overlying rocks of Bampokha Group (Table 1), in the immediate vicinity of MCT, are composed predominantly of marbles with subordinate calc-pelites and graphitic schist. However, a fuller Palaeozoic sequence has developed in the Peshawar basin further south. The Dargai Formation, as well as the Bampokha Group, has undergone metamorphism in the lower greenschist facies. The age of the Dargai Formation is considered Upper Proterozoic whereas the age of the Bampokha Group is not known but may be anywhere from Palaeozoic to Mesozoic.

## Structure of the Higher- and Lesser Himalaya

There is a marked contrast in the structural style and in the nature of deformation across the Main Central Thrust. To the north of the MCT in the Higher Himalayan slab, the structure is characterised by the development of kilometric scale elongated domes and basins (Figure 4 and Figure 5).

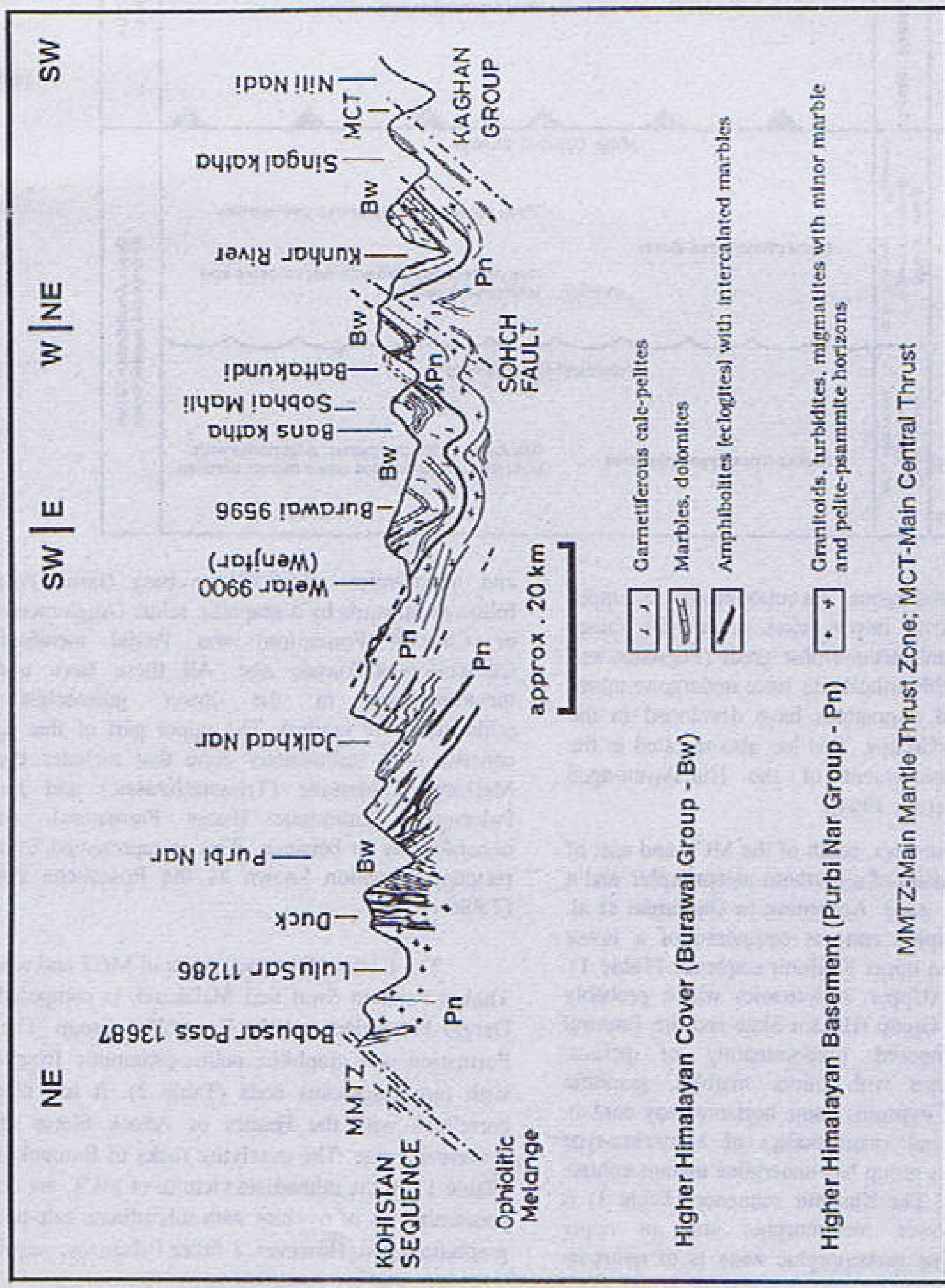
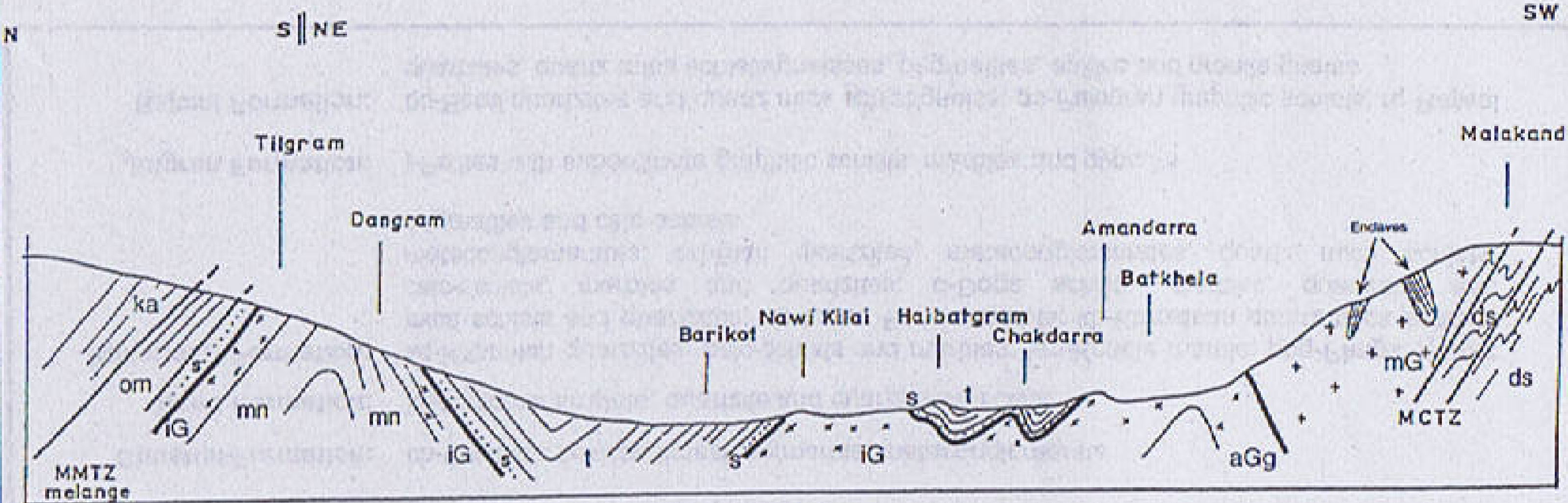



**Fig. 4.** Generalised geological section through Upper Kaghan showing the structural style of deformation consisting of large scale basins and domes. Section drawn by M. Nawaz Chaudhry and Munir Ghazanfar.




Kohistan Sequence: ka-Kamilla amphibolites

Indus Suture: om-Ophiolitic melange

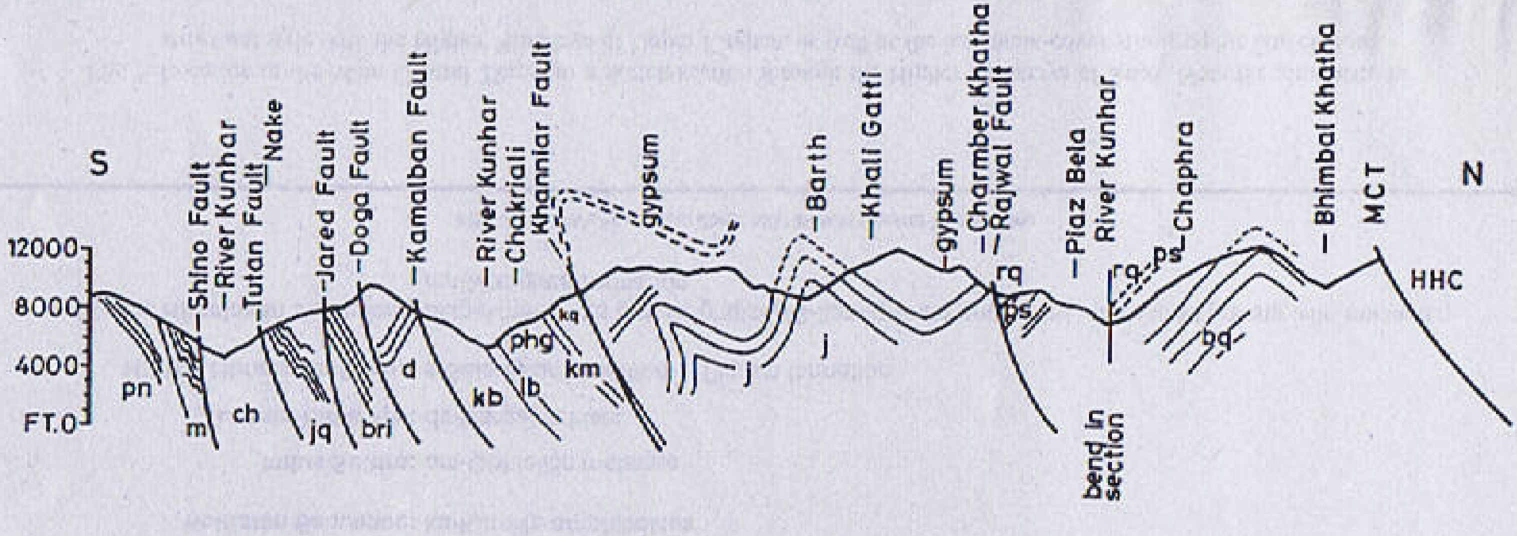
Lesser Himalaya: ds-Dargai schists

Higher Himalayan Cover: s-Salampur formation; t-Tilgram formation

Higher Himalayan Basement: aGg-Amandarra granite gneiss; iG-Ilam granite gneiss; mG-Malakand granite with enclaves; mn-Manglaur formation

MMTZ-Main Mantle Thrust Zone; MCTZ-Main Central Thrust Zone

**Fig. 5.** Location of the Main Central Thrust in a sketch section through the Higher Himalaya of Swat. Note the similarity in structural style with the Higher Himalaya of Upper Kaghan, as well as the basement-cover stratigraphic correlations.




**Panjal Formation:** pn-Panjal basic volcanics; m-marbles

**Chushal Formation:** ch-Graphitic schists, limestone/marble, metaconglomerate

**Jared Formation:** jq-Agglomeritic slate, quartzite and quartz mica schist

**Mahandari Formation:** kq-Khannian quartzites, calc-schists and marbles; km-Kandla marble; phg-Phagal quartz mica schists and quartzites; lb-Lohar Banda marble; kb-Kamalban quartz mica schists, calc-schists, marbles and quartzites; d-Doga schists, marbles, quartzites and metaconglomerates; bri-Biari quartzites, metaconglomerates, quartz mica schists, pegmatites and calc-schists

**Julgran Formation:** j-Pelites with subordinate graphitic schists, marbles and gypsum

**Rajwal Formation:** bq-Batal quartzites and quartz mica schist/gneiss; ps-Paludran graphitic schists; rq-Rajwal quartzites, quartz mica schists/gneisses, pegmatites, aplites and granite gneiss

**Fig. 6.** Generalised north-south geological section through the Lesser Himalaya of Middle Kaghan showing the imbricate schuppen structures. Section drawn by M. Nawaz Chaudhry and Munir Ghazanfar.

These structures trend in a general north-south direction. More specifically, in Kaghan the fold axial trace is NE-SW; in Besham the dome trends north-south and in Swat they trend NNW-SSE. This divergence in the orientation of fold axial trace may indicate minor bending and rotation of the Higher Himalayan slab as a whole in response to the NNW-SSE transport direction west of Nanga Parbat Syntaxis. In the Higher Himalaya, the nature of deformation can be broadly described as ductile, with localised brittle overprinting. Greco et al. (1989) and Spencer et al. (1991), for example, interpreted the ubiquitous NE-SW trend of stretching lineation (in the Upper Kaghan nappe) as the initial southwest thrusting direction. The rotation of first phase schistosity and the second phase crenulation cleavage into sub-parallelism with the shortening direction resulted from this ductile deformation.

South of the MCT in the Lesser Himalaya, the structural style is very different from that to the north of MCT. The folds in the Attock Hazara Fold and Thrust Belt of the Lesser Himalaya trend ENE-WNW with abundant faults. The faults are marked by breccias and gouges. The belt may be called an imbricate schuppen zone (Figure 6). In the Peshawar Basin, the folds generally trend east-west and faulting is common with numerous development of breccias and gouges. It is therefore apparent that the folding style, trends and nature of deformation in the Higher Himalaya and the Lesser Himalaya are very different - ductile to the north of MCT and brittle to the south. This, combined with the clear discordance in fold axial traces across the MCT, indicated that this fault is separating two distinct structural domains that have undergone different deformational histories.

**Metamorphism in the Higher and Lesser Himalaya**

Mapping has clearly revealed that in numerous sections perpendicular to the MCT, there is a sudden upward jump from greenschist facies to upper amphibolite facies (from Lesser Himalaya to Higher Himalaya). For example, the rocks of the Higher Himalaya are metamorphosed to the upper amphibolite facies and kyanite-sillimanite grades just north of Batal in the Naran area of Kaghan. The basement rocks of Besal dome (Spencer et al., 1990, 1993; Pognante and Spencer, 1991) are known to have even undergone eclogite facies metamorphism. The eclogites formed from a tholeiitic protolith at T=650°±50°C and P=15-17 Kbars. The depth of burial is therefore calculated to be between 55 to 60 km. Tonarini et al. (1993) and Spencer (1993) clearly prove an Eocene (49±6 Ma) peak metamorphic age for these high pressure lithologies. Furthermore, Spencer and Gebauer (1996) now provide SHRIMP U-Pb evidence for a Permian protolith age for the eclogites. These amphibolite (and locally eclogitic) lava sheets and feeder dykes are invariably garnetiferous; plagioclase is generally a labradorite in the amphibolite facies. Extensive migmitisation in the Purbinar Group in Kaghan (Chaudhry and Ghazanfar, 1987) and in Pacha Group of Lower Swat (Chaudhry et al. 1994a, 1994b) indicates a sillimanite grade. In summary, the presence of kyanite and sillimanite, partial anatexis and high grade amphibolites show that the Higher Himalaya, in this example of Upper Kaghan, has been metamorphosed in upper amphibolite (-eclogite) facies.

These pressure-temperature conditions are not uncommon. Treloar et al. (1989a, 1989b) calculated temperatures of 600° to 650°C with pressures of 7 to 11 Kbars in the Alpurai Schists (the cover to the migmatised basement) in Lower Swat, an area which we regard as Higher Himalaya. Dipietro (1991) and Dipietro and Lawrence (1991) give the final equilibrium conditions of the main phase metamorphism for Manglaur and Salampur sequences of the basement and high grade cover successively at 600-700°C at 9-11 Kbars. The depth of burial is therefore calculated between 35 to 45 km beneath the MMT for the Higher Himalaya in Lower Swat. These metamorphic conditions for the Higher Himalaya clearly prove that these rocks belong to the upper amphibolite facies. As a result of anatexis due to high grade metamorphism, Himalayan-age granites cut the country rocks throughout the Higher Himalaya. The 40Ar/39Ar hornblende ages and U/Pb ages of leucocratic dykes cross cutting metamorphic fabric yield a minimum age constraint of 40-50 Ma for the Upper Kaghan and Besham areas (Zeitler and Chamberlain 1991; Treloar et al. 1989c) and 38 Ma for Lower Swat (Zeitler and Chamberlain 1991).

South of the MCT demarcated by Ghazanfar and Chaudhry (1986) and Chaudhry and Ghazanfar (1990), the rocks in both Neelum and Kaghan valleys were metamorphosed upto greenschist facies. However, we note that below the MCT the development of tiny grains of garnet in metapelites in the Lesser Himalayan Kaghan Group do occur. We attribute this to the 'hot iron effect' (Le Fort, 1976), caused by the effect of the thrusting of the 'hot' Higher Himalaya over the 'colder' Lesser Himalaya. The original grade of metamorphism probably did not anywhere exceed biotite or lower greenschist facies as the peristerite gap is not bridged within pelites. Further evidence is provided by the fact that the metabasic rocks, and the rocks underlying the MCT, are still in greenschist facies. In Lower Swat (around Malakand), the Lesser Himalayan Dargai schist (Chaudhry et al., 1976) is still in the chlorite and biotite grades (lower greenschist facies) of regional metamorphism (Chaudhry et al., 1994a, 1994b).

## CONCLUSIONS

The Main Central Thrust is an intracontinental dislocation that demarcates the boundary between the Lesser and the Higher Himalaya, resulting in a considerable thickening of the continental crust. It is a north dipping low- to high-angle shear zone associated with a pervasive mylonitisation. a strong stretching lineation and numerous sense of shear criteria. It is also marked by an inverse metamorphism which separates a clear jump in metamorphic grade from greenschist (in the footwall) to upper amphibolite facies (in the hanging wall). This is accompanied by a clear difference in stratigraphy and tectonic style on either side of the shear zone. It has been argued in this paper that the position of the MCT that was delineated by Ghazanfar and Chaudhry (1986), Chaudhry and Ghazanfar (1990) and Chaudhry et al. (1994a), in the Kaghan Valley (east of Nanga Parbat) and in the Lower Swat area further to the west, are as yet the only locations that completely fulfil the stratigraphic, structural, metamorphic and tectonic requirements that allow this fault to be clearly demarcated as the MCT. These positions of this fault is shown as thrust 12 in Figure 2 (and Figure 3). There are still refinements of its positions to be made in some intervening areas, although it is worth noting here that even in the classic locations of the MCT in the Nepal Himalaya. marked changes in tectonic style along strike of the fault are not uncommon.

We have also discussed in detail the various positions of the MCT proposed by various workers in the Pakistan Himalaya. Our aim was to point out that in defining the 'MCT', it is not considered adequate to use only one tectonic criterion (e.g.. change in stratigraphy, or metamorphic grade, in the footwall compared to the hanging wall) to indicate that this fault has the character of the MCT. Reasons for this were numerous [for example, the 'MCT' of Tahirkheli (1987, 1988, 1989, 1992, 1996) which put the eclogite facies rocks of Upper Kaghan in the 'Lesser Himalaya' is one clear example where all the criteria necessary for the MCT definition were not followed]. In Pakistan, to date, only the Batal Fault near Naran (Ghazanfar and Chaudhry, 1986; Greco, 1989; Chaudhry and Ghazanfar, 1990) in Kaghan Valley and the tectonic lineament near Pacha and Malakand in Lower Swat (Chaudhry et al., 1994a), are the only fault locations that have clear evidence giving the definition of a MCT. No other fault locations fulfils all the required criteria specified above. Similarly, in India, the Vaikrita Thrust is the only Thrust that fulfils the requirements of a boundary fault in the region where two other possibilities exist. The Vaikrita Thrust and its equivalent in Pakistan (Figure 3), are therefore recognisable as the faults fulfilling the criteria as the Main Central Thrust in the Northwest Himalaya of Pakistan and western Kashmir.

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# THE HIGHER HIMALAYA IN PAKISTAN – A TECTONO-STRATIGRAPHIC SYNOPSIS

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**Abstract**.- *Following the demarcation of the Main Central Thrust (MCT), the mapping and tectonostratigraphic characterisation of the Higher Himalaya across northern Pakistan and Azad Kashmir has been made for the first time. This slab has a variable width. It is widest in the area of the Nanga Parbat Syntaxis and is attenuated in the region of the Hazara-Kashmir Syntaxis. This paper presents an integrated account of the stratigraphy; deformation and metamorphism of this major tectonic division and hinterland area of the Northwest Himalaya. The Higher Himalaya is comprised of a lower basement and an upper cover unit. The basement is constituted predominantly of granitoids, migmatites, pelite schists and micaceous quartzites with minor calc-pelite gneisses, marbles and discordant amphibolites. The cover consists predominantly of calc-pelite gneisses, with subordinate marbles and pelite schists and extensive amphibolites at its base. The Higher Himalaya is characterised by the development of kilometric scale elongated structural basins and domes with a fold interference pattern (types 1 & 3) that trend either northeast-southwest (Kaghan), north-south (Besham) and north northwest-south southeast (Swat). These fold trends are truncated at a high angle to the south across the Main Central Thrust in the Lesser Himalaya and to the north by the Tethyan/Indus Suture Zone rocks. The nature of deformation in the Higher Himalaya is ductile. The rocks of the Higher Himalaya have been metamorphosed to upper amphibolite facies or kyanite-silliminite grade. However around Besal in Upper Kaghan and at places in Upper Neelum valley the rocks have suffered eclogite facies metamorphism. The Pressure-temperature estimates by various workers give generally upper amphibolite facies metamorphism which range from 600° to 700° C at 7-11 Kbars. However, the basement and cover lithologies of the Besal area in Upper Kaghan valley have undergone eclogite facies metamorphism at T=650±50° C and P=15-17 Kbars, corresponding to depths of 55 to 65 kilometers. To the south of the Higher Himalaya across the Main Central Thrust, the Lesser Himalayan rocks take a marked downward jump in metamorphic grade to greenschist facies. Similar observations also were found to the north in the Tethyan lithologies which overlie the HHC slab or occur as fault slivers close to the suture.*

## INTRODUCTION

Systematic geological mapping of Neelum and Kaghan Valleys (Ghazanfar et al., 1983; Ghazanfar and Chaudhry, 1985, 1986; Chaudhry and Ghazanfar, 1987; Bossart et al., 1988; Greco, 1989; Papritz, 1989; Rey, 1989; Greco et al., 1989; Greco and Spencer, 1993; Spencer, 1993; Fontan and Schouppe, 1994; Schouppe et.al., 1994; Schouppe, 1995), as well as in Besham, Lower Swat, Malakand and Bajaur (Chaudhry et al., 1994a, 1994b) has incorporated into their work the delineation of Main Central Thrust and, thus, the tectonostratigraphic differentiation between the Higher and the Lesser Himalaya of Pakistan and Azad Kashmir (Fig. 1 and Fig. 2). These workers, combined with other notable mapping contributions by Kazmi et al. (1984), Coward et al. (1988), Madin et al. (1989), Williams (1989), Treloar et al. (1989a, 1989b), DiPietro (1991) and DiPietro and Lawrence (1991), to name but a few, have over the last decade debated the existence or the extension of the tectonic subdivisions from the better known Central Himalaya into the western Himalaya.

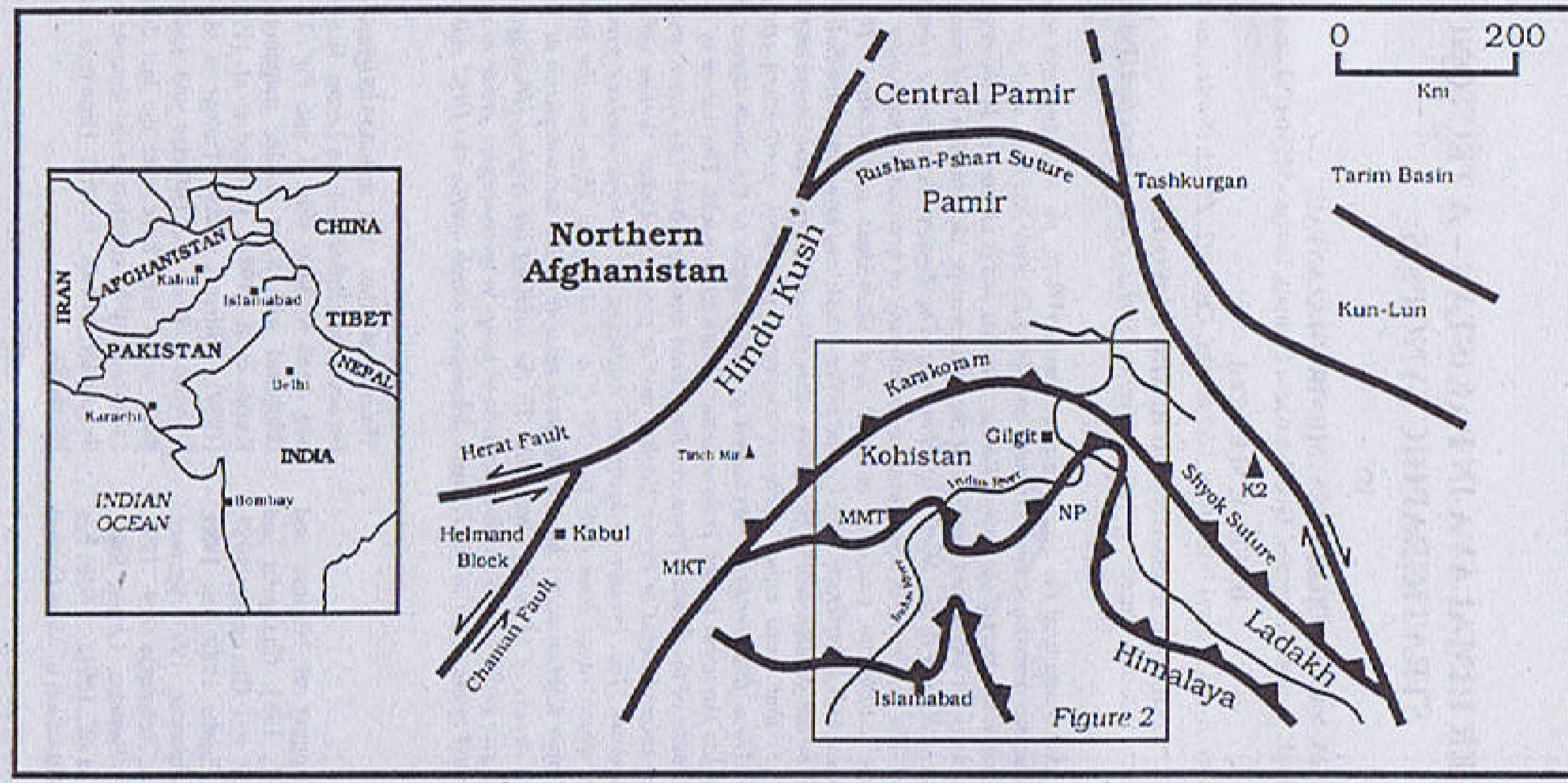



**Fig. 1.** Tectonic sketch map of Northern Pakistan and the surrounding regions (redrawn from Zanchi, 1993). **MMT** – Main Mantle Thrust; **MKT** – Main Karakoram Thrust; **NP** – Nanga Parbat.

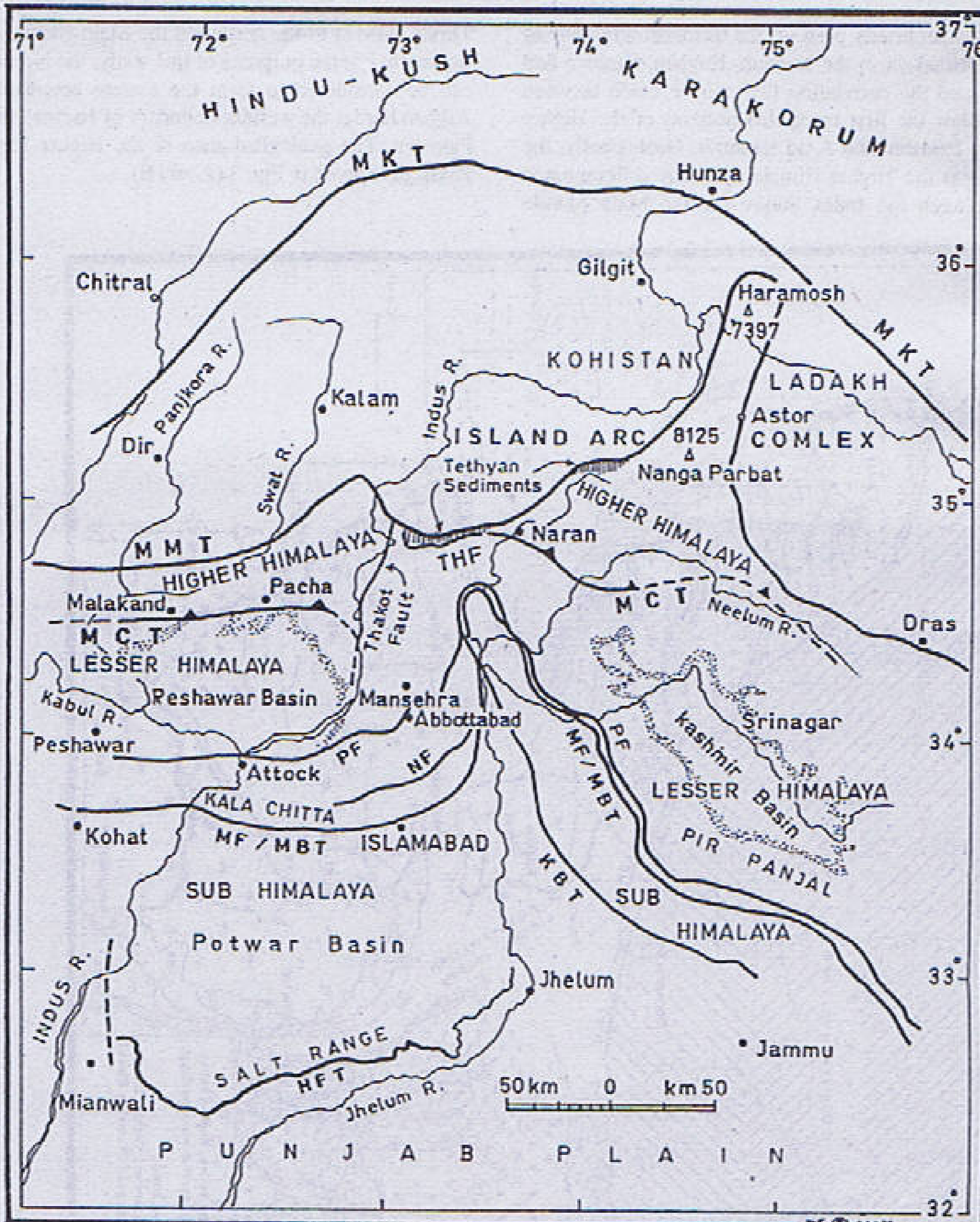



**Fig. 2.** Simplified location of the Main Central Thrust and the interpreted tectonic framework of the northwest Himalaya according to Chaudhry and coworkers. The position of this MCT in the Neelum/Kaghan Valleys and Lower Swat are suggested here to be the only locations that completely fulfils the stratigraphic, structural, metamorphic and tectonic requirements that allow this fault to be clearly demarcated as the MCT. There are still refinements of its positions to be made in some of the intervening areas.

**HFT** – Himalayan Frontal Thrust; **KBT** – Kashmir Boundary Thrust; **MCT** – Main Central Thrust; **MF/MBT** – Muree Fault/Main Boundary Thrust; **MMT** – Main Mantle Thrust; **MKT** – Main Karakoram Thrust; **NF** –Nathia Gali Fault; **PF** – Panjal Fault; **THF** – Trans Himadri Fault.

This paper briefly presents the tectonostratigraphy of the Higher Himalaya in the Neelum, Kaghan, Besham and Swat areas and the correlation that can be made between them. It is thus the first integrated account of the Higher Himalaya in Pakistan and Azad Kashmir. Geologically, the area defined as the 'Higher Himalaya' is here differentiated as lying between the Indus Suture (or the Main Mantle Thrust, MMT) to the north and the Main Central Thrust to the south. For the purposes of this study, the Neelum Valley can be considered to form the eastern boundary and the Afghan border the western boundary of Higher Himalaya in Pakistan. The geological map of the Higher Himalaya of Pakistan is given in Fig. 3 (A and B).

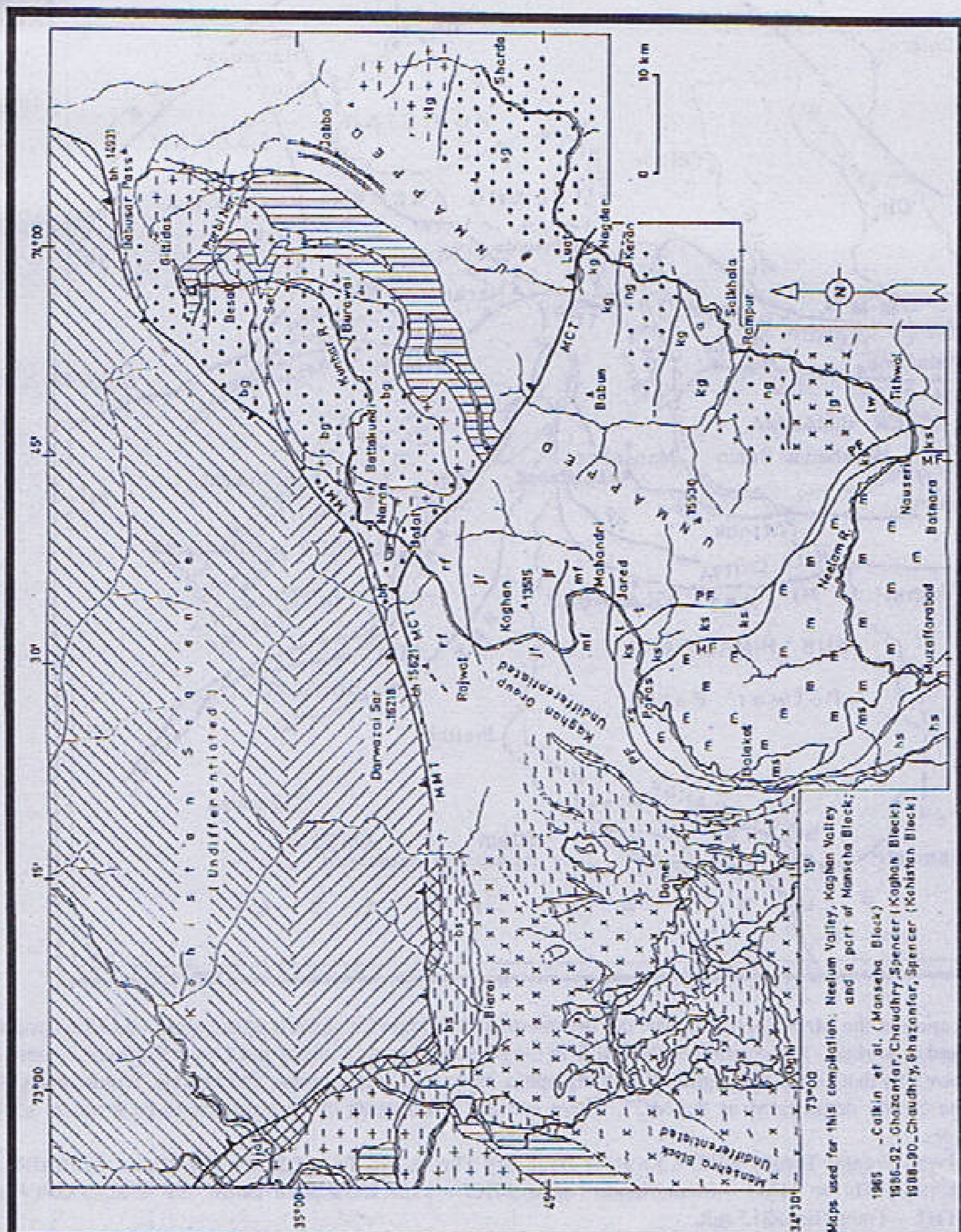
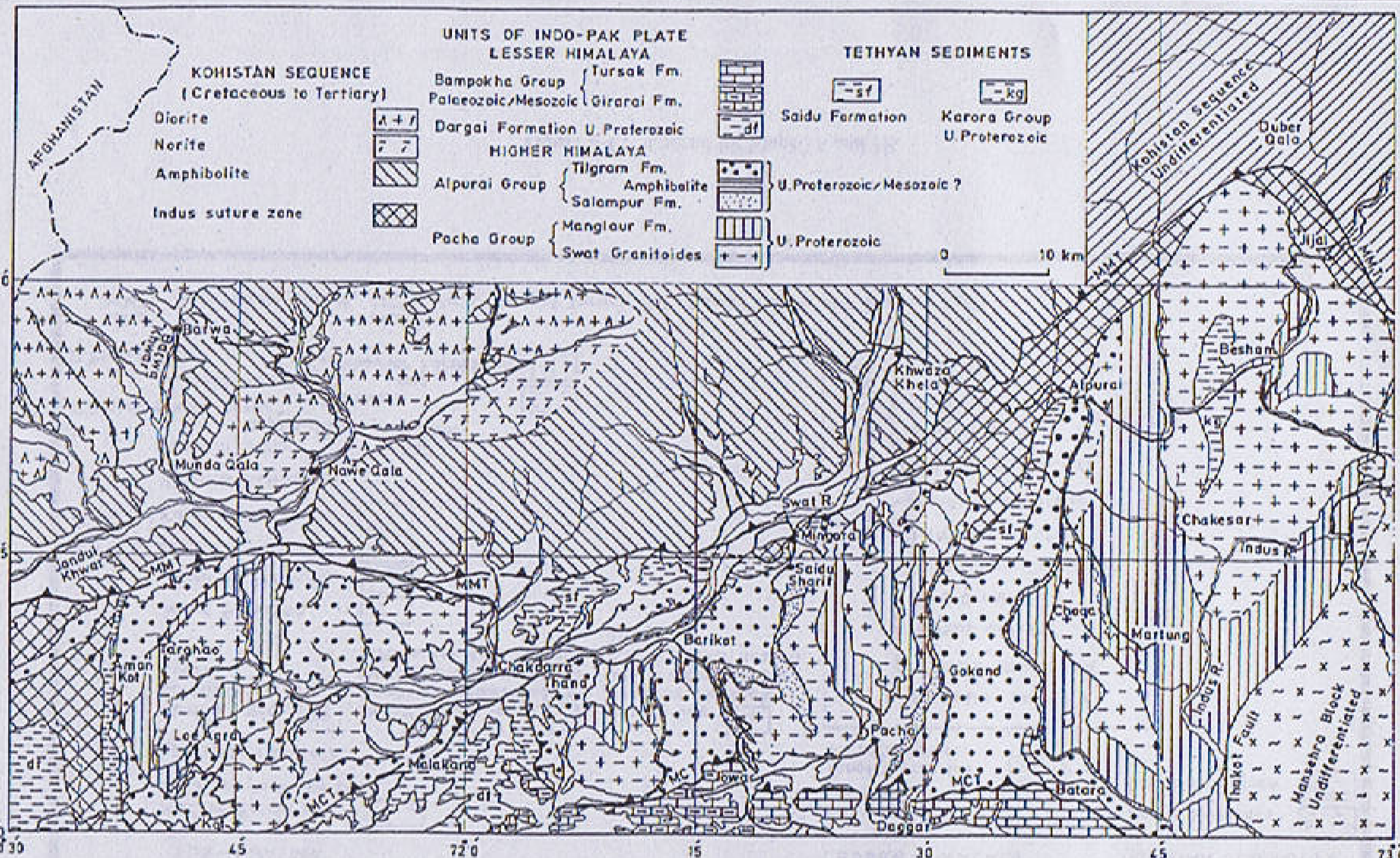



**Fig. 3A.** Geological maps of the Higher Himalaya of Pakistan.

Geological map of a part of Besham, Mansehra Block, Kaghan and Neelum Valleys.




Maps used for this compilation; Lower Swat and Malakand; 1974 - Chaudhry, Hussain, Iqbal (38 N/14)., 1975-78 - Ashraf, Chaudhry, Hussain (38 N/10)., 1979 - Chaudhry, Hussain, Ashraf (43 B/13) 1980-86 - Hussain, Dawood, Tahseen (43 B/5 & B/9, 38 N/10 & N/11)., 1990-95 - Hussain, Chaudhry, Dawood (43 B/6, B/10, B/2, B/5, B/14 & B/15)
Dir; 1970-75 - Chaudhry, Asif, Iftikhar, Kaphle, Ghafoor, Kausar, Shafiq, Aftab, Shahid Iqbal, Safdar, Zafar, Qaiser, Sabih.
1976-78 - Chaudhry, Hussain, Ashraf (Revised, corrected and partially remapped)

Figure 3B. Geological map of a part of the Malakand Block, Dir, Swat and Besham.

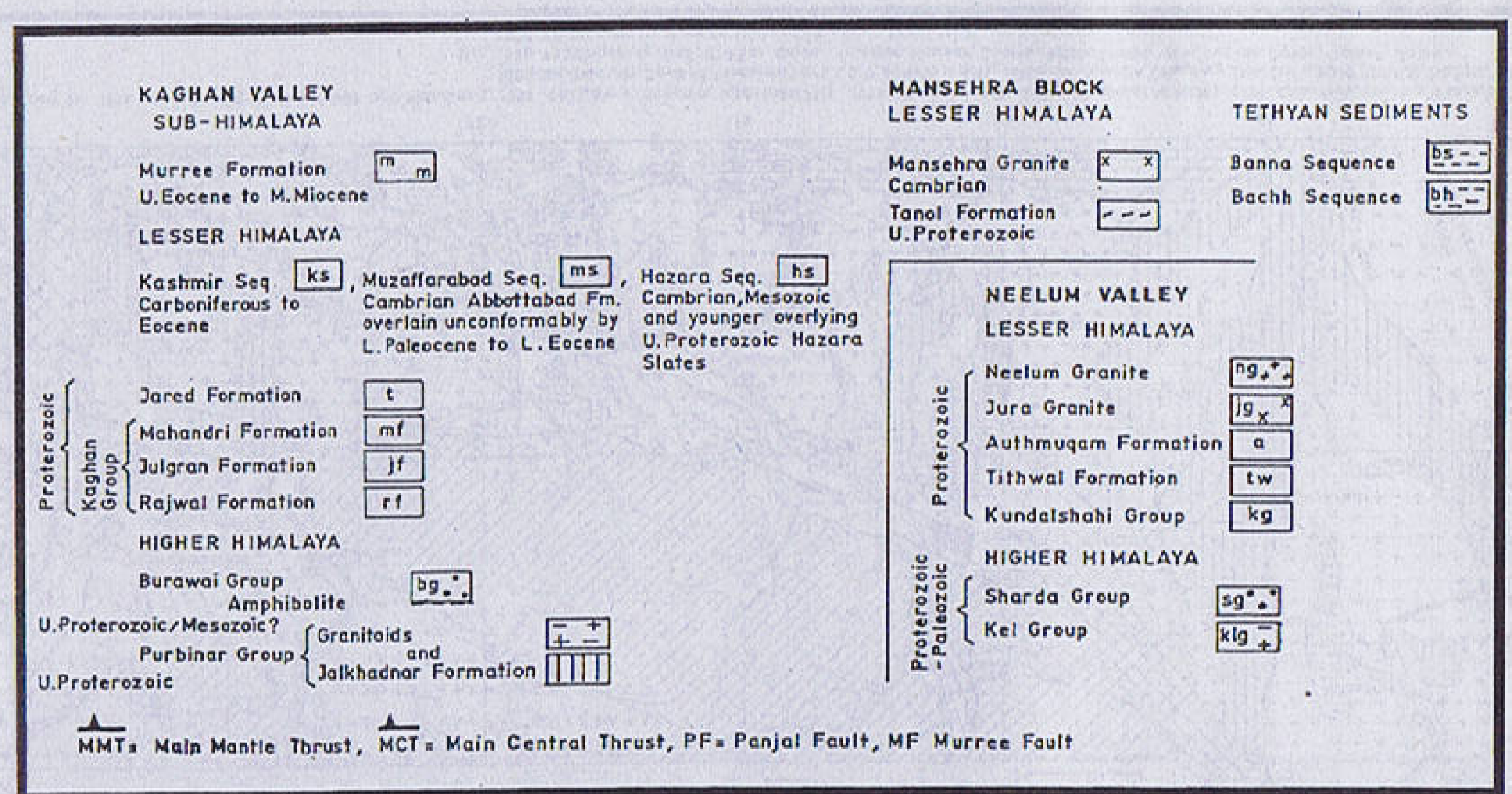



**Figure 3-C.** Legend for Maps 3A and 3B.

## GEOLOGY AND STRATIGRAPHY

### Neelum valley

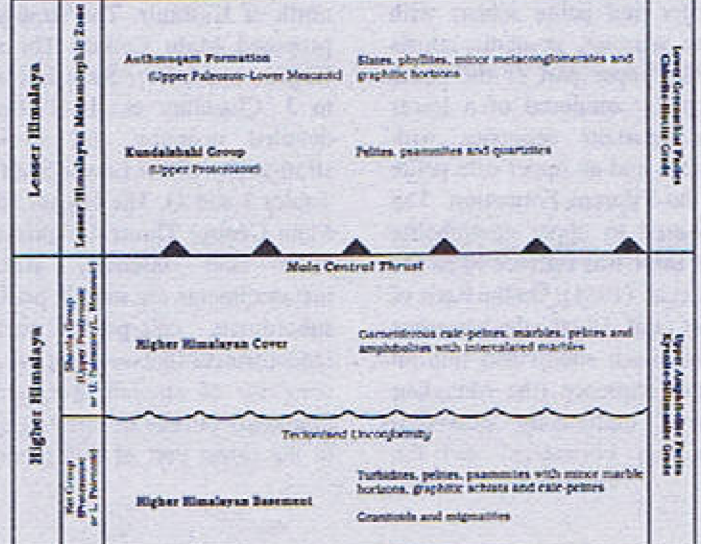
The Neelum Valley of Azad Kashmir is the easternmost part of the Northwest Himalaya that is accessible to the geologists working in Pakistan (Fig. 3A). This valley provides a nearly 200 Km long northeast-southwest section through the western margin of Kashmir. During a preliminary survey, Wadia (1931, 1934) placed the metamorphic rocks of middle and upper Neelum Valley in an all embracing unit called the Salkhala Series. Ghazanfar et al. (1983) carried out a reconnaissance mapping of the nearly 80 Km long stretch of this valley between Tithwal and Kel (the last locality being nearly 170 Km up the valley, north of Muzaffarabad, the capital of Azad Kashmir). More recently geological mapping (1:50000 scale) has been undertaken all over the north western flank of Neelum Valley (Gourirane, 1993; Schouppe et.al., 1994; Schouppe, 1995).

Ghazanfar et al. (1983) and Chaudhry and Ghazanfar (1990) defined two major groups of rocks in the Lesser Himalaya of Neelum Valley: the Kundalshahi-Nagdar garnet mica-schist and the Authmuqam biotite and chlorite phyllites and schists. The Kundalshahi-Nagdar garnet mica-schists and quartzites are now being formalised as the Kundalshahi Group since it can be subdivided into formations on a lithological basis. The Authmuqam biotite and chlorite phyllites and schists are now being formalised as the Authmuqam Formation.

The Kundalshahi Group is equivalent of Tanawal Formation of Hazara area and Authmugam Formation is equivalent of Dogra Slates/Hazara Slates. In the Higher Himalaya, the Sharda Group (Ghazanfar et al., 1983) lies to the north of the Main Central Thrust at Luat (Fig. 3A). The name Sharda Group is now being restricted to the upper calc-pelite gneiss and marble sequence with amphibolite sheets. This unit lies unconformably on a basement unit composed of granitoids, migmatites, pelite schists and quartzites which was formerly regarded as a part of the Sharda Group (Ghazanfar et al., 1983). The basement rocks are now being formalised as the Kel Group after the town of Kel in Upper Neelum Valley. Fontan and Schouppe (1994) and Schouppe et.al., (1994) have also confirmed the division between the Higher Himalaya to the north and Lesser Himalayan metasedimentary formations to the south of the Main Central Thrust near Luat. The Kundalshahi Group and Authmuqam Formation consist mainly of pelite schists and quartzites metamorphosed to greenschist facies and corresponding to the Tanawal and Hazara/Dogra slate formations of the Lesser Himalaya.

The Kel and Sharda Group of rocks as defined here represents the Higher Himalaya in the Neelum Valley. It comprises calc-pelitic gneisses, pelitic gneisses, graphitic gneisses, marbles and amphibolites underlain, with a regional unconformity by S-type sheet granites, migmatites, pelite schist-micaceous quartzites as well as some quartzites and amphibolites. The whole sequence is intruded by tourmaline-garnet granites of Himalayan age. The metamorphism reaches upto almandine amphibolite facies with a significant pressure-temperature break across the Main Central Thrust in the south (Chaudhry and Ghazanfar, 1990; Fontan and Schouppe, 1994). A relevant summary of the stratigraphy in Neelum Valley is presented in Table 1.

**Table 1.** Stratigraphic subdivisions of the Higher Himalaya and part of the Lesser Himalaya in Neelum Valley.



## Kaghan Valley

East of the Besham Syntaxis in Kaghan valley the Higher Himalaya is composed of a lower basement and an upper cover (Greco et al., 1989) (Fig. 3A). The lower part is known as the Purbi Nar Group in Ghazanfar (1993). It is composed predominantly of granitoids, migmatites, micaceous quartzites and pelite schist, marbles, calc-pelite gneisses, graphitic schists and quartzites with minor amphibolites. The upper part of the sequence, now considered cover to the basement, is the Burawai Group (Chaudhry et al., 1994a, 1994b). It is composed of amphibolite sheets intercalated with marbles grading upwards to a sequence of calc-pelite gneisses and marbles which are in turn overlain by a pelite schists and micaceous quartzites sequence. There is a regional unconformity between the basement and the cover which extends throughout the Higher Himalaya of Pakistan and Azad Kashmir from the Neelum Valley in the east to Afghan border in the west. This unconformity has been considered Permian by Greco, (1989), Greco et al., (1989), Spencer et al., (1990, 1991) and Spencer, (1993) but older by Chaudhry et al., (1994a, 1994b). The lithostratigraphic detail of the cover and basement are given in Table 2. South of the Higher Himalaya in Kaghan valley across the Main Central Thrust near Batal (Ghazanfar and Chaudhry, 1986; Greco, 1989; Greco et al., 1989; Spencer, 1993, 1995), the Lesser Himalayan rocks take a downward jump in metamorphism and fall in greenschist facies. The stratigraphic sequence in Kaghan valley is given as Table 2.

## Lower Swat Area

The Higher Himalaya in Lower Swat, west of the Besham syntaxis, is comprised of a basement overlain unconformably by a cover sequence (DiPietro and Lawrence, 1991). The basement is known as the Pacha Group (Chaudhry et al., 1994a, 1994b) and is composed of granitoids, migmatites, quartzites and pelite schists with subordinate calc-pelite gneisses, marbles, graphitic schists and amphibolites (Fig. 3B). The upper part or the cover unit, called the Alpurai Group, is composed of a lower pelite schist and micaceous quartzite sequence with amphibolites (Slampur Formation) and an upper calc pelite gneiss-marble unit known as the Tilgram Formation. The whole sequence is metamorphosed to upper amphibolite facies. The basement in Lower Swat was reffered to as the Manglaur Formation by Kazmi et.al. (1984). On the basis of more recent mapping (Chaudhry et.al. 1994b) the basement in Lower Swat & Malakand has been subdivided into an overlying pelitic-schist quartzite sequence (the Manglaur Formation) and an underlying dominantly quartzite-migmatitic sequence (the Kolangi Formation) and the lowermost granitoid (the Targhao Granite). The Swat Granite cuts through and generally overlies the basement as sheets. The entire basement sequences have been together termed here as the Pacha Group (Table 3).

The pelitic schists south of the Malakand Pass fall in the lower greenschist facies (chlorite-biotite grade). North of the Malakand Pass, there is a sudden jump in metamorphic grade to upper amphibolite facies (kyanite/sillimanite grades) in a terrane comprising granite gneiss, pelite schist and micaceous quartzite (turbidites) and a thick sequence of calc-pelite schists. Between the lower greenschist facies (chlorite/biotite grades) and the upper amphibolite facies (kyanite/sillimanite grades) the almandine and staurolite grades (notwithstanding suitable composition) are missing. Further north of the high grade assemblage, a melange is found which is the site of the Main Mantle Thrust or the Indus Suture.

Apart from the jump in metamorphic grade, there is also a sudden change in the stratigraphy and the tectonic style on two sides of a line that, from the Malakand Pass, extends eastward to Jawar and Pacha (Fig. 3B). Yeats and Lawrence (1984) also noted this when they wrote "In the Buner area south of Lower Swat these Mesograde metamorphic rocks come into abrup contact with Devonian marine sedimentary rocks (Martin et.al., 1962; Stauffer, 1968). The nature of this contact is unclear: it may be a thrust or a steep to overturned fold flank. However, the Devonian rocks are not metamorphosed to any significant degree and are only gently folded on east-west axes." This tectonostratigraphic discontinuity which is also marked by mylonitisation in the low grade pelite schists to the south of Malakand Pass is proposed herein as one of the main boundary faults of the Himalayas, the Main Central Thrust. It may be pointed out here that the ultramafic bodies of Dargai, which occur south of the MCT, represent a klippe of the suture zone like the Spongtang klippe of Ladakh area north of Kashmir. The stratigraphy on both sides of this proposed Main Central Thrust in the areas of Neelum, Kaghan and Lower Swat has been summarised in Tables 1 to 3. Chaudhry et al. (1994a, 1994b) have carried out detailed mapping and worked out a comprehensive stratigraphy of the Lower Swat and Besham areas (Fig. 3B, Tables 3 and 4). The Higher Himalayan region north of the Main Central Thrust comprises granitoids, migmatites and older and intensely metamorphosed rocks. The metasediments are mainly pelite schists and quartzites with subordinate calc-pelite gneisses and marbles. The igneous/meta-igneous rocks which intrude this unit comprise of amphibolites, granites and pegmatites. The granitoids intrude to form an extensive migmatite complex in the lower part of this predominantly pelite schists and

**Table 2.** Stratigraphic subdivisions of the Higher-, Lesser- and sub Himalaya in Kaghan Valley.

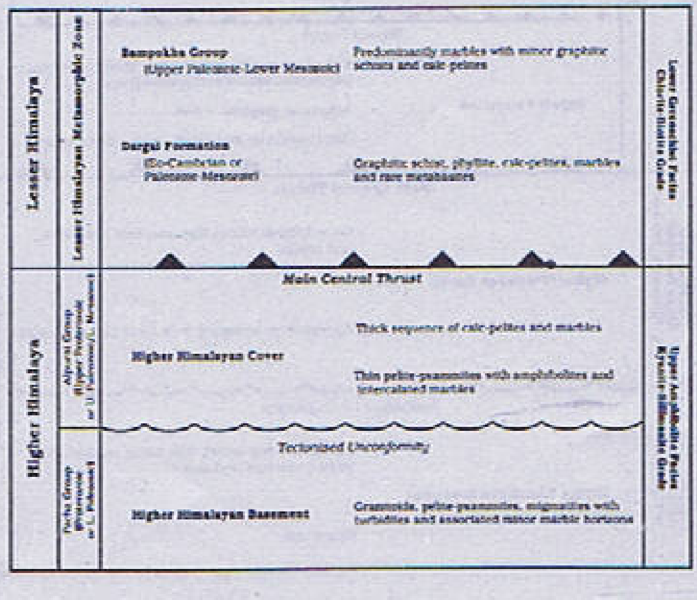
| Domain | Zone / Group | Formation | Lithology | Metamorphic grade |
|---|---|---|---|---|
| **Sub Himalaya** | | **Murree Formation** (Mid Eocene-Miocene) | Sandstone, Shale sequence | Unmetamorphosed |
| | | ***Main Boundary Thrust*** | | |
| **Lesser Himalaya** | **Lesser Himalayan Sedimentary Zone** | **Paras Formation** (Paleocene/Eocene) | Foraminiferal limestone | Unmetamorphosed |
| | | **Rosachcha Formation** (Paleocene) | Calc-arenite, quartzite, laterite/pisolitic claystone etc. | |
| | | *Unconformity* | | |
| | | **Malkandi limestone** (Trias/Jurassic) | Dark grey oolitic limestone with shale partings | |
| | | ***Panjal Thrust*** | | |
| | **Lesser Himalayan Metamorphic Zone** | **Panjal Formation** (Permian) | Panjal basic volcanics and associated Ling, Bhunja and shino bands of limestone/marble | Lower Greenschist Facies Chlorite Grade |
| | | **Chushal Formation** (Carboniferous) | Graphitic schist, limestone/marble, metaconglomerate | |
| | | *Unconformity* | | |
| | | **Jared Formation** | Quartzite, quartz mica schist | |
| | | *Jared Thrust* | | |
| | Kaghan Group (Late-Proterozoic) | **Mahandri Formation** | Dart quartzites, metaconglomerate, quartz mica schists, calc-schist and pegmatites. | Middle Greenschist Facies Biotite Grade |
| | | | Doga schists, marbles, quartzites and metaconglomerates | |
| | | | Kamalban quartz mica schists, quartzites calc-schists and marble | |
| | | | Lohar Banda Marble | |
| | | | Phagal quartz mica schists and quartzites. | |
| | | | Kandla marble | |
| | | | Khannian quartzites, calc-schists and marbles | |
| | | *Khannian Thrust* | | |
| | | **Julgran Formation** | Pelites with subordinate graphitic schist, marble, gypsum | Middle-Upper Greenschist Facies Garnet Grade |
| | | *Rajwal Thrust* | | |
| | | **Rajwal Formation** | Rajwal quartzites, quartz mica schists/gneisses, pegmatites, aplites and granite gneiss | |
| | | | Paludaran graphitic schist | |
| | | | Batal quartzites and quartz mica schist/gneiss | |
| | | ***Main Central Thrust*** | | |
| **Higher Himalaya** | Burawai Group (Upper Proterozoic or U. Paleozoic/L. Mesozoic) | **Higher Himalayan Cover** | Garnetiferous calc-pelites, marbles, dolomites and pelites | Upper Amphibolite to Eclogite Facies Kyanite-Sillimanite Grade |
| | | | Amphibolites (eclogites) with intercalated marbles | |
| | | *Tectonised Unconformity* | | |
| | Purbi Nar Group (Proterozoic or L. Paleozoic) | **Higher Himalayan Basement** | Turbidites, migmatites with minor marble and pelite-psammite horizons | |
| | | | Granitoids | |

quartzite unit. The basement Pacha Group is overlain by a high grade cover sequence, the Alpurai Group with an older siliceous part (Salampur Formation) and a younger calcareous part (Tilgram Formation). The Salampur Formation is a relatively thin sequence of pelite-schist and micaceous quartzite (turbidites) with interbedded amphibolites, while the Tilgram Formation is a much thicker sequence of calc-pelite gneisses and marbles. The Salampur Formation rests with an unconformity generally over Swat granite gneiss, but at places directly over the Pacha Group. Wherever the Swat granite gneiss underlies the Salampur Formation, the contact is tectonised and mylonitised. It should be noted that the basement Pacha Group of Lower Swat is distinctly different from the Tanawal Formation of Mansehra area, a correlation suggested by Kazmi et.al. (1984). As against the above mentioned description of Pacha Group the rocks of Tanawal Formation are pelite-schists - micaceous quartzites (turbidites) quartzites and the granites are Lesser Himalayan porphyritic type. Further more the Pacha Group rocks with their extensive migmatite terranes represent a distinctly lower part of the crust compared to rocks of Tanawal Formation east of Thakot Fault.

This stratigraphic order of superposition is based on structural and stratigraphic mapping that was carried out by Martin et al. (1962), Kazmi et al. (1984), DiPietro (1991), DiPietro and Lawrence (1991) and Chaudhry et al. (1994a, 1994b). The basement-cover in the Higher Himalaya are separated on the basis of a well recognised regional unconformity (Kazmi et al., 1984; Greco, 1989; Greco et al., 1989; Spencer et al., 1990, 1991; Spencer, 1993; Chaudhry et al., 1994a, 1994b). The basement is an igneous-metamorphic complex and represents middle to perhaps even lower crustal levels. The principal rock types include granitoids, migmatites, pelitic schists-psammitic gneisses and amphibolites. The cover sequence above the basement is less complexly deformed and is not migmatised. It is also much different lithologically and mainly comprises calc-pelitic gneisses and marbles with subordinate pelite schist and micaceous quartzites. At the base there is a persistent amphibolite horizon. The basement and cover groups have again been subdivided into formations on the basis of well recognised marker horizons like regionally persistent amphibolites (Martin et al., 1962), or on the basis of distinct and persistent and marked change in lithology like for instance from silici-clastic meta-turbidites of Slampur Formation to calc-pelite gneisses and associated platform carbonates (now marbles).

To the south of the Higher Himalaya, across the Main Central Thrust lies, with a pressure-temperature break (Chaudhry et.al., 1994a, 1994b) a sequence of low grade graphitic schists, phyllites and marbles. They are all metamorphosed in the lower greenschist facies. To the north of the Higher Himalaya lie the rocks of Indus Suture zone with a faulted contact (Tahirkheli et al., 1979). The stratigraphic sequence of lower Swat is given in Table 3. The Lesser Himalaya is characterized by exclusion of an older high grade basement and related highly metamorphosed cover rocks. These units have been briefly described in Table 3 and are discussed below.

**Table 3.** Stratigraphic subdivisions of the Higher- and Lesser Himalaya, west of the Thakot Fault (Lower Swat Valley).



### Besham and Northern Hazara

The stratigraphy of Besham area has been discussed by Ashraf et al. (1980, 1994), Butt (1983), Chaudhry et al. (1983, 1994a, 1994b), Fletcher et al. (1986), Baig and Lawrence (1987) and Treloar et al. (1989a, 1989b) (Fig. 3B). Baig (1990) considered the Besham block as a separate entity demarcated on the east by the Thakot Fault and to the west by the Puran-Chakesar Fault (Ashraf et al., 1980). According to Ashraf et al. (1980), Treloar et al. (1989a, 1989b, 1989c) and Treloar and Rex (1990), the Precambrian Besham quartzo-feldspathic gneisses are overlain by a cover sequence which now occurs as faulted and folded inliers.

The Besham dome is one of the many domal structures that characterize the Higher Himalaya of Lower Swat and Kaghan. Its stratigraphy, structure and metamorphism are a continuity of the stratigraphy, structure and metamorphism of Lower Swat. Although some previous workers (Ashraf et.al., 1980 and Baig, 1990) noted a fault west of Besham but this is of minor significance and does not effect the essential continuity of stratigraphy, structure and metamorphism. The high grade Proterozoic Besham Group of Baig et al. (1989) consists of dominant micaceous and feldspathic quartzites and pelite schists, subordinate calc-pelite gneisses, marble with interlayered amphibolites, granites and pegmatites. These in turn are overlain with an unconformity (Kazmi et al., 1984) by the high grade Alpurai Group and a low grade second cover. The latter is seen unconformably overlying the quartzo-feldspathic gneisses with a boulder bed at its base at Sassoi between Karora and Besham (Ashraf et al., 1980; Treloar et al., 1989b).

In the area of Northern Hazara, on the other hand, the stratigraphic sequence of the Higher Himalaya (as already described for Kaghan, Besham and Lower Swat) is missing. The predominant quartzites, micaceous quartzites and pelite schists of the Tanawal Formation, which are intruded by the Cambrian Mansehra cordierite granite (Le Fort et al., 1980) belongs to the domain of the Lesser Himalaya. The Main Central Thrust in this area appears to merge into the Trans Himadri Fault (THF) underlying the low grade Banna sequence to the north. After attenuation in Northern Hazara, the Higher Himalaya again expands eastwards in upper Kaghan and has the Main Central Thrust at its base. In the Banna -Biari area the MCT comes close to MMT and the disappearance of the HHC Block in this area might indicate a late stage movement on the MMT. Westwards, the stratigraphy of Northern Hazara is abruptly truncated by the Thakot Fault (Ashraf et al., 1980) along the Indus River. Across the Thakot Fault, further west, the Higher Himalaya abruptly starts again and continues throughout the extent of Lower Swat, through Malakand Agency towards the Afghanistan border (Fig. 1 and Fig. 2). Southwards the Tanawal Formation grades into the Precambrian Hazara Slates which form the basement for the Phanerozoic sedimentary sequence of the southern Hazara in the Lesser Himalaya.

### Upper Hunza Valley

Prior to Permo-Carboniferous rifting and opening of Neo-Tethys (Gaetani & Garzanti, 1991), the Karakoram Plate is considered (Chaudhry et al., 1997 in review) to have been a part of the northern margin of the juvenile Indian plate. This view is further strengthened by the discovery of a crystalline basement underlying the early Ordovician sedimentary cover in the northern Karakoram sedimentary zone of Le Fort et al. (1994). According to Le Fort et al. (1994) *"The presence of Pre-Ordovician granitic intrusions and transgressive Ordovician sedimentary successions seem to characterise a large area of the Indian part of the Gondwana super continent"*. To the south of this sedimentary zone and the Karakoram axial batholith lie the high grade pre-rifting metamorphic rocks which can be tentatively correlated with similar rocks on the Indian plate margin in Kaghan and Swat (Table 4) (Chaudhry et al., 1997 in review). Since stratigraphic nomenclature used above is different for different areas, a stratigraphic correlation is given for comparison (Table 4).

## METAMORPHISM IN THE HIGHER HIMALAYA

The following points may be noted about the metamorphism in the Higher Himalaya of Pakistan and Azad Kashmir.

There is a sudden upward jump from greenschist facies to upper amphibolite facies as we move from Lesser Himalaya across the Main Central Thrust into the Higher Himalaya. Likewise there is a sudden downward jump from upper amphibolite facies to greenschist facies as we move from Higher Himalaya, across the THF northwards into the rocks which are suggested to be of Tethyan affinity (Chaudhry and Ghazanfar, 1993; Ghazanfar et al., 1996; in review). Here we are referring to low grade slivers along Indus Suture and patches as at Biari and west of Besham (Fig. 3)and not to the underlying high grade cover which has also been considered Tethyan by many (Greco et.al., 1989, Spencer 1993).

The rocks of both the predominantly psammite and pelite migmatised basement (Pacha, Purbinar, Kel and Baltit Groups) and of the predominantly calcareous cover (Alpurai and Burawai Groups) are metamorphosed to the upper amphibolite facies. Kyanite is ubiquitous in the appropriate lithologies of this Cover whereas the basement and cover rocks near Besal, Upper Kaghan (Spencer et al., 1990; Pognante and Spencer, 1991) are known to have locally undergone eclogite facies metamorphism during the

**Table 4.** Stratigraphic correlation between the Higher Himalaya (Lower Swat & Besham, Kaghan & Azad Kashmir) and the Higher Karakoram (Hunza Valley).

| | Higher Himalaya (Indian Plate) | | | Higher Karakoram | |
|---|---|---|---|---|---|
| | Lower Swat & Besham | Kaghan Valley | Neelum Valley | Hunza Valley | |
| **Cover** (Upper Proterozoic or U. Paleozoic/L. Mesozoic) | *Alpurai Group*<br>Calc-pelite, marbles with minor pelite<br>Pelite psammite; Turbidites with amphibolite sheets | *Burawai Group*<br>Pelites<br>Thick sequence of calc-pelite and marble with amphibolites<br>Pelite psammite; Turbidites with amphibolite sheets | *Sharda Group*<br>Calc-pelite, marbles, amphibolites<br>Turbidites | *Baltit Group*<br>Marble, calc-pelite, pelite and amphibolite | **Upper Amphibolite Facies**<br>**(locally eclogite facies in Upper Kaghan and Neelum Valleys)**<br>Kyanite-Sillimanite Grade |
| | *Tectonised Unconformity* | | | | |
| **Basement** (Proterozoic or L. Paleozoic) | *Pacha Group*<br>Pelite-psammites, Turbidites, Migmatites, minor marble, calc-schist and graphitic schists<br>Migmatites<br>Granite gneisses and Migmatites | *Purbinar Group*<br>Pelite-psammites, minor marbles and graphitic schists<br>Migmatites and enclaves<br>Granite gneisses and Migmatites | *Kel Group*<br>Pelite-psammites<br>Migmatites<br>Granite gneisses and Migmatites | *Baltit Group*<br>Pelite-psammites with minor marbles and graphitic schists<br>Granite gneisses and Migmatites with meta-sedimentary enclaves | |

Himalayan orogeny. The Higher Himalaya, therefore, in general falls in the kyanite/sillimanite grades. The amphibolites are invariably garnetiferous; plagioclase is very often a labradorite and extensive migmitisation near Dharir, Dadar Nar, Khote Nar, Jora Nala, Jalkhad Nar and Purbinar in Upper Kaghan (Chaudhry and Ghazanfar, 1987), at Surgan, Naril and Chatthewala in Upper Neelum (Schouppe et.al., 1994) in Besham (Butt, 1983) and in Lower Swat (Ghazanfar, 1993 and Chaudhry et al., 1994a, 1994b) is significant. Presence of kyanite and sillimanite, partial anatexis and high grade amphibolites show that the Higher Himalaya belongs to the upper amphibolite facies.

The eclogite facies metamorphism (Spencer et al., 1990; Pognante and Spencer, 1991; Spencer, 1993) recognized in the Besal area of Kaghan Valley represents some of the deepest derived rocks of the Indian Plate. They formed at T=650±50°C and P=13-18 Kbars corresponding to depths of 55 to 65 Km (Spencer, 1993). These eclogites are derived from the Panjal Volcanics which subsequently suffered burial during the Himalayan orogenesis (Spencer, 1993; Spencer et al., 1995; Spencer and Gebauer, 1996). Tonarini et al. (1993) and Spencer (1993) assigned an Eocene peak metamorphic age (49 ± 6 Ma) to the eclogite facies metamorphism. A Permian protolith age (265± m.a.) was obtained by SHRIMP U-Pb analyses of zircons found in the eclogites (Spencer and Gebauer, 1996).

Eclogite facies has also been identified in Surgun, Naril and Chatthewala areas of Upper Neelum. The most extreme eclogitic conditions were estimated on the basis of the garnet-clinopyroxene Mg-Fe exchange (as << thermometer>>) on the Jadeite content of the omphacite (as << barometer >>). Temperatures reached 600+/-50°C and pressures ranged upto 13-14 Kbar (Schouppe et.al., 1994, Gourirane, 1993). These workers reported a second metamorphic stage under conditions of decompression: T=600°C and P=8 to 10 Kb (evaluated using symplectite intergrowths developed over the eclogite omphacite). A third step was identified: T=450°C-550°C and P=3.5-4.5 Kb (evaluated on the basis of mineral metamorphic assemblages in the pelitic rocks of the cover).

As for metamorphism in the Mansehra it varies from lower greenschist facies near Mansehra to amphibolite facies in the north. Eclogite facies has not been found. On the other hand the HHC slab north of MCT is entirely in the amphibolite facies except for some patches of low grade Tethyan sediments. Even eclogite facies has been reported from Besal area Kaghan and from Upper Neelum Valley. Furthermore pressures for given temperatures are lower in the Mansehra block. Treloar et.al. (1989) report 5 kb for 430°C at garnet isograd and 9 kb for 650-700°C in sillimanite K-feldspar zone in Mansehra area as against 9 to 11 kb for 600-700°C in the staurolite to kyanite-sillimanite grade, in Lower Swat. Dipietro (1991) and Dipietro and Lawrence (1991) give the final equilibrium condition of main phase metamorphism for Manglaur and Marghazar (over Salampur) sequences at 600-700°C at 9-11 kbars, 35 to 45 km beneath the Indus Suture for the Higher Himalaya in Lower Swat. For the same HHC slab north of MCT in Upper Kaghan Spencer et.al. (1990) and Pognante and Spencer, (1991) worked out T=650 ±50°C and P=13-18 Kbars for the eclogite facies in Besal area. Schouppe et.al. (1994) and Gourirane (1993) reported most extreme eclogite conditions in HHC slab of Upper Neelum Valley. They used garnet-clinopyroxene Mg-Fe exchange as "thermometer" and the Jadeite content of the omphacite as "barometer". Temperatures reached 600±50°C and pressures ranged upto 13-14 kb. It should also be noted that except for a small part of the Mansehra area the rest of the Lesser Himalaya rocks south of the MCT are in the greenschist facies or are sedimentaries. Finally the metamorphism in Lower Swat and the metamorphism in Northern Hazara are two distinctly different events. According to Dipietro (1991) peak metamorphism and ductile deformation appear to have ended in Lower Swat by the Late Eocene (38 Ma) when the rocks cooled through the argon blocking temperature for hornblends. As against this the Main metamorphism of Northern Hazara is now known to be Precambrian as has been documented by Baig et.al. (1988) and Chaudhry et.al. (1989). Baig (1990) has dated unmetamorphosed dolerite dykes from Mansehra area at 270 Ma. It should be noted that the basement Pacha Group of Lower Swat is distinctly different from the Tanawal Formation of Mansehra area, a correlation suggested by Kazmi et.al. (1984). As against the above mentioned description of Pacha Group, the rocks of Tanawal Formation are pelite schists, micaceous quartzites (turbidites) and the granites are Lesser Himalayan porphyritic type. Furthermore the Pacha Group rocks with their extensive migmatite terrains represent a distinctly lower part of the crust compared to rocks of Tanawal Formation east of Thakot Fault.

The $^{40}Ar/^{39}Ar$ hornblende ages and the U/Pb ages of leucogranite dykes that cross-cut metamorphic fabric suggest a minimum age constraint of 40 to 50 Ma for the Upper Kaghan (Zeitler and Chamberlain, 1991; Smith et al., 1994) and Besham areas (Treloar et al., 1989c) and 38 Ma for Lower Swat (Zeitler and Chamberlain, 1991).

Based on cooling ages and interpreted peak metamorphic ages of some leucogranites, the trend of modern workers has been to consider the metamorphism of the upper Kaghan, Northern Hazara, Besham and the Lower Swat areas as Himalayan in age (i.e. peak metamorphism at 50 to 38 Ma (Frank et al., 1973; Le Fort, 1975; Bird, 1978;

Bard, 1983; Coward et al., 1988; Treloar et al. 1989c; DiPietro, 1991; Chamberlain et al., 1991; Tonarini et al., 1993; Spencer, 1993). They consider that the Himalayan metamorphic event resulted from the collision between India and Asia at about 60-55 Ma (also see Patriat and Achache, 1984) and the subsequent burial of the Indian Plate edge under its own imbricated slices as well as under Kohistan. Spencer (1994) suggested a relatively earlier collision for the Northwestern Himalaya to account for the Eocene metamorphic age of the eclogites.

Contrary to modern workers, Gansser (1964) had considered the metamorphism in the Higher Himalaya as Precambrian. Chaudhry (1964), based on the evidence of the presence of chips of Hazara slates in the overlying Tanakki conglomerate (regarded as Carboniferous at that time) and representing the base of the Phanerozoic sedimentary sequence in Hazara, proposed a Palaeozoic orogeny. Baig et al. (1988) have documented the Precambrian metamorphism of the Hazara slates. Based on radiometric dating using U-Pb and $^{40}Ar/^{39}Ar$ methods on the rocks of Besham Block (Baig et al., 1988, 1989; Baig, 1990) magmatic events at 2000, 1400, 900, 510-550, 400 Ma and Tertiary have been suggested. These ages are in line with those summarised by Metha (1980) from Higher Himalaya of India. Greco et al. (1989) and Williams (1989) also recognized pre-Himalaya relic schistosities and slatey cleavage in the areas of Middle Kaghan and of Hazara. They considered the main metamorphism of these areas as Himalayan in age. Baig et al. (1988, 1989) showed that unmetamorphosed dolerite dykes, dated radiometrically giving an age of 270 Ma, were present in the metamorphosed belt of Northern Hazara. More than one Pre-Himalayan metamorphic events in the Lesser Himalaya have been confirmed (Baig et al., 1989; Treloar et al., 1989a; Chaudhry et al., 1989). However evidence for pre-Himalayan metamorphism in the Higher Himalaya has also been found (e.g., Greco et al., 1989; Wheeler et al., 1995). Two problems remain however: the intensity of older metamorphism and the degree of Tertiary reheating. Chaudhry et al. (1989), based on field evidence which shows garnet to kyanite isograds of regional metamorphism being abruptly truncated by the thermal metamorphic event associated with the emplacement of Mansehra Granite (516 ± 16 Ma; Le Fort et al., 1980), suggested that not only at least one phase of the polymetamorphism of the Himalayas is Precambrian, but also in intensity reached amphibolite facies. This orogenic event has been called the Hazaran Orogeny by Baig and Lawrence (1987). Baig et al. (1988) correlated it with Pan African and the Karelian orogenies (Chaudhry et al., 1989). At least one Precambrian event (Baig and Lawrence, 1987; Williams et al., 1988; Chaudhry et al., 1989) and one weak Hercynian event (Chaudhry et al., 1989, Papritz and Rey, 1989; Spencer, 1993) are now established in the Northwest Himalaya of Pakistan. Their evidence is restricted to magmatic dating in Higher Himalaya and the geological constraints are better exhibited in the Lesser Himalaya terrane of Northern Hazara to the south of the Higher Himalaya. Tertiary granites in the Higher Himalaya of Pakistan form a minor percentage of the lithologies but the cooling evidence on the basis of $^{40}Ar/^{39}Ar$ and K/Ar data for a Tertiary event at 50 to 38 Ma is preponderant. This indicates that this later event related to collision was largely restricted to the northern belt of the Himalayas (the Phanerozoic sequence of southern Himalaya in Hazara is completely unmetamorphosed). This includes the Higher Himalaya and at least the northernmost fringe of the Lesser Himalaya in Hazara. The Tertiary Himalayan event reached at least medium to high grade metamorphism overprinting most but did not erase the entire evidence of Pre-Himalaya events (Chaudhry et al., 1989; Wheeler et al., 1995).

## DEFORMATION

The structure of Higher Himalaya in Pakistan is characterized by the presence of kilometric scale elongated basins and domes trending in a general north-south direction with westward vergence in Lower Swat. This is superimposed by another set of folds at right angles to the first, giving a fold interference pattern (type 1 and 3, Ramsay, 1967). The domes and basins are aligned northeast-southwest in Upper Kaghan and Neelum Valley and generally north northwest-south southeast in Lower Swat (Fig.3).

Greco (1989), Greco et al. (1989), Spencer et al. (1991), Spencer (1993) and Greco and Spencer (1993) stressed the ductile nature of deformation in the Higher Himalaya of Upper Kaghan. They interpreted the ubiquitous northeast-southwest trend of stretching lineations as the initial southwest thrusting direction. The rotation of first phase schistosity and the second phase crenulation cleavage into sub parallels with the shortening direction resulted from the ductile deformation. The early northwest-southeast folds were superimposed by northeast-southwest folding event due to anticlockwise rotation of the transport direction.

DiPietro (1991) worked out a four phase deformation sequence for Lower Swat. His F1 and F2 folding phases together climaxed in north northwest-south southeast trending west overturned folds, and a weak F3 deformation produced large scale north-south trending open upright folds associated with overall cooling. A final F4 deformation produced large scale east-west trending, open, upright to S-vergent folds during greenschist facies conditions leading to retrogression.

Coward et al. (1988) and Treloar et al. (1989a) worked out a three phase deformational history for basement cover sequence in Northern Hazara and Besham. The first phase was a south directed schistosity forming event D1. D2 crenulating S1 and forming tight northeast-southwest directed structures with curvilinear axes followed by D2a imbrication. Both D1 and D2 structures and D2a imbrication are refolded by upright north-south structures formed during D2 and parasite on the north plunging Besham antiform.

Schouppe (1995) worked out a 5 phase Himalayan deformational history that affected both the Pre-Himalayan basement and the Himalayan cover in the Higher Himalaya of the Neelum Valley.

1. Development of D1 cylindrical isoclinal folds in the southern part of the Higher Himalaya and D1 non cylindrical (sheath-like) folds in the northern part (high-grade area close to the MMT).

2. Development of D2 isoclinal folds superposed over D1 structures.

3. Southward thrusting of the Higher Himalaya over the Lesser Himalaya, Development of the MCT, development of tight folds D3 and crenulation cleavage S3.

4. Development of regional open folds D4 trending NW-SE.

5. Development of large open folds D5 with fold axes trending NE-SW. Fold interference produced domal structure.

Structurally speaking everything in the Higher Himalaya is very different from the structural regimes below the Main Central Thrust. Below the Main Central Thrust the deformation is generally brittle rather than ductile as seen in Middle Kaghan, in the Panjal Imbricate Zone and the Hazara area further south where localised thrusts or imbrication structures are common accommodation features. Above the Main Central Thrust, however, the accommodation of tectonic compression is essentially by folding as expected in a more ductile deformed area (Greco et al., 1989; Spencer, 1993). The north south trending domes and basins combined with a general lack of visible cross-cutting thrusts stands in marked contrast to Kohistan north of the Indus Suture (characterized by an imbricate schuppen structure) and to the areas south of the Main Central Thrust like in Peshawar Basin (characterised by east-west Jura-type folds) and the Attock-Hazara (an east northeast-west northwest trending fold and thrust belt). Finally, DiPietro and Lawrence (1991), Coward et al. (1988) and Treloar et al. (1989a, 1989b, 1989c), amongst others, have all stressed the Himalayan character of the entire deformation except for a passing mention of a pre-Himalayan relic schistosity.

## EXHUMATION AND UNROOFING

The initial collision between India and Kohistan is generally dated at ca. 65-50 Ma. The argon blocking ages in hornblende are generally 40 to 38 Ma which necessitates an extremely quick sequence of burial, metamorphism and exhumation. Evidence seems to indicate that the cooling histories of Kaghan, Neelum and Lower Swat areas of Higher Himalaya are somewhat different in the initial stage (initially rapid for Kaghan and slow for Lower Swat) and likewise the cooling history of Kohistan and Upper Kaghan is also different in the period upto about 20 Ma. In Lower Swat, initial slow cooling took place directly after metamorphism although it was followed by fast cooling during the period 40-25 Ma (hornblende $^{40}Ar/^{39}Ar$ ages ~40 Ma; mica $^{40}Ar/^{39}Ar$ ages ~23-30 Ma; biotite and muscovite $^{40}Ar/^{39}Ar$ ages ~25-20 Ma) about the same or very close (Treloar and Rex, 1990; Chamberlain et al., 1991).

The biotite $^{40}Ar/^{39}Ar$ ages of the Indian Plate (25-20 Ma) and the Kohistan Terrane are quite different indicating different rates of cooling before the 25-20 Ma but the lower temperature cooling history of the two terranes is the same from 20 Ma to present indicating that faulting ceased about 15-20 Ma when the two terranes of Kohistan and Indian Plate were locked in the present structural position. However, north of Babusar Pass, in the vicinity of Nanga Parbat, the Indian Plate now continues to thrust over the Kohistan Terrane (Chamberlain et.al., 1989). The tectonic history of Indian Plate in the Nanga Parbat massif is markedly different. There plutonism, metamorphism and deformation is much younger (i.e., less than 20 Ma). In lower Swat on the other hand evidence shows rapid exhumation from 38 to 25 Ma (Hornblende $^{40}Ar/^{39}Ar$ ages 38 ± 3 Ma, Muscovite $^{40}Ar/^{39}Ar$ ages 30 ± 2 Ma) and slow rate of exhumation after 25 Ma as shown by continued ductile deformation during the dome forming phase and general lack of thrusts.

How was burial of the now exposed crustal slab attained to such great depths (i.e., 35 to 45 Km in Lower Swat; 45 to 65 Km in Upper Kaghan)? Coward et al. (1988) and Treloar et al. (1989a) working in Mansehra-Banna-Besham-Alpurai area presented a tectono-metamorphic model in which initial collision led to imbricate thrusting at the Indian Plate margin resulting in crustal thickening and Barrovian metamorphism. Further imbrication after metamorphic peak resulted in metamorphic discontinuities seen in the area. By 20 Ma, the Kohistan Terrane and Indian Plate were structurally locked after which time their cooling histories are similar.

It has been felt that involving simple erosion for the rapid exhumation of the Higher Himalaya after deep (35-65 Km depth) burial after collision is not plausible (Spencer, 1993). Moreover, there is the problem of low grade Phanerozoic Tethyan cover overlying the high grade Higher Himalaya (Ghazanfar et al., 1997 in review). Extension has therefore also been invoked and with erosion together considered sufficient to account for the rapid exhumation as well as the metamorphic discontinuity between the Higher Himalaya and the Tethyan cover sequence (Treloar and Rex, 1990; Spencer, 1993; Burg et al., 1996). Structural evidence of extension does exist in the Indian Plate gneisses in the footwall of the Indus Suture at Jijal, Babusar (Treloar et.al., 1991; Hubbard et.al., 1995), Naran (Burg et.al., 1996) as well as in the low grade cover below Indus Suture melange at Charbagh in Swat. Likewise a major boundary normal fault, the Trans-Himadari Fault (THF), has been placed to the north of the Higher Himalaya in India. (Valdyia, 1984). The age of this normal faulting or tectonic denudation is generally related to the 25-20 Ma period of rapid cooling.

## DISCUSSION

The stratigraphy of the Higher Himalaya in the Upper Kaghan and Lower Swat areas of Pakistan is characterised by a remarkable lateral continuity of major groups over a distance of more than two hundred kilometres as is evident from description above on the stratigraphy and geology and as shown on the geological map (Fig.3). A predominant pelite schist-quartzite basement with amphibolites, sheet granites and profuse migmatization is overlain by a thick predominantly calc-pelitic gneiss high grade cover sequence with amphibolites limited to the basal part. The Higher Himalaya is suggested to be overlain to the north by low grade rocks of Tethyan affinity which occur only close to the Indus Suture as slivers in upper Kaghan but are much more extensive in Lower Swat (Ghazanfar et al., 1997 in review).

A controversy continues as to the age of the crystallines of the Higher Himalaya. Some intruding granites in Besham (Baig, 1990) and many in the Higher Himalaya in India (Mehta, 1980) have been dated as old as 2000 Ma, with others at 1400, 950, 270, 40 and younger. A Proterozoic age for the Higher Himalaya Basement is now generally agreed. There is more controversy regarding the cover. Greco et al. (1989), Spencer (1993) and Spencer and Gebauer (1996) have considered the calc-pelitic gneisses of the Burawai Group in Upper Kaghan as Permo-Triassic. They have contended that the situation in Pakistan is analogous to that in Zanskar and Suru Valley where Honegger (1983) has described a metamorphosed Palaeozoic cover over the Higher Himalaya and where the amphibolites at the base of the cover have been correlated with the Permian Panjal volcanics on the strength of geochemical affinities and U/Pb SHRIMP data on zircons which gave a protolith age of 269 Ma. Chaudhry and Ghazanfar (1987) and Chaudhry et al. (1994a), by contrast, considered the mainly calcareous cover metasediments as Upper Proterozoic because of complete structural and metamorphic concordance between cover and the basement as well as the Precambrian age (Baig and Lawrence, 1987) of some granites cutting the cover rocks near Besham (see Ghazanfar et al., 1997 in review, for full discussion).

According to Schouppe (1995) in the Neelum Valley, a correlation between the leucogranites of the Lesser Himalaya and the Mansehra Granite of Le Fort et.al., (1980) exists. It was also pointed out that the Neelum leucogranites always disappear suddenly when reaching the cover sequence from the basement through the MCT. In addition, the basal formation of the cover occurs very differently from place to place (500-0 metre thick), pointing out the existence of unconformity between the basement and the cover sequences of the Higher Himalaya (Schouppe et.al., 1994). As Mansehra Granites are 516±16 m.a. old, this unconformity and the overlying cover must be younger. The presence at the base of the cover of the amphibolite layers correlated with the Permian to carboniferous Panjal Traps (Schouppe, 1995) and chemical and stratigraphical correlations between the marbles of the cover sequence situated in the Higher Himalaya of the Neelum Valley with some Triassic, fossiliferous marbles of the Treri Group (Greco, 1989) confirm the most probable Palaeozoic to Mesozoic age of the calcareous cover metasediments.

DiPietro (1991) and Pogue et al. (1992) consider the cover calc-pelite gneisses (their Kashala Formation) as Triassic and the underlying pelitic schists and micaceous quartzites cover (their Marghazar Formation) containing amphibolites as Permian in Lower Swat. They correlated the two with the fossiliferous Triassic limestone and the greenschist (Karapa Formation and part of Jafar Kandao Formation) of the Peshawar Plain to the south. The lithostratigraphy of the compared formations of Lower Swat and the Peshawar Basin are different. There are hardly any psammites (quartzites) associated with Karapa volcanic greenschist and the predominant massive marbles of the Triassic of Peshawar plain are different from the calc-pelite gneisses of the Tilgram Formation in Lower Swat. Secondly the calc-pelite gneisses of the Tilgram Formation in Lower Swat are overlain by the same Dargai schist which forms the Precambrian basement to Peshawar Plain sediments. This is quite apart from the difference in metamorphism between the marbles of Peshawar plain and calc-pelite gneisses of Tilgram Formation. Smith et al. (1994) have radiometrically dated a small body of granite known as the Malakand granite which intrudes the Triassic Kashala Formation of DiPietro (1991) as Carboniferous on the basis of U-Pb. This body not only contains xenoliths of the "Kashala Formation" but also produces a thermal aureole with andalusite hornfels in the pelitic schists. It is therefore hard to correlate it with fossiliferous Triassic Karapa Formation of DiPietro (1991)south of the Main Central Thrust in Swat. Alternatively, the Malakand Granite was remobilised during the Himalayan metamorphism (and incorporated the protolith zircons), indicating that the cover would be Pre-Tertiary. This would then prove that the age of the cover (Upper Paleozoic-Mesozoic) as concurred by DiPietro (1991) is correct.

## CONCLUSIONS

The Higher Himalaya extends across northwest Himalaya of Pakistan and adjoining Kashmir. It is demarcated from the Lesser Himalaya by the Main Central Thrust to the south and the generally northern limit is the Indus Suture to the north. However, a recent interpretation that Tethyan sediments occur in between the Higher Himalaya and the Indus Suture has been made (Ghazanfar et al., 1997; in review), indicating an extensional fault at the base of these Tethyan Himalayan sediments. Widespread extension below the Indus Suture has been documented by Treloar et.al. (1991), Hubbard et.al., (1995) and Burg et.al., (1996). The poly-metamorphosed and multiply deformed Higher Himalaya is comprised of a lower basement (predominantly pelite schist-quartzite sequences with migmatites, granitoids) and a cover sequence composed mainly of calc-pelite gneisses, amphibolites and marbles metamorphosed in upper amphibolite (-eclogite) facies. The Higher Himalaya is ductily deformed and is characterised by kilometric scale northeast-southwest to north northwest-south southeast trending elongated structural basins and domes. The axes of these folds are roughly at right angles to the fold trends in the Lesser Himalaya to the south and Tethyan sediments/ Indus Suture rocks to the north.

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# GEOCHEMICAL EVIDENCE FOR THE TECTONIC SETTING OF THE PANJAL VOLCANICS IN AZAD KASHMIR AND KAGHAN AREAS

BY

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**Abstract:** *The Permian to Early Triassic age Panjal Volcanics in Azad Kashmir and Kaghan areas are exposed along Main Boundary Thrust. Studies of the major and trace elements in the Panjal volcanic rocks indicate that they formed in a tectonic setting transition from within plate to oceanic conditions. These rocks show $TiO_2$ contents from. 1.08 to1.59wt. %, $SiO_2$ from 47.93 to 51.24wt.%, MgO from 5.05 to 9.07wt.% and $P_2O_5$ from 0.09 to 0.19wt.%. Mg# varies from 59.7 to 66.10 $Na_2O$ contents range from 1.11 to 4.99wt.%, $K_2O$ from 0.11 to 2.67wt.%. Major elements especially $Na_2O$ and $K_2O$ indicate alteration of these rocks.*

*Trace element contents of the Panjal volcanics also show variation. Zr contents range from 53 to 110ppm, Ni 56 to 229ppm and Cr from 54 to 677ppm. Major and trace elements and Mg# of the rocks indicate that the Panjal magma has been evolved as tholeiitic to slightly alkalic in composition with geochemical characteristics similar to enriched mid ocean ridge (P-type) basalts or ocean island tholeiities. The interbedded chert, limestone and associated turbidite deposits indicate shallow marine environment during the time of eruption of magma. The volcanics represent rifting of the northern margin of Indian continent and development of shallow marine oceanic conditions during Upper Paleozoic.*

## INTRODUCTION

In the Himalayan region the Late Carboniferous to Early Triassic volcanic activity was widespread in terms of time and space. In the NW Himalayas the extensive Panjal volcanics occur in the Lesser Himalayas. The rocks are fault bounded i.e. the Main Boundary Thrust (MBT) and the Panjal Thrust (PT) as shown in Fig. 1. The area lies around the Hazara Kashmir Syntaxis (HKS) in the Lesser Himalaya. Here the Himalayas can be divided from south to north into three tectonic subdivisions into Sub, Lesser and Higher Himalayas. Subhimalaya comprises sedimentary rocks while Lesser and Higher Himalayas contain igneous and metamorphic rocks.

The volcanic rocks in Azad Kashmir and Kaghan region of Lesser Himalayas comprise a sequence of pyroclastic rocks and metabasalts (Calkins et al. 1975; Wadia, 1928, 1934; Greco, 1989; Khan and Ashraf 1989; Chaudhry et al., 1992; Khan et al., 1991; Khan, 1994). The Panjal volcanics are massive lava flows with subordinate pillow structures. They are interbedded with limestone and turbidities cropping out in Kaghan, Neelum, Jhelum and Kahuta areas. The Panjal volcanic rocks in the region are largely spilitized and metamorphosed. The geology of the Panjal volcanic rocks have been studied by Lydekker (1983), Wadia (1928, 1934), Ghazanfar and Chaudhry (1985) and Greco (1989).

The lava flows have been considered as continental basalts (Wadia, 1934; Honegger et al., 1982; Papritz and Rey 1989). However, in the Lesser Himalaya the geological evidence such as pillow lavas, bedded chert, limestones and turbiditic deposits associated with the Panjal volcanics have been found. The geochemical data show a close geochemical affinity with oceanic tholeites (Butt et al., 1985; Khan and Ashraf 1989; Khan et al., 1991; Chaudhry et al., 1992; Khan, 1994). Evidence for submarine conditions of such volcanics has also been reported from India (Pareek, 1976 and Nakazawa and Kapoor, 1973).

In Azad Kashmir and Kaghan areas the geochemical characteristics of the Panjal volcanic rocks have studied by Butt et al. (1985), Chaudhry and Ashraf,

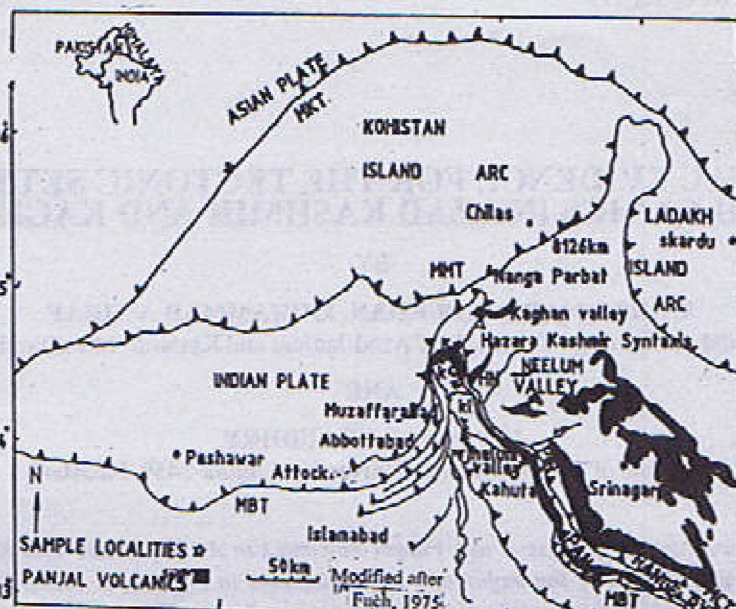


Fig. 1 Distribution of the Punjal Volcanics in the NW Himalayas
Stippled area.

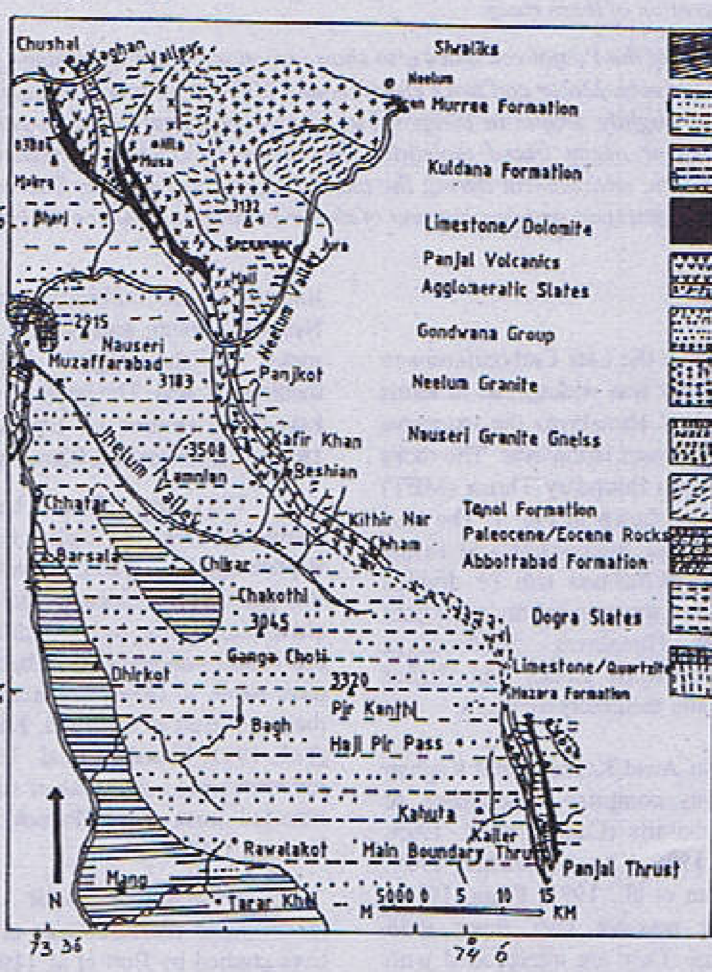


Fig. 1a. Geological map of Kahuta-Jhelum-Neelum-Kaghan, Region of North West Himalaya, Pakistan

(1980), Khan and Ashraf (1989),Papritz and Rey (1989), Khan et al. (1991), Khan (1994). Geochemical studies of the Panjal volcanic rocks were also carried out by other workers (Nakazawa and Kapoor, 1973; Bhat and Zainuddin, 1978, 1979; Honegger et al., 1982) from the Srinagar region in the valley of Kashmir.

The purpose of this paper is to identify the tectonic setting of the Panjal volcanics in Azad Kashmir and Kaghan area. The immobile elements of the Panjal volcanic rocks were plotted on tectonic discriminant diagrams to find the tectonic setting.

## GEOLOGICAL SETTING

The Panjal Volcanics lie in the Lasser Himalayas extending from Kahuta to Kaghan area (Fig 1.). They are bound between the MBT and the PT. Along the PT the older metasedimentary rocks were thrust over the Panjal volcanics.

The pryroclastic rocks, Agglomeratic Slates, and predominantly Panjal volcanic rocks (lava flows) are exposed on the eastern and western flanks of the HKS. The Panjal volcanic rocks comprise massive basaltic lava flows with pillow structures. They are altered, metamorphosed to greenschist facies and are subordinately spilitized probably during hydrothermal alteration and Himalayan orogeny.

The Panjal Volcanics in the Kaghan area are associated with turbidite beds and carbonate bands. The carbonate and chert bands were found associated with these rocks in Muzaffarabad and Kahuta areas. The Panjal volcanics show pillow structures, which are deformed and stretched.

A Permian to Triassic age for the Panjal volcanic rocks in Azad Kashmir and Kaghan areas, is based on (1) correlation of these rocks in Baramula and Srinager region where a Permian to Triassic age has been accepted (Wadia, 1934) (2) using Ar40/Ar39 ages of the Panjal volcanics were obtained from 284±4 to 262±1 Ma (Baig 1991).

## PETROGRAPHY

Comprehensive petrographic description of the Panjal Volcanics have been provided in a number of papers (Khan and Ashraf, 1989; Khan et al. 1991). Hence in this paper only a condensed petrographic data of the Panjal Volcanics will be discussed.

The Panjal Volcanic rocks are altered and metamorphosed to lower greenschist facies. They are plagioclase phyric basalts in the Muzaffarabad and clinopyroxene phyric basalts in the Kahuta area.

The Panjal Volcanics are greenish grey to dark grey, and violet coloured, massive to foliated fine grained rocks. In general, all the Panjal Volcanics are petrographically similar in the Lesser Himalaya. They are fine grained; mostly aphyric rocks and at places weakly to moderately cleaved. The vesicles are of different size and shape. They are usually rounded to sub rounded but at places elongated vesicles also occur. The amygdules show chalcedony in core characterized by fibrous or radiating sheaths lined by chlorite layer, which is succeeded by epidote layer. Generally vesicles and veins are filled by aggregates dominated by chlorite, epidote, albite and calcite or quartz and chalcedony. Porphyroblasts of chlroite are common in these rocks.

Mineralogically these rocks consist predominantly of epidotized plagioclase (albite). However, in Kahuta and Muzaffarabad areas, more calcic plagioclase occurs in relatively less altered rocks. The plagioclase is generally saussritized occuring as microlits and crystals. At some places the twinning character of the plagioclase and their boundaries are not conspicuous due to their intense alteration. The plagioclase cryatala are sometimes traversed by epidote, calcite and chlorite veinlets. In the more altered samples the plagioclase has been altered to sericite and chlorite. The rocks are composed of various proportions of albite, chlorite, epidote, actinolite, sphene, calcite and opaque minerals. In Kaghan and Muzaffarabad areas, clinopyroxene has been completely replaced and at places only relics are found. In Kahuta area pyroxene alters to chlorite and actinolite. No modal olivine was found and probably has been completely replaced by chlorite.

All the Panjal Volcanics rocks have experienced hydrothermal alteration and Himalayan metamorphism. These rocks have been metamorphosed to greenchist facies (Greco, 1989; Khan and Ashraf, 1989; Khan et al., 1991; Chaudhry et al., 1992; Khan, 1994).

## GEOCHEMISTRY

The rock samples of the Panjal Volcanics (lava flows) were analysed by ICP for major elements $SiO_2$, $TiO_2$, $Al_2O_3$, $Fe_2O_3$ ($Fe_2O_3$ was analysed as total iron), MnO, MgO, CaO, $Na_2O$, $K_2O$, $P_2O_5$. Trace elements like Ba, Sr, Cr, Ni, La, Ce, Y, Nb, Zr, CO, Cu and Zn were analysed by ICP-MS method (Table 1). Major oxides are presented in wt.% while trace elements are in ppm.

Geochemical data of the Panjal Volcanic rocks are discussed mainly for interpretation of tectonic environment. Analyses were carried out of the rocks from Kahuta, Muzaffarabad and Kaghan areas. Petrographic data indicate a pervasive alteration of these rocks. The alteration of the Panjal Volcanic rocks has also been reflected by their major element data like $Na_2O$, $K_2O$ and LOI values (Table 1). Therefore, Immobile elemental abundances will be used for interpretation of the tectonic environment.

The Panjal Volcanics are mainly basalt's in composition (Table 1). The trace elements of the Panjal Volcanics are normalized to mid ocean ridge basalts (MORB). The normalizing values are after Pearce (1983). The trace element patterns of the Panjal Volcanics are shown in Fig. 6.

To identify the original tectonic setting of these rocks immobile elements and high field strength elements are used. These elements are thought not to be greatly effected during the alteration and metamorphism of the basaltic rocks that the Panjal Volcanics have undergone (Cann, 1970; Hart, 1973; Hart et al. 1974 Pearce and Cann, 1973; Floyd and Winchester, 1978; Condie et., 1977; Humphris and Thompson 1978; Pearce et al., 1981; Pearce and Norry, 1979).

**Table 1**
**Geochemical composition of the Panjal Volcanic rocks**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 48.01 | 48.71 | 48.73 | 49.69 | 49.99 | 49.24 | 51.24 | 50.64 | 47.93 |
| $TiO_2$ | 1.3 | 1.38 | 1.08 | 1.33 | 1.42 | 1.20 | 1.59 | 1.48 | 1.29 |
| $Al_2O_3$ | 14.90 | 14.41 | 15.36 | 15.45 | 14.19 | 14.19 | 14.33 | 14.39 | 13.00 |
| $Fe_2O_3$ | 10.50 | 10.89 | 9.64 | 10.46 | 11.21 | 10.85 | 11.06 | 11.53 | 12.90 |
| MnO | 0.19 | 0.15 | 0.27 | 0.17 | 0.16 | 0.20 | 0.17 | 0.16 | 0.26 |
| MgO | 8.08 | 6.91 | 7.97 | 7.73 | 8.05 | 9.07 | 6.12 | 5.05 | 8.42 |
| CaO | 8.08 | 10.38 | 8.37 | 7.02 | 7.20 | 8.04 | 7.60 | 8.93 | 8.73 |
| $Na_2O$ | 2.22 | 2.30 | 3.24 | 4.17 | 4.22 | 3.21 | 3.12 | 2.34 | 2.67 |
| $K_2O$ | 2.51 | 1.08 | 0.87 | 0.67 | 0.53 | 0.57 | 1.18 | 1.36 | 1.03 |
| $P_2O_5$ | 0.09 | 0.13 | 0.11 | 0.19 | 0.14 | 0.13 | 0.16 | 0.18 | 0.13 |
| LOI | 3.80 | 3.40 | 4.00 | 2.90 | 2.70 | 3.00 | 3.10 | 3.40 | 3.00 |
| Total | 99.68 | 99.74 | 99.64 | 99.78 | 99.81 | 99.70 | 99.67 | 99.46 | 99.36 |
| Mg# | 64.20 | 59.70 | 65.80 | 63.30 | 62.60 | 66.10 | 56.30 | 50.50 | 60.30 |
| Ba | 418 | 234 | 191 | 105 | 116 | 102 | 356 | 267 | 152 |
| Sr | 161 | 431 | 224 | 312 | 162 | 246 | 308 | 364 | 163 |
| Cr | 120 | 54 | 92 | 93 | 150 | 170 | 71 | 98 | 677 |
| Ni | 97 | 80 | 77 | 56 | 84 | 120 | 90 | 82 | 229 |
| La | 9 | 8 | 11 | 34 | 55 | 6 | 19 | 7 | 4 |
| Ce | 65 | 20 | 39 | 59 | 109 | 25 | 46 | 20 | 20 |
| Y | 24 | 23 | 17 | 27 | 22 | 20 | 27 | 24 | 21 |
| Nb | <9 | <9 | 10 | <9 | 12 | 12 | 11 | <9 | <9 |
| Zr | 91 | 82 | 53 | 110 | 77 | 61 | 120 | 91 | 81 |
| CO | 50 | 58 | 62 | 23 | 44 | 65 | 42 | 33 | 70 |
| Cu | 147 | 166 | 122 | 84 | 39 | 38 | 25 | 65 | 29 |
| Zn | 127 | 99 | 95 | 77 | 105 | 79 | 40 | 86 | 118 |

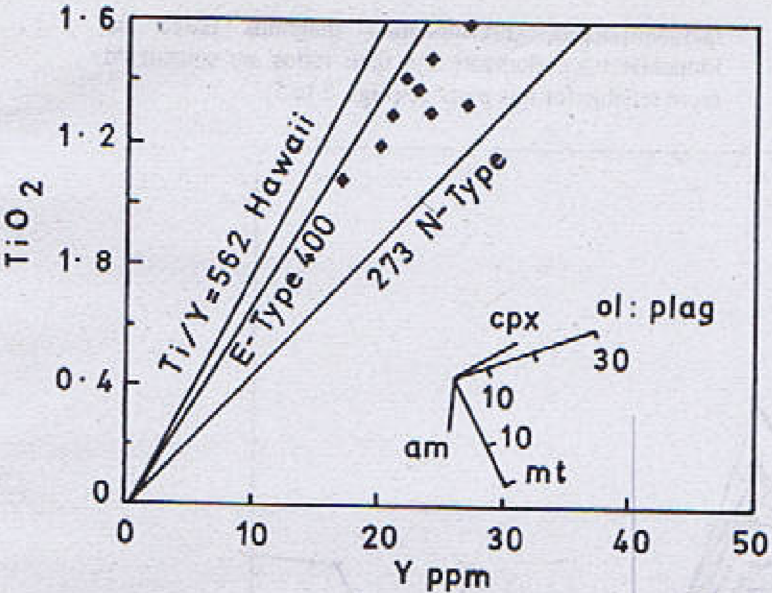


Fig. 2. $TiO_2$ - Y variation diagram for the Panjal volcanics. Trends for N and E - type MORB (represented by Iceland and the surrounding seafloor), intra plate basalts (IPB) represented by Hawaii basalts and calculated fractionation models for cpx, ol, pl, am, mt, are after Perfit et al. (1979).

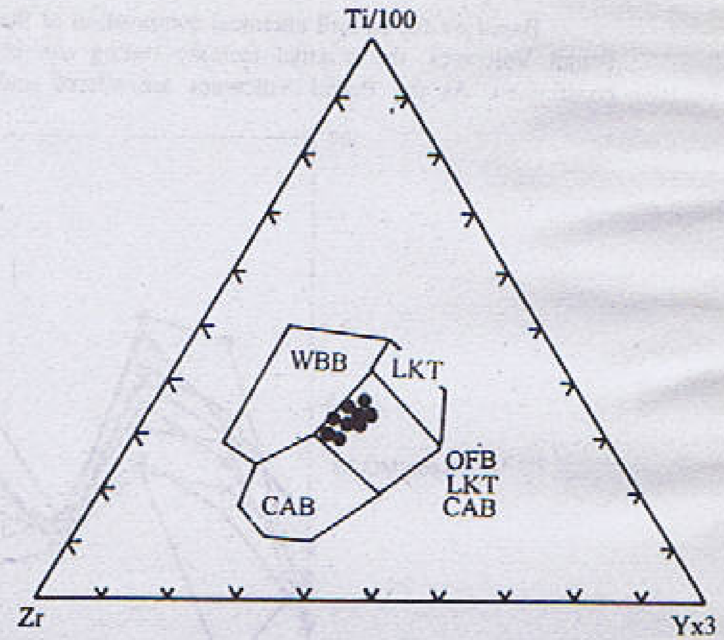


Fig. 3 Plot of Panjal Volcanics in Ti-Zr-Y diagram fields discriminating ocean floor basalt (OFB), continental flood basalt(WPB),low potassium tholeiites(LKT), and calc alkaline basalts(CAB) are from Pearce and Cann,(1973

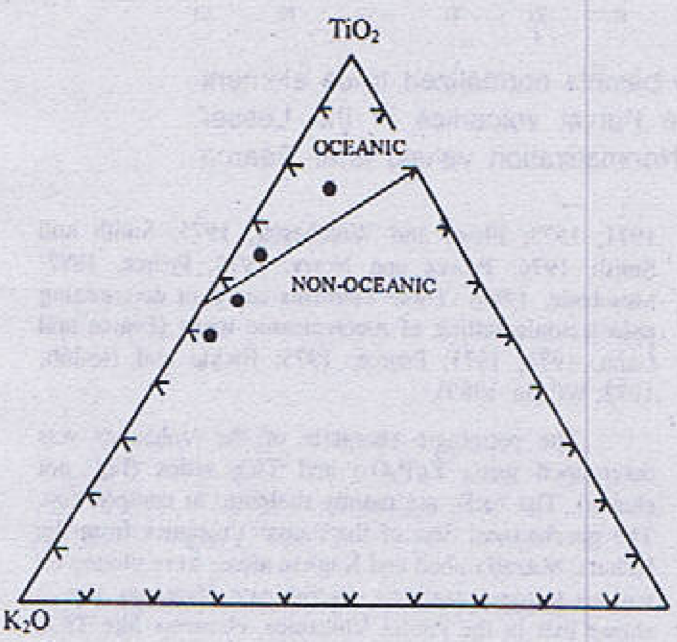


Fig. 4 $TiO_2$-$K_2O$-$P_2O_5$ diagram to distinguish oceanic and non-oceanic tectonic setting for the Panjal volcanics. Dividing line for twofields is from Pearce et al. (1975).

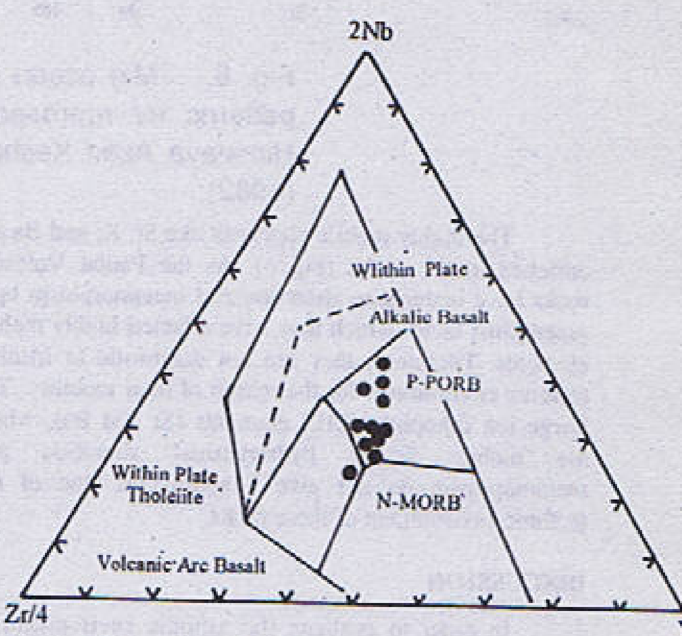


Fig. 5 Plot of the Panjal Volcanics in 2Nb-Zr/4-Y diagram to distinguish within plate, volcanic arc, P-type and N-type MORB. Field boundaries after Meschels(1986).

Based on the overall chemical composition of the Panjal Volcanics, the original tectonic setting can be constrained. As the Panjal Volcanics are altered and metamorphosed, discrimination diagrams based on immobile trace elements and their ratios are considered more reliable for this purpose (Figs. 2 to 5).

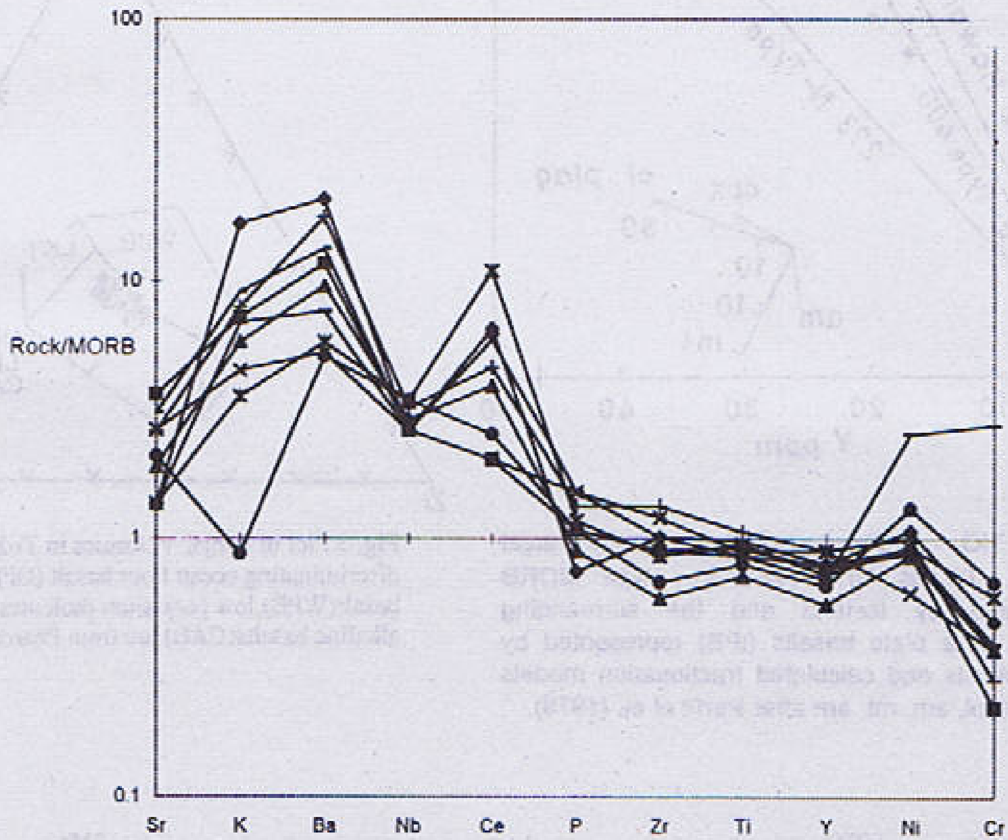


Fig. 6. Mid ocean ridge basalts normalized trace element patterns for representative Panjal volcanics in the Lesser Himalaya Azad Kashmir. Nonmalization values after Pearce (1982).

The highly mobile elements like Sr, K, and Ba are enriched in the rocks (Fig 6). As the Panjal Volcanic rocks have undergone alteration and metamorphism upto greenschist facies which may have affacted highly mobile elements. Therefore, they are not diagnostic to identify tectonic environment for the reason of their mobility. The Large ion lithophile (LIL) elements (Sr and Ba), which are mobile during hydrothermal alteration and metamorphism do not give a significant clue of the tectonic environment of these rocks.

## DISCUSSION

In order to evaluate the tectonic environment of these rocks their geochemical data were plotted on different tectonomagmatic discriminat diagrams. Discrimination of tectono-magmatic environment of the altered basalts can be determined by using elements like P, Zr, Nb, and Ti which are less affected and are immobile by the processes of alteration and metamorphism up to greenschist facies (Pearce and Cann, 1971, 1973; Floyd and Winchester, 1975; Smith and Smith, 1976; Pearce and Norry, 1979; Pearce, 1982; Meschede, 1986). These elements serve in determining paleotectonic setting of metavolcanic rocks (Pearce and Cann, 1971, 1973; Pearce, 1975; Bickle and Nesbitt, 1972; Wilson, 1989).

The petrologic character of the Volcanics was determined using $Zr/P_2O_5$) and $TiO_2$ ratios (Fig. not shown). The rocks are mainly tholeiitic in composition. The geochemical data of the Panjal Volcanics from the Kahuta, Muzaffarabad and Kaghan areas, were plotted on various tectono-magmatic discriminate diagrams. Fig. 2 shows that in the Panjal Volcanics, elements like TiO2 and Y were not mobilized during the alteration and metamorphism of these rocks to greenschist facies metamorphism. Pearcee and Cann (1973) used Ti, Zr and Y ratios to determine the paleotectonic environment of the altered Volcanic rocks. This diagram distinguishes island arc (low-potassium tholeiite (LKT), ocean floor basalts (OFB), calc-alkaline basalts (CAB) and within plate basalts (WPB). On the Ti-Zr-Y diagram (Fig. 3) after Pearce and Cann (1973) the samples plot mainly in ocean floor basalts (OFB) field. Some samples lie close to the WPB field boundary. The Ti-Zr-Y diagram (Fig. 3) indicate that the Panjal Volcanics have within plate to ocean floor affinity.

Pearce et al. (1975) used $TiO_2$-$K_2O$-$P_2O_5$ contents to discriminate tectonomagmatic environment of oceanic and non-oceanic basalt's (WPB). The geochemical data of the Panjal Volcanic rocks from the western and eastern side of the HKS plot both in the non-oceanic and oceanic fields (Fig. 4).

The 2Nb-Zr/4-Y diagram (Fig. 5) after Meschede, (1986) for the Panjal Volcanics show that most of the geochemical data fall in the P-type MORB field. Other samples plot in the field of within plate tholeiites whereas some samples lie in the field of within plate alkalic basalts (Khan 1994). The geochemical data indicate that these rocks were not erupted in island arc environment as suggested by Ghazanfar et al. (1985).

The spiderdiagram of the Panjal Volcanics show that except for lower values of Ni, Cr, Y, the analyzed rocks have higher abundances of the elements than MORB. The elements commonly thought to be relatively mobile like Sr. K, and Ba are enriched in the Panjal Volcanics. Alteration processes generally affect these alkali elements. The increase in elemental abundances can be attributed to varying degree of crystal fractionation in the Panjal Volcanics. These rocks show some depletion in Ni, Cr and an enrichment of mobile elements relative to immobile elements. The alteration and crustal contamination could also cause $K_2O$ enrichment in rocks. The K, Sr and Ba may show enrichment due to alteration processes and mobility of these elements under greenschist conditions. The Panjal Volcanic rocks are spilitized due to which they may have both enrichment and depletion of $K_2O$ and Ba. Therefore, another possibility of enrichment of $K_2O$ and Ba in some of the Panjal Volcanic rocks may be related with alteration processes. These rocks are depleted in the Y and enriched in HFS element (Fig. 6). Some rocks have low Ba and K content. The Y content in the Panjal Volcanic rocks indicate derivation of the tholeiitic melt from the garnet stability field. Ti/Y ratios for the Panjal Volcanics are shown in Fig. 2. The Ti/Y ratios indicate an enriched P. type MORB source for these rocks.

Geochemical variation in the Panjal Volcanics indicate that they have been effected by fractional crystallization (Fig. 2). Fractional crystallization was accompanied by olivine and clinopyroxene fractionation. Fractionation is evident from the trace elements of these rocks from Kahuta, Muzaffarabad and Kaghan areas. The trace elements Ni, Cr and Co variable values of the Panjal Volcanics rocks show crystal fractionation in olivine while Cr and Co are strongly partitioned into garnet and clinopyroxene (Wilson 1989), so garnet clinopyroxene rapidly depletes a residual liquid in these elements. The Mg-rich samples have high Ni and Cr contents. It is, therefore, envisaged that both processes of crystal fractionation and partial melting of upper mantle have been operated together, resulting into slight alkalinity of the Panjal Volcanics.

The MORB normalized patterns of the Panjal Volcanics show many similarities to "enriched" P-type. The MORB trace element patterns indicate a trough for Nb values relative to Ba and Ce (Fig. 6). The Nb trough indicates a signature of crustal contamination. Enrichment of Sr-Ba values in the rocks indicates some effect of crustal contamination. However, other possibility of their enrichment may be alteration of these rocks. The trace element patterns of the Panjal Volcanics show enrichment in Sr, K Ba (Fig. 1). The enrichment of these elements in the Panjal Volcanics may indicate that these rocks may have undergone crustal contamination.Dupy and Dostal (1984) and Dostal et al. (1986) have suggested that the continental magma could be derived from a MOR type mantle source and subsequently modified by alteration with continental crust. The elements like Sr. K and Ba of the Panjal Volcanics reflect the influence of crustal contamination. The elemental patterns suggest that the Panjal Volcanic rocks have been effected by minor crustal contamination. Y is considered a good index of fractionation (Thompson et al. 1983). This element is also considered relatively insensitive to crustal contamination. In Fig. 6 Y with Ni and Cr show fractionation. Therefore, enrichment of incompatible elements can be related to the processes of possibly different degrees of partial melting, fractional crystallization, crustal contamination and alteration of these rocks. Other possibility is that Panjal magma has inherited these elements from the enriched source.

Primary basaltic magma equilibrated with mantle olivine (Fo 88-92) should have magnesium number (100/Mg+Fe). 68 (Frey et al., 1978; Green et al., 1979; Hanson and Langmuir, 1978; and Sato, 1977). The Panjal Volcanics show low magnesium number (50-66) and Ni contents as compared to the primary basaltic magma (Table 1). Low Ni contents in the basaltic rocks show fractionation of olivine (Wilson, 1989). Considering these values the Panjal Volcanics do not indicate primary melt (Table 1). They are evolved, with Ni content from 56 to 229ppm, Mg number 50 to 66 and MgO in the range of 5 to 9%. These elemental values in the Panjal Volocanics indicate that they have undergone fractional crystallization of olivine and pyroxene during evolving of the melt.

The Panjal Volcanics represent different degree of partial melting as is indicated by their trace element patterns (Fig. 6). Degree of partial melting of these rocks can be calculated by using the batch partial melting equation Cl/C0=I/F which can be written as F=C0/CI, assuming that D is negligible or much smaller. C0 is the trace element in the mantle source and CI is the trace element concentration in the liquid and F is the degree of partial melting (Shaw, 1970). Zr is used to know the degrees of partial melting as it remains in the residual melt and least effected by alteration processes (Erlank and Kable, 1976). A mantle source composition of 2.5 times chondrite values for Zr (15.5ppm; Frey et al., 1978) and using averages of Zr contents of the Panjal Volcanics the degree of partial melting is calculated as 18%. One rock (Sample No. 6, Table 1) with Mg No. 66 and Zr content 61ppm show 25% degree of partial melting. These values indicate degrees of partial melting of these rocks from 15 to 25%.

In general the early development of the Panjal Volcanics appears to be shallow water, associated with limestones and shallow water sediments. The earlier formed basalts are transitional and show a within plate affinity. The late stage lava flows of the Panjal Volcanics show pillow structures. These lava flows are associated with chert bands, at places, turbiditic rocks and black shales. This stage represents deeper water conditions. Therefore, the Panjal Volcanics started from within plate rifting leading to development of shallow marine conditions.

The field evidence and geochemistry suggest that the Panjal Volcanic rocks were erupted in the northern margin of India in a widening continental rift, which had developed an oceanic conditions Upper in Paleozoic to Early Triassic.

## CONCLUSIONS

The Panjal Volcanics exposed in the NW Himalayan region is thrust bounded in the Lesser Himalayas. The Volcanics are altered, metamorphosed to greenschist facies and are subordinately spilitized.

The Panjal Volcanics is tholeiitic to mildly alkalic basalts in composition.

The Panjal Volcanics are associated with interbedded turbiditic deposits which indicate submarine conditions for the Panjal Volcanics.

The carbonate bands occur as interbeds within the Volcanics.

Lava flows with pillow structures in the Panjal Volcanics indicate submarine environment.

These rocks have been fractionated. The olivine and pyroxene has been removed from the magma. They are evolved in terms of low Ni and Cr values.

Tectonomagmatic discriminate diagrams show that the Panjal Volcanic rocks were erupted in a within plate setting to an oceanic environment.

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# Provenance, Alkali Aggregate Reaction (AAR) and Inservice Behaviour of N.W.Himalayan Sands and Gravels in Cement Concrete at Tarbela and Warsak Dams N.W.F.P-Pakistan.

By

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**Abstract:** *This is the first paper in which deleterious as well as innocuous clasts of the natural aggregate of Indus catchment are classified with reference to their provenance. It will help to identify the belts of deleterious as well as innocuous rock types of Himalaya and Karakoram and serve as a general guide for quarry development for producing safe aggregate.The study is useful for future planning and construction of hydropower structures from these aggrgate.*

*The NW Himalaya in Pakistan from which the gravel and sand of Indus River and its major tributaries are derived is geologically very complex. The mountain chains comprising this area have been formed by India-Eurasia collision initiating at ca 65 m.a. with the Kohistan-Ladakh Island Arc trapped in between. The Indian plate at the leading edge is composed of Higher Himalayan S-type granitoids, migmatites and a sequence of high grade calc-pelites, marbles, pelites and psammites with layers of amphibolites. Granitoid, migmatite, carbonate, amphibolite and hard schists derived from these blocks are innocuous. Extensive mylonites have developed along Main Central Thrust, Indus Suture Zone and Thakot Fault and rarely within the Higher Himalayan Crystallines (HHC). Quartz rich clasts of mylonites derived from these zones contain highly strained quartz with anomalous optics and are potentially deleterious.*

*The Lesser Himalaya to the south of the Higher Himalayan Block is composed of a northern metamorphic-igneous zone comprised predominantly of porphyritic S-type cordierite granitoids, pelites and psammites. The southern sedimentary zone comprise pelites and psammites and a sequence of unmetamorphosed shelf carbonates with minor sandstone and shale horizons. The granitoid, hard schist and medium to high grade psammites of metamorphic zone are innocuous. Slates, phyllites and graywackes in lower greenschist facies are potentially deleterious. Carbonate and sandstone clasts from the sedimentary part are innocuous. However chert clasts from this zone are potentially deleterious. The Balakot Mylonite Zone (B.M.Z) and Oghi Shear Zone (O.S.Z) yield deleterious strained quartz rich clasts. Microfractured quartz clasts derived from Hazara slate and Tanawal Formation of pelite psammite character from Lesser Himalaya are also potentially deleterious since they contain cryptocrystalline quartz along fracture cleavage developed during the second major deforamtion phase. The Kohistan Island Arc is composed of amphibolites, acid to intermediate volcanics and I-type granitoids ranging in composition from granite to diorite and minor chert, volcanogenic arenites, carbonates, pelites and marl. The Kohistan terrane yields slightly reconstituted acid to intermediate merro to cryptocrystalline volcanics, pyroclasts and volcanogenic chert/chalcedony and arenites metamorphosed to a very low grade.*

*A gabbronorite batholith also occurs in this terrane. The huge batholith is composed of about 95% gabbronorite, 1% ultramafics and 4% diorites and tonalites. The clasts derived from this source are innocuous.*

*The Kohistan Arc is bounded by two suture zones the northern of which is known as the Main Karakoram Thrust (MKT) while the southern branch is known as the Indus Suture Zone or the Main Mantle Thrust (MMT). The suture is composed of pillow lavas, peridotite and dunite cumulates, harzburgite tectonites, bedded cherts, volcanogenic chalcedonic cherts and flysch. The two suture zones contribute only small quantities of deleterious clasts derived from bedded/ribbon chert and other flyschoid sediments. The Karakoram Plate to the north of MKT is composed of a basement S-type granitoid complex overlain by high grade pelites, psammites, marbles and clac-pelites. This in turn is overlain by*

*a sequence of slates and low grade carbonates. Only small quantities of potentially deleterious volcanics and low grade meta-argillites are contributed by this terrane.*

*The sand and gravel derived from this complex terrane has so far exhibited excellent physical characteristics. But these have shown alarming petrographic and chemical behaviour in concrete at Warsak and Tarbela Dams. A controversy has therefore continued over the past one decade as to the actual causes of deleterious deterioration in parts of already placed concrete.*

*The aggregates were considered safe by earlier workers on the grounds that the deleterious rock types like argillites, greywakes, quartzite and acid to intermediate volcanics had undergone metamorphism. We suggest that these rocks have been reconstituted in very low grade metamorphic zone or prehnite-pumpellyite to lower greenschist facies. As such the reactive silica phases and phyllosilicates have not been reconstituted completely to innocuous mineral phases.*

## INTRODUCTION

Indus River which flows through Ladakh - Kohistan Island Arc and Northwest Himalayas is the single most important and also the major potential source of water and power in Pakistan. Most of the future high dams, barrages and bridges are planned to be sited on this river (Fig.1). This activity will require billions of cubic feet of concrete, more than two thirds of which will be comprised of Indus aggregate.

Aggregate may limit the strength of concrete, its durability and structural performance. Aggregate has generally been considered as an inert material. In actual practice, aggregate is far from inert in its characteristics and exerts a profound influence on the performance and durability of concrete. Indus aggregates have shown excellent physical characteristics and are designated as most suitable for concrete (Chaudhry et al. 1992, Chaudhry and Zaka 1994). However in service behaviour of concrete fabricated from Indus aggregates have shown the development of significant distress mainly due to expansion resulting in microfractures, fractures, misalignment and rotation of concrete members. The stress is very often related to AAR .

The evidence of alkali aggregate reaction in concrete structures of Tarbela and Warsak Dams has raised concern over the future safety of the concrete structures to be built with Indus and similar aggregates in Pakistan. Sampling from Indus River bed, its terraces and from Tarbela and Warsak Dams has been carried out to identify the deleterious rock and mineral types and to understand the phenomenon of alkali aggregate reaction in already placed concrete.

## GENERAL GEOLOGY OF THE UPPER INDUS RIVER CATCHMENT

The terrane through which Indus River flows is geologically very complex. The mountain chains comprising this area have been formed by India-Eurasia collision (Patriat and Achache 1984), there by trapping the Kohistan-Ladakh Island Arcs . The Indus River orginates east of Karakoram from Kailas Mountains of south west Tibet. In Ladakh region it flows along and close to the Indus Psngpo Suture Zone for about 300 km and then cuts across the Ladakh Kohistan batholith complex. With intervening promontory of Nanga Parbat Haramosh Massif. Near Jijal it flows across the Higher and Lesser Himalayas upto Tarbela and cuts across the outer Himalaya about 30Km south of Attock. For simplification the terrane has been divided into three geological domains namely Northwest Himalaya, Kohistan and Karakoram. In the text below a brief of the general geology of the Upper Indus River catchment comprising these domains is presented:

### Northwest Himalaya

The Northwest Himalaya may be subdivided into five zones. A brief description of rock types that cropout in these lithostratigraphic divisions is given below:

***Tethys Himalaya :*** This thin slice of low grade slates, pelites and calcpelites, of Bachh and Richhpar sequence of Kaghan, the Banna sequence of Kohistan and the Karora sequence of Swat occurs as a narrow belt between H.H.C. and the Main Mantle Thrust (Chaudhry et al. 1994, Ghazanfar 1993).

***Higher Himalaya :*** The Higher Himalaya which lies between Trans Himadri Fault (THF) and Main Central Thrust (MCT), (Ghazanfar 1993, Chaudhry et al. 1994a, 1994b) is composed mainly of psammite, calc-pelites, marbles, sheet granites and subordinate sheets and dykes of amphibolite metamorphosed to upper amphibolite and at places to eclogite facies (Spencer 1993, Spencer et al. 1990). The Higher Himalayas include areas between MMT and areas north of Batal near Naran in Kaghan Valley and north of Luat in Neelum Valley, the Besham Block and areas north of Girarai in Swat and Malakand Pass. The MCT passes close to the localities mentioned and constitutes the southern boundary of the Higher

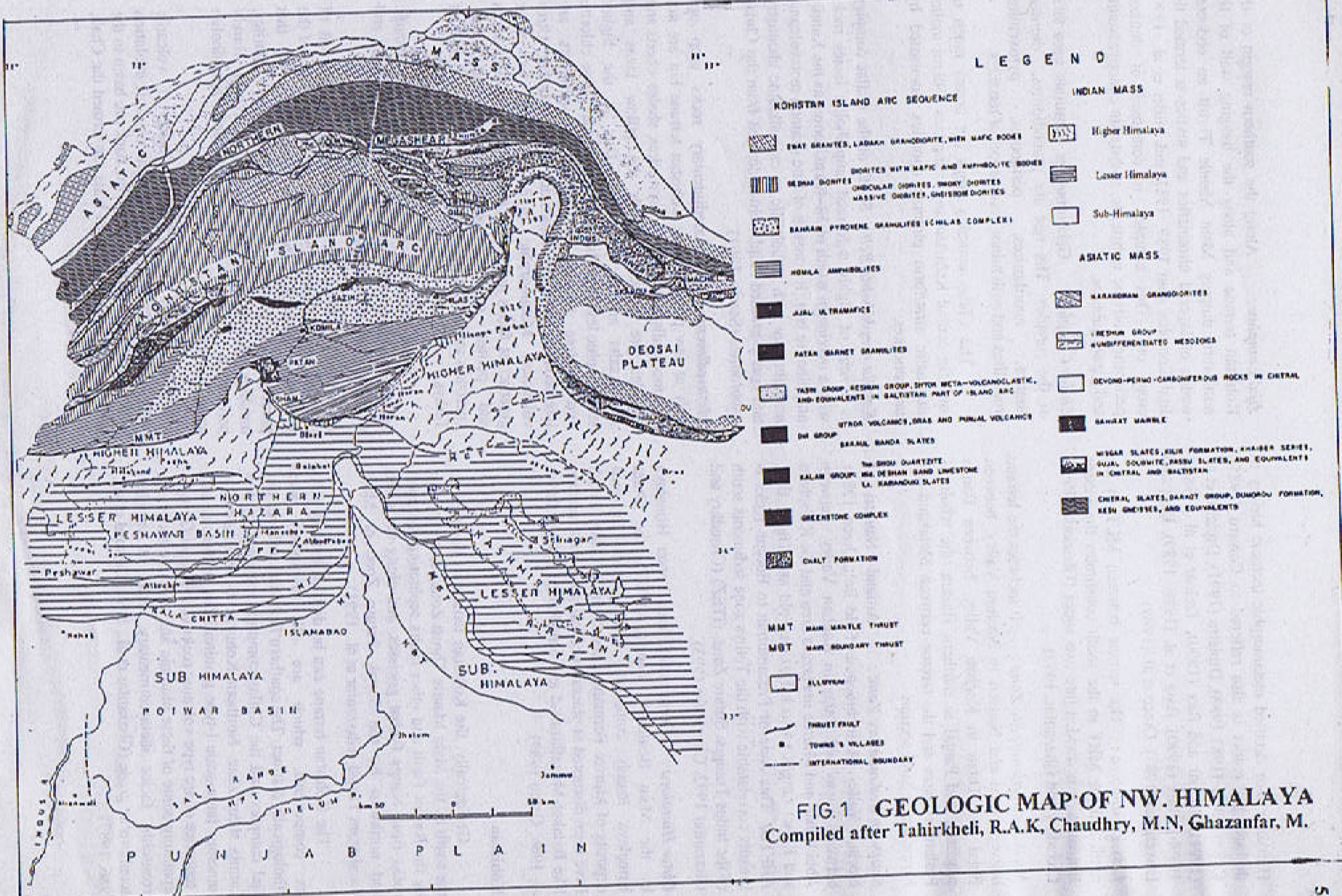


FIG.1 **GEOLOGIC MAP OF NW. HIMALAYA**

**Compiled after Tahirkheli, R.A.K, Chaudhry, M.N, Ghazanfar, M.**

Himalaya. For detailed metamorphic tectonic history of the area the reader is also reffered to Coward (1985), Coward et al. (1982,1988), Dipietro (1991), Dipietro et al. (1991), Treloar and Rex (1990), Treloar et al. (1989a, 1989b), Baig (1990), Baig et al. (1988, 1989), Baig and Lawerence (1987), Greco et al. (1989).

***Lesser Himalaya*** : The terrane between MCT in the north and the MBT in the south constitutes the Lesser Himalaya. It is divided into two zones (Ghazanfar 1993; Chaudhry and Ghazanfar, 1992).

***Northern Metamorphic Zone :*** It includes the terrane between Luat and Nauseri in Neelum Valley, between Batal and Tutan in Kaghan Valley, between Banna sequence and Panjal in northern Hazara, the whole of Peshawar Basin and the terrane between Malakand and Nowshera in Swat section.

***Southern Sedimentary Zone :*** Around Nauseri in Neelum Valley (Autochthonous Fold Belt Greco 1986), between Tutan and Paras in Kaghan Valley, between Abbottabad and Murree in Hazara area and the Kalachitta and Kohat ranges (Attock-Hazara Fold and Thrust Belt, AHFTB). This zone of Precambrian to Eocene rocks is broadly correlatable with the Tethys zone sediments south of the Indus Tsangpo Suture Zone, (ITSZ) (Chaudhry and Ghazanfar 1992, Ghazanfar 1993).

***Outer Himalaya :*** Demarcated from Lesser Himalaya by the Main Boundary Thrust, (MBT), the Outer Himalaya mainly comprises red molassic foredeep deposits of Murree Formation and Siwalik Group which have been disrupted at places to reveal upthrust structures like Balakot-Muzaffarabad and Salt Range (Ghazanfar et al. 1986; Greco 1989).

**Kohistan**

Geologically, the Kohistan terrane is bounded to the south by the Main Mantle Thrust Zone, along the east by the Raikot Fault and other faults separating Kohistan rocks from Nanga Parbat gneisses, and along the north and northwest by the Shyok Suture Zone or Main Karakoram Thrust (Ghazanfar et al., 1991).

The Kohistan terrane can be divided broadly into six components, which are all structurally and lithologically distinct. The southern Kohistan includes the Jijal complex and the Chilas complex separated by the Kamila shear zone. Northern Kohistan is dominated by numerous large-scale I-type granitoid-diorite plutons and a sequence of arc type volcanic rocks (Dir-Kalam Group). Separating some of these plutonic and volcanic rocks are greenschist facies metasedimentary rocks of variable metamorphic grade (Ghazanfar et al., 1991; Coward et al., 1986, 1987).

***Jijal Complex :*** Along the southern margin of the Kohistan terrane and along the hanging wall of the northward dipping Main Mantle Thrust an obducted wedge of layered ultramafics and mafics is termed the Jijal Complex (Jan 1989, 1981 and Miller et al., 1990) crops out. This complex is composed of dunites, peridotites, olivine websterite, websterite clinopyroxenite and garnet gabbros.

***Chilas Complex :*** Gabbronovites constitute upto 90% of the complex. The rest are granodiorites, diorites, dunites, anorthosites, peridotites, pyroxenites, troctolites,and with minor occurrences of tonalites.

The Chilas complex crops out across much of southern central Kohistan and comprises (10km) mafic-ultramafic stratiform plutonic complex dominated by gabbronorites.

***Kamila Amphibolite Belt*** : South of the Chilas complex is a zone of highly deformed amphibolite facies rocks with a maximum width of 38-40km known as the Kamila amphibolite belt. It consists of fine grained metavolcanic amphibolites with a tholeiitic to calc-alkaline chemistry and coarse-grained amphibolites derived from the Chilas gabbronites (Searle, 1991).

***Metasediments :*** Metasedimentary rocks crop out only at few places in the Kohistan terrane but are not volumetrically significant. Greywackes, shales, cherts and marbles are associated with the pillow lavas and metabasalts around Utror and Dir, at the higher stratigraphic levels of the Kohistan terrane. These chlorite and epidote beating low-grade metasediments are interbedded with the andesitic to rhyodacitic Utror volcanics. Metamorphic grade increases to upper greenschist facies in northern Kohistan, where psammites and pelites represent metamorphosed sandstones, quartzites and shales deposited within the northern part of Tethys.

These sediments are lithic arenites with volcanic and cherty clasts, volcanogenic slates and phyllites and quartzites with deleterious quartz polymorphs.

***Kohistan Batholith*** : The northern and southern part of the Kohistan terrane is dominated by plutonic rocks of the Kohistan batholith. The main lithologies of this predominantly plutonic arc are diorites, quartz diorites, tonalites, granodiorites and granites of I type. Rarely peridotites, dunites, hornblendites and amphibolite screens also occur.

***Kohistan Volcanic Arc :*** Several belts of volcanic rocks crop out across Kohistan and the volcanic evolution of both the Kohistan terrane and the back arc basin to the north is complex. Three main belts are termed the Chalt, Shamran (or Ghizar) and Dir Volcanic groups (Searle, 1991).

**Karakoram**

The Karakoram Mountains form the southern margin of the collage of plates and terrane that made up Asia prior to the final closing of Tethys and the main India-Asia collision during the Eocene (Searle, 1991).

This terrane is composd of a pelite-psammite-granitoid basement with overlying pelitic and carbonate cover rocks with amphibolites followed southwards by a Palaeozoic to Mesozaic package. The latter low grade sediments are composed of slates and meta-graywacke sequences overlain by a thick sequence of shelf carbonates. This sequence is intruded by the Karakoram Axial Batholith.

## ENGINEERING CHARACTERISTICS

The intended use of an aggregate determines the engineering properties which are likely to be important in relation to its performance. As the several demands on aggregate call for different characteristics, a wide range of tests has been devised to describe the material and to assess its potential value. Few important physical tests were performed to evaluate the engineering characteristics of Indus aggregate, which are discussed in the following.

**Gradation**

Sand and gravel of excellent physical properties occur in the terraces and bed of the Indus River. Required gradation of coarse aggregate can be obtained after processing and crushing oversize clasts.

**Abrasion Resistance**

The abrasion resistance losses measured range from 5.0% to 19.8% (Table-12)

**Specific Gravity and Water Abrasion.**

The average values of specific gravity of the tested samples range from 2.68 to 2.81 and maximum water absorption is 0.60.

**Soundness Test**

The weighted average percent losses of aggregate range from 0.47% to 0.95%.

## INSERVICE BEHAVIOUR

**Alkali Aggregate Reaction at Tarbela Dam**

Tarbela dam was built in 1976 on River Indus in Northwest Frontier Province of Pakistan. The Indus aggregate was considered non-deleterious and was used with Ordinary Portland Cement (OPC) having alkali level ranging from 0.91% to 1.03% (Table-11). Samples of coarse as well as fine aggregate from river bed as well as terraces of river at Tarbela were studied by Mielenz in order to evaluate AAR potential (Tams Report 1966). The results are given in Tables 1 & 2.

Mielenz regarded these aggregate as non deleterious if used with OPC. Later on he (Mielenz, 1979 petrographic examination of samples of concrete from Tarbela Dam Pakistan. Unpublished report for WAPDA) identified alkali aggregate reactions in the service spillway chute and in the auxiliary spillway approach slab. Inservice behaviour of Indus aggregate in Tarbela Dam concrete proved Mielenz's alkali aggregate reaction potential evaluation incorrect. Subsequent studies carried out by the authors identified the type of the AAR and established its causes (Chaudhry & Zaka 1994).

***Petrographic Evaluation of Indus River Aggregate-Tarbela :*** The coarse as well as fine aggregate were analysed in detail in accordance with ASTM Designation C295 1996. The weighted average compositions of coarse as well as fine aggregate is given in Tables 3 and 4. The potentially deleterious types identified are acid to intermediate merrocrystalline volcanics, microfractured quartzite, phyllite / slate, metagreywacke group and small amount of chert.

***Petrographic Evaluation of AAR Affected Cores :*** Five concrete cores and pieces taken from service spillway, right stair stilling basin, service spillway chute, gate passage and transition tunnel were examined. They were examined megascopically, under 10 and 20 magnifications, under stereomicroscope and in thin sections and grain mounts under petrographic microscope. The modal analysis of the samples are given in Tables 5 and 6. Petrographic examination of concrete cores showed the following features :-

i) Darkened reaction rims around some potentially deleterious rock types were identified.

ii) Microfractures filled with hardened alkali aggregate gels and air void filled with ettringite were identified.

iii) Embayed grains and croded boundaries of some clasts were identified.

iv) Deterioration due to A.A.R. of the exposed surfaces of cores were obvious with the development of abundant carbonates and some alkali aggregate gel.

There are three main types of reactions between aggregate and alkali in the concrete. These are as under :-

i) Alkali reaction with amorphous microcrystalline silica (A.S.R.)

ii) Alkali reaction with silicates caused by reactions in polyphase siliceous aggregates (A.St. R).

iii) Alkali reaction with argillaceous dolomitic carbonates (A.C.R.).

In case of Tarbela and Warsak Dams, we identified Alkali Silica Reaction (A.S.R.) and no evidence of alkali carbonate or alkali silicate reaction was noticed.

**Warsak Dam**

The Warsak Dam is located about 20 miles north-west of the historic city of Peshawar and to the north of the well known Khyber Pass. It was completed in early 1960. It is about 750 feet long, 235 feet high and 210 feet wide at the foundation. About 1.2 million cubic yards of aggregate was used for the construction of dam. Both coarse and fine aggregates were taken from the bed of the Kabul River.

Since the commissioning of the four power units in 1960 the power house showed signs of what was initially considered to be differential settlement in the form of opening of construction joints and cracks that developed in the floor and walls.

After the development of cracks in concrete, instruments were installed by Dams Monitoring Organization (DMO), WAPDA during 1975 to monitor the development of these cracks and associated movements. M/s Golder Associates were associated with these studies from 1984-86 who installed additional instruments. Instruments were subsequently increased as required from time to time. Their related details are given as under :-

| Pin No. | Movements upto 15 Nov. 1980 (Inches) | Movements upto 15 Nov. 1984 (Inches) | Movements upto 15 Feb. 1988 (Inches) | Movements upto 15 Feb. 1989 (Inches) |
|---|---|---|---|---|
| L1 | 0.045 | 0.115 | 0.175 | 0.196 |
| L2 | 0.198 | 0.382 | 0.51 | 0.525 |
| L3 | 0.245 | 0.453 | 0.63 | 0.655 |
| L4 | 0.335 | 0.52 | 0.725 | 0.75 |
| L5 | - | 0.1075 | 0.22 | 0.23 |
| L6 | - | 0.025 | 0.0325 | 0.04 |

***Studies Carried Out :*** Golder Associates (Dec. 1986) carried out a preliminary examination of the river aggregate and cores obtained from the affected parts of the dam. According to them "Petrographic analysis of the aggregate revealed that it consisted of approximately 60% of granite, gneiss and quartzitic rock types; 20% carbonate rocks (including limestones) and the remaining 20% less durable rock types including schists, argillites and phyllites".

It was further pointed out that "In isolated areas some direct evidence of alkali aggregate reaction was noted characterized by the presence of silica gel." According to Golder Associates (Dec. 1986). "In general, the exposed concrete surfaces over the Project look sound and showed little signs of deterioration in the form of scaling or spalling, however most areas exhibited random cracking."

We carried out petrographic studies of natural aggregate sampled from Kabul River and AAR affected cores. Summary of detailed studies is presented in the following text:

***Petrography :*** The petrographic studies were carried out by the authors in accordance with ASTMC-295. The composition of the fine and coarse aggregate of the bed of Kabul River, from which aggregate was extracted for the construction of the dam is presented in Tables 7 and 8. Six core samples were also analyzed petrographically to determine the composition of the aggregate present in the concrete undergoing deterioration. The composition of fine aggregate was determined using point counting techniques. The composition of coarse aggregate was determined by classifying the pieces/pebbles of coarse aggregate. The modal analysis of coarse and fine aggregate of the representative cores is give in Tables 9 and 10. The deleterious constituents in the aggregate are phyllite/slate. micro fractured and strained quartzite, strained quartz, acid to intermediate merrocrystalline meta volcanics and chert. The deleterious rock types and their percentages are indicated by an asterisk in the tables.

i) The cores were examined visually and by hand lens having magnifications of 10x and 20x.

ii) The cores were also examined under binocular stereo microscope. The examination revealed cracks and microcracks filled with hardened alkali silica gel deposits. The fractures may cut both the pebbles and the paste. Some zones were clearly carbonitized and had pale colours. Some parts show open fractures with copious white deposits. These carbonitized zones were fairly strongly affected by ASR. Some reactive grains have dark reaction rims around them. A few fragments of phyllite and microfractured quartzite with corroded surfaces were seen.

A total of 20 thin sections were examined under polarizing microscope. The following observations were made. A few pores and microfractures are filled with hardened alkali silica gels. Some strained quartz grains (Buck, 1983), quartzite and phyllite/slate fragments developed ASR on their margins. The carbonitized parts are generally more strongly affected by ASR than the non carbonitized parts. Expansive processes developed through deleterious reactions produced microfractures which may cut both the grains and the paste.

The reaction products were extracted and studied microscopically. Most of these turned out to be a mixture of hardened alkali silica gels, ettringite and carbonates.

Table-1

Petrographic examination of sand from tarbela dam

Constituents Amount as Number of Particles (percent) In the Fractions Shown Below.

| Aggregate | No. 4-8 | No. 8-16 | No. 16-30 | No. 30-50 | No 50-100 | In the Whole |
|---|---|---|---|---|---|---|
| Granitic rocks and gneiss | 24.1 | 18.0 | 42.2 | 28.3 | 22.5 | 28.3 |
| Weathered granitic rocks and gneiss rocks and gneisses | 8.7 | 8.7 | 6.2 | 2.2 | 0.9 | 3.1 |
| Deeply Weathered granitic rocks and gneisses | - | 0.6 | - | - | - | Trace |
| Hornfelds | 4.2 | 5.5 | 3.3 | 4.0 | 1.5 | 3.2 |
| Weathered schists | 4.2 | 4.8 | 3.6 | 2.5 | 2.8 | 3.0 |
| | 2.9 | 5.8 | 0.3 | 0.3 | | 0.6 |
| Sub graywackes and metasubgraywacke | 13.5 | 12.2 | 5.9 | 1.9 | 2.8 | 4.0 |
| Weathered subgraywackes and metagraywackes | 7.1 | 5.1 | 1.3 | - | - | 0.8 |
| Axdesite porphyries | - | 0.3 | - | - | - | Trace |
| Dacite porphyries | 0.3 | - | - | - | - | Trace |
| Phyllites | 10.3 | 12.6 | 2.0 | 1.5 | 0.9 | 2.3 |
| Weathered phyllites | 0.6 | 2.3 | 0.3 | - | - | 0.2 |
| Limestone | 6.8 | 5.5 | 1.0 | - | - | 0.8 |
| Pourous limestone | 1.6 | 1.3 | - | - | - | 0.2 |
| Feldspars | 0.3 | 1.6 | 6.2 | 12.4 | 11.7 | 10.0 |
| Micas | - | 1.9 | 7.2 | 7.1 | 7.7 | 6.7 |
| Heavy minerals, mainly hornblende, magnatite, and epidote | - | - | 1.3 | 5.0 | 6.5 | 4.3 |
| Quartz, quartz schists. | 15.4 | 13.8 | 19.2 | 34.8 | 42.7 | 32.5 |

BY Mielenz, Tarbela

Table-2
Petrographic examination of gravel from tarbela dam
Amount as Number of Particles (percent)
In the Fractions Shown Below

| Constituents | 1,1/2" to 3/4" | 3/4" to 3/8" | 3/8" to 3/16" |
|---|---|---|---|
| Granitic rocks and gneisses | 48.9 | 36.6 | 28.4 |
| Weathering granitic rocks and gneisses | 5.9 | 6.3 | 10.7 |
| Deeply weathered granitic rocks and gneisses | - | 0.3 | 0.3 |
| Homfels | 3.8 | 5.0 | 4.7 |
| Diabases and gabbros | 0.4 | 0.3 | - |
| Hard schists | 3.0 | 5.7 | 3.3 |
| Weathered schists | 0.8 | 1.3 | 1.3 |
| Quartz, quartz schists, and quartzites | 11.0 | 10.0 | 11.0 |
| Subgraywackes and metasubgraywackes | 6.8 | 7.3 | 15.7 |
| Weathered subgray-wacke and metasubg-raywackes | 5.9 | 7.0 | 9.3 |
| Andesite porphyries | 0.4 | 0.3 | 0.3 |
| Decite porphyries | 0.8 | 0.7 | - |
| Phyllites | 2.1 | 6.3 | 5.7 |
| Weathered phyllites | - | 2.7 | 1.0 |
| Limestones | 10.2 | 10.2 | 8.3 |

By Mielenz, Tarbela

Table-3
Modal composition of the coarse aggregate:
Indus river near tarbela

| | |
|---|---|
| Amphibolite/Foliated Diorite: | 7.6% |
| Granodiorite/Granite: | 16.1% |
| Graywacke Group* | 13.7% |
| Quartzite/Micaceous Quartzite: | 13.0% |
| Schist/Subschist: | 7.4% |
| Acid to Intermediate Volcanics.* | 6.8% |
| Phyllite.* | 5.5% |
| Carbonates: | 4.2% |
| Garnet Amphibolite: | 2.4% |
| Basic Volcanics: | 2.2% |
| Diabase: | 0.9% |
| Chert.* | 0.2% |

Table-4
Composition of fine aggregate:
Indus river near tarbela

| | |
|---|---|
| Quartz/Quartzite/Micaceous Quartzite: | 30.5% |
| Granite/Granodiorite: | 20.2% |
| Amphibolite/Foliated Diorite: | 10.7% |
| Feldspar: | 10.0% |
| Micas: | 5.8% |
| Graywacke Group.* | 5.3% |
| Amphibole: | 4.6% |
| Schist: | 4.0% |
| Phyllite/Slate* | 3.3% |
| Iron Ore: | 1.3% |
| Epidote: | 1.3% |
| Carbonates: | 1.2% |
| Volcanics* | 0.6% |
| Garnet: | 0.3% |
| Sphene: | 0.3% |
| Chert* | 0.2% |
| Tourmaline: | 0.2* |
| Appetite: | 0.1% |
| Zircon: | 0.1% |

*potentially deleterious minerals/rocsk types

Table-5

Modal Composition of Fine Aggregate (Cores)

Tarbela Dam

| | |
|---|---|
| Qiuartz/Quarzite/Micacceous Quarziute: | 31.9% |
| Granite/Granodiorite: | 18.7% |
| Feldspar: | 11.5% |
| Amphibolite/Fdiated Diorite: | 9.0% |
| Micas: | 6.0% |
| Greywacke Group:* | 5.6% |
| Amphibole: | 4.8% |
| Schist: | 4.3% |
| Phyllite/Slate:* | 3.5% |
| Iron Ore: | 1.5% |
| Carbonates: | 0.8% |
| Volcanics:* | 0.7% |
| Epidote: | 0.7% |
| Garnet: | 0.4% |
| Chert.* | 0.2% |
| Sphene: | 0.2% |
| Tourmaline: | 0.1% |
| Apatite: | 0.1% |
| Zircon: | Tr |

Table-6

Modal Composition of Coarse Aggregate (Cores)

Tarbela Dam

| | |
|---|---|
| Amphibolite/Foliated Diorite: | 22.8% |
| Granodiorite/Grranites: | 16.3% |
| Acid to intermediate Volcanics:* | 13.7% |
| Greywacke group:* | 12.4% |
| Quartzite/Micasseous Quartzite: | 2.0% |
| Phyllite/Subphylite:* | 6.0% |
| Schist: | 5.9% |
| Carbonate: | 4.0% |
| Basic Volcanics:* | 3.5% |
| Garnet Amphibolite: | 2.3% |
| Diabase: | 0.5% |
| Homfelse: | 0.4% |
| Chert:* | 0.2% |

* Potentially deleterious minerals/rock types

Table-7

Model Composition of Coarse Aggregate

Kabul River Bed

| | |
|---|---|
| Schist | 11.6 |
| Phyllite/Slate* | 8.8 |
| Amphibolite/Amphibole Gneiss | 23.0 |
| Quartzite | 20.9 |
| Granite/Granite Gneiss | 21.5 |
| Microfractured and Strained Quartzite* | 7.8 |
| Acid to intermediate Volcanics with * Microcrystalline Matter* | 2.6 |
| Limestone | 3.0 |
| Chert* | 0.8 |

Table-8

Model Composition of Fine Aggregate

Kabul River Bed

| | |
|---|---|
| Quartz | 35.2 |
| Amphibole | 12.3 |
| Plagioclase/Albite | 7.9 |
| Amphibolite/Amphibole Gneiss | 7.0 |
| Orthoclase/Microcline | 6.4 |
| Quartzite | 5.2 |
| Schist | 3.5 |
| Granite/Granite Gneiss | 4.1 |
| Phyllite/Slate* | 2.0 |
| Magnetite | 1.3 |
| Biotite | 2.6 |
| Strained Quartz* | 3.5 |
| Microfractured and strained Quartzite* | 2.7 |
| Muscovite | 1.0 |
| Chlorite | 0.6 |
| Limonite | 0.8 |
| Garnet | 0.5 |
| Acid to intermediate Volcanic with Microcrystalline Matter* | 1.1 |
| Limestone | 1.6 |
| Sphene | 0.2 |
| Chert + Microcrystalline Quartz* | 0.5 |
| Tourmaline | Tr |

*Potentially deleterious minerals/rock types.

Table-9
Model Composition of Coarse Aggregate (Cores)
WARSAK DAM

| Mineral/Rock Type Core | Core No.1 | Core No.2 | Core No.3 | Core No.4 | Core No.5 | No.6 |
|---|---|---|---|---|---|---|
| Schist | 10.3 | 8.8 | 11.8 | 13.2 | 12.3 | 10.4 |
| Phyllite/Slate* | 7.5 | 7.6 | 8.5 | 9.7 | 9.5 | 10.1 |
| Amphibolite/ Amphibole Gneiss | 21.8 | 22.1 | 22.0 | 25.2 | 20.6 | 23.8 |
| Quartzites | 29.0 | 26.9 | 24.6 | 23.8 | 20.1 | 21.3 |
| Granite/Granite Gneiss | 20.1 | 20.0 | 21.3 | 15.0 | 23.0 | 20.5 |
| Microfractured and strained Quartzite* | 5.9 | 6.1 | 6.1 | 7.3 | 7.9 | 7.5 |
| Acid to intermediate Volcanics with Microcrystalline Matter* | 2.0 | 2.7 | 2.3 | 2.8 | 3.0 | 3.1 |
| Limestone | 3.0 | 5.5 | 2.8 | 2.3 | 2.9 | 2.5 |
| Chert* | 0.4 | 0.3 | 0.6 | 0.7 | 0.7 | 0.8 |

*Potentially deleterious minerals/rock types.

Table-10
Model Composition of Fine Aggregate (Cores)
WARSAK DAM

| Mineral/Rock Type | Core No.1 | Core No.2 | Core No.3 | Core No.4 | Core No.5 | Core No.6 |
|---|---|---|---|---|---|---|
| Quartz | 39.3 | 35.9 | 38.8 | 39.5 | 41.3 | 39.0 |
| Amphibole | 12.1 | 10.9 | 13.3 | 10.6 | 9.6 | 11.7 |
| Plagioclase/ Albite | 8.7 | 8.1 | 8.5 | 9.7 | 8.5 | 8.5 |
| Amphibolite/ Amphibole Gneiss | 8.3 | 9.2 | 8.7 | 7.0 | 7.6 | 8.0 |
| Orthoclase/ Microcline | 6.5 | 6.7 | 6.6 | 5.9 | 5.9 | 6.8 |
| Quartzite | 6.0 | 6.3 | 4.9 | 6.2 | 5.0 | 6.3 |
| Schist | 3.4 | 3.7 | 3.0 | 3.0 | 3.8 | 3.2 |
| Granite/Granite Gneiss | 3.3 | 3.9 | 3.2 | 2.9 | 3.2 | 3.1 |
| Phyllite/ Slate* | 2.0 | 2.6 | 1.8 | 1.8 | 2.3 | 2.0 |
| Magnetite | 1.9 | 1.3 | 1.3 | 2.0 | 1.7 | 1.6 |
| Biotite | 1.7 | 2.0 | 2.3 | 2.3 | 2.2 | 1.5 |
| Strained Quartz* | 1.7 | 2.5 | 1.6 | 2.0 | 1.5 | 2.2 |
| Microfractured and Strained Quartzite* | 1.0 | 1.4 | 1.3 | 1.4 | 1.6 | 1.8 |
| Muscovite | 0.8 | 1.1 | 1.4 | 1.5 | 1.3 | 1.0 |
| Chlorite | 0.8 | 0.7 | 0.8 | 1.2 | 1.1 | 0.7 |
| Limonite | 0.6 | 0.5 | 0.5 | 0.5 | 1.0 | 0.5 |
| Garnet | 0.5 | 0.5 | 0.6 | 0.7 | 0.7 | 0.6 |
| Acid to intermediate Volcanics with Microcrystalline matter* | 0.4 | 0.6 | 0.5 | 0.5 | 0.6 | 0.7 |
| Limestone | 0.5 | 1.5 | 0.4 | 0.6 | 0.5 | 0.5 |
| Sphene | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| Chert/Microcrystalline Quartz* | 0.2 | 0.3 | 0.3 | 0.3 | 0.4 | 0.2 |
| Tourmaline | 0.1 | 0.1 | Tr | 0.2 | Tr | Tr |

*Potentially deleterious minerals/rock types

**Table-11**

Typical summary of test Results of coments Used for

Tarbela Dam Construction

| | | Cement Type | SRC | OPC |
|---|---|---|---|---|
| Plant Period | | Associated Cement Wah | Mustehkum Cement | |
| Farooqia | | | | |
| | | | AUG-DEC. 1971 | Nov.Dec 1971 |
| | Range | Average | Range | Average |
| Specific surface (sq-cm/gm) | 3042-3350 | 3220 | 2859-3081 | 2981 |
| Setting time | | | | |
| Initial (minutes) | 130-180 | 153 | 160-205 | 117 |
| Final (minutes) | 180-220 | 193 | 212-296 | 253 |
| Soundness expansion (mm) | 0.5-9.5 | 3.7 | 0.5-1. | 50.9 |
| Compressive Strength three days cubes (psi) | 3190-3480 | 3349 | 4020-4590 | 4195 |
| Chemical analysis(%) | | | | |
| Loss on ignition | 1.10-2.49 | 1.94 | 1.00-1.53 | 1.19 |
| SiO2 | 1.10-2.49 | 1.94 | 1.00-1.53 | 1.19 |
| | 21.25-22.9 | 21.77 | 20.70-21.3 | 21.06 |
| Al2O3 | 3.30-3.95 | 3.55 | 6.23-6.68 | 6.48 |
| Fe2O3 | 4.05-4.54 | 4.37 | 2.50-2.68 | 2.62 |
| CaO | 64.42-65.1 | 64.64 | 62.33-63.3 | 62.84 |
| MgO | 1.28-1.32 | 1.30 | 1.90-2.92 | 2.43 |
| SO3 | 1.50-1.96 | 1.75 | 1.84-2.46 | 2.22 |
| Solube Residue | 0.20-0.35 | 0.27 | 0.16-0.20 | 0.11 |
| Sasturation | 0.90-0.95 | 0.93 | 0.88-0.91 | 0.90 |
| C3S | 56.70-66.3 | 62.64 | 38.82-45.5 | 42.30 |
| C2S | 10.80-22.8 | 15.22 | 25.43-31.8 | 28.69 |
| C3A | 1.75-2.81 | 2.08 | 11.99-13.16 | 47.96 |
| C4AF | 12.40-13.8 | 13.29 | 7.60-8.16 | 47.96 |
| Alkali content(%) (Na2 Equivalent) | Not known | | 0.91-1.03 | 0.95 |

Table-12

Engineering characteristics of indus aggregates

a) Engineering characteristics of coarse aggregate

i) Specific Gravity

Range of values 2.68 to 2.81

ii) Water absorption

Maximum water absorption 0.60

iii) Soundness test

Percent losses after 5 cycles of immersion in sodium sulphate 0.47% to 0.95% (ASTM TEST C88 - X)

iv) Abrasion resistance

Abrasion losses range 5.0% to 19.8% (ASTM C-131 and C-535)

b) Engineering Characteristics of Fine Aggregate

i) Soundness Test

Percent losses after 5 cycles of immersion in sodium sulphate 1.56% to 10%

ii) Organic Content

No organic impurities indicated under test USBR Designation 14.

## DISCUSSION

In the following are discussed boundaries of various Himalayan sub-divisions with respect to the potential of alkali aggregate reaction. These transverse sub-divisions have been defined on the basis of major crustal scale shear zones and persist throughout the entire length of Himalayan chain. The boundaries are of special importance because deleterious material of different kinds is being contributed from each region.

The Lesser Himalaya to the south of the Higher Himalayan Block is composed of a northern metamorphic-igneous zone comprised predominantly of porphyritic S-type cordierite granitoids, pelites and psammites. The southern sedimentary zone is comprised of pelites and psammites and a sequence of unmetamorphosed shelf carbonates with minor sandstone and shale horizons. The granitoids, hard schists and medium to high grade psammites of metamorphic zone are innocuous. Slates, phyllites and graywackes in lower greenschist facies are potentially deleterious. Carbonate and sandstone clasts from the sedimentary part are innocuous. However chert clasts from this zone are potentially deleterious. The Balakot Mylonite Zone (B.M.Z) and Oghi Shear Zone (O.S.Z) yield deleterious strained quartz rich clasts. Microfractured quartz clasts derived from Hazara slate and Tanawal Formation of pelite psammite character from Lesser Himalaya are also potentially deleterious since they contain cryptocrystalline quartz along with fracture cleavage developed during the second major deformation phase (D-2, Ghazanfar et al. 1990, Ghazanfar 1993).

The aggregates used at Tarbela and Warsak were considered safe by earlier workers on the grounds that the deleterious rock types like argillites, greywakes, quartzite and acid to intermediate volcanics had undergone metamorphism. We suggest that these rocks have been reconstituted in very low grade metamorphic zone or prehnite-pumpellyite to lower greenschist facies. As such the reactive silica phases and phyllosilicates have not been reconstituted completely to innocuous mineral phases.

## CONCLUSIONS

The Indian plate at the leading edge is composed of Higher Himalayan S-type granitoids, migmatites and a sequence of high grade calc-pelites, marbles, pelites and psammites with layers of amphibolites. Granitoid, migmatite, carbonate, amphibolite and hard schists derived from these blocks are innocuous. Extensive mylonites have developed along Main Central Thrust, Indus Suture Zone and Thakot Fault and rarely within the Higher Himalayan Crystallines (HHC). Quartz rich clasts of mylonites derived from these zones contain highly strained quartz with anomalous optics and are potentially deleterious.

The granitoid, hard schist and medium to high grade psammites derived from Southern Sedimentary Zone are innocuous. Slates, phyllites and graywackes in lower greenschist facies are potentially deleterious. Carbonate and sandstone clasts from the sedimentary part are innocuous. However chert clasts from this zone are potentially deleterious. The Balakot Mylonite Zone (B.M.Z) and Oghi Shear Zone (O.S.Z) yield deleterious strained quartz rich clasts. Microfractured quartz clasts derived from Hazara slate and Tanawal Formation of pelite and psammite character from Lesser Himalaya are also potentially deleterious since they contain cryptocrystalline quartz along fracture cleavage developed during the second major deforamtion phase. The Kohistan terrane yields slightly reconstituted acid to intermediate merro to cryptocrystalline volcanics, pyroclasts and volcanogenic chert/chalcedony and arenites metamorphosed to a very low grade. These are again potentially deleterious. I-type granitoids and amphibolites are innocuous.

The clasts derived from gabbronorite batholith are innocuous.

The two suture zones contribute only small quantities of deleterious clasts derived from bedded/ribbon chert and other flyschoid sediments. Only small quantities of potentially deleterious volcanics and low grade meta-argillites are contributed by this terrane.

The aggregates used in Warsak Dam and Tarbela Dam are similar. Both contain slate/phyllite, microfractured and strained quartzite, acid to intermediate merrocrystalline metavolcanics, metagreywacke group and chert. However Tarbela aggregates contain more graywackes.

The ASR in Tarbela Dam is still at a initial stage and studies are underway whereas ASR in parts of Warsak Dam is in relatively advanced stage.

Indus aggregate from Tarbela to Kalabagh show excellent engineering characteristics. Studies carried out by the authors over a number of years however cast serious doubts on the innocuous nature of these aggregates. However, the aggregates can be safely used for the construction purposes after proper investigations (petrographic and chemical tests), by using low alkali cement and by using natural or artificial pozzolan. The potentially deleterious mineral/rock types are acid to intermediate merrocrystalline meta-volcanics, phyllite/slate, meta-greywacke group microfractured and strained quartzite and chert. The innocuous clasts are I and S type granitoids, diorite, hard schist, amphibolite, limestone, quartzite, dolerite and hornfels.

This study can be used to predict the course of further deterioration likely to occur in Tarbela Dam built sixteen years later than Warsak Dam where ASR has recently been evaluated by Chaudhry and Zaka (1994).

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# SOME NEW INFORMATIONS ON THE GEOCHEMISTRY AND ECONOMIC GEOLOGY OF TIMARGARA AREA, DIR DISTRICT, NWFP

BY

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**Abstract:** *The Timargara quadrangle and a part of adjoining area consisting of about 673 sq.km was remapped to work out structural geology, petrology, geochemistry and economic geology. Accordingly it was found that the amphibolites in northern and southern extreme of the area were the parts of a single ocean floor under which the Kohistan island arc was built and underplated. Discrimination diagrams based on major and trace elements revealed that the arc related rocks such as norite gabbronorites, diorites, tonalites, trondhjemite, adamellites/ granites etc were calcalkaline in nature while Dir amphibolites were of tholeiitic character. Structural studies showed that the rocks of the area were folded into northwards dipping southward verging tight folds near MMT which opened up northwards. The geotechnical properties of norite, diorite and hornblendite showed that they could be used as excellent dimention stones and as aggregates. The aplite and quartz porphyries could be used as raw materials in glass and ceramic industries. Ruby corundum found in pyroxenite of Dir amphibolite can be used as abrasives and as semipraceous to precious stone.*

## INTRODUCTION

Geological remapping of 673 sq. Km area of Timargara- Lal Qila and Wari areas District Dir N.W.F.P. was carried out to reinterpret structural, petrographical, geochemical and economic geological studies. The area lies in the western extremity of Kohistan Island Arc (Fig.1). The area was previously studied by Chaudhry et al.(1974, 1983, 1984), Butt (1983) and Butt et al. (1980). Details on the geology, geochemistry, tectonics, structure and petrogenesis will be presented elsewhere.

## GEOLOGICAL SETTING

The geology of the area can be divided into three stratigraphic provinces which are juxtaposed to each other due to tectonic movements. These include the Indian continental mass, Shamozai greenschist melange and the rocks of Kohistan Island Arc.

Indian mass in the project area is exposed in the Shamozai area. It occupies the southwestern portion of the mapped area and thrust under the greenschist melange. The Indian mass in the project area is composed of para and orthogneisses. The gneisses are highly foliated and banded and are composed mainly of Malakand granitic and associated metasedimentary rocks.

The Shamozai greenschist melange is exposed as a tectonic slice between the gneisses of the Indian mass and the Dir Amphibolites along the Main Mantle Thrust (MMT) at Mir Khan Kandao in Shamozai area. This melange zone trends east west comprising of lenses and blocks of altered and unaltered basic rocks, volcanics and metasediments. Compositionally these lenses and blocks consists of phyllites, carbonates, talc carbonates, serpentinites and quartz porphyries. The phyllites are green to olive green in colour at weathered surface showing $S_1$ and $S_2$ foliations. $S_1$ foliation is well developed whereas $S_2$ foliation is not so prominent.

The Kohistan Island Arc is mainly built up under the Dir Amphibolites. These amphibolites are intruded by norite, gabbronorite, diorite, and their differentiates like tonalite, trondhjemite, granite / adamellite, pegmatites /aplites and quartz porphries. The ultramafic rocks present in the area are of three types 1. wehrlite and pyroxenite bodies in Dir amphibolites, 2. hornblendites and wehrlites and websterites in plutonic sequence. In the following major rock units are described and discussed with respect to field relations, minerals and chemical compositions.

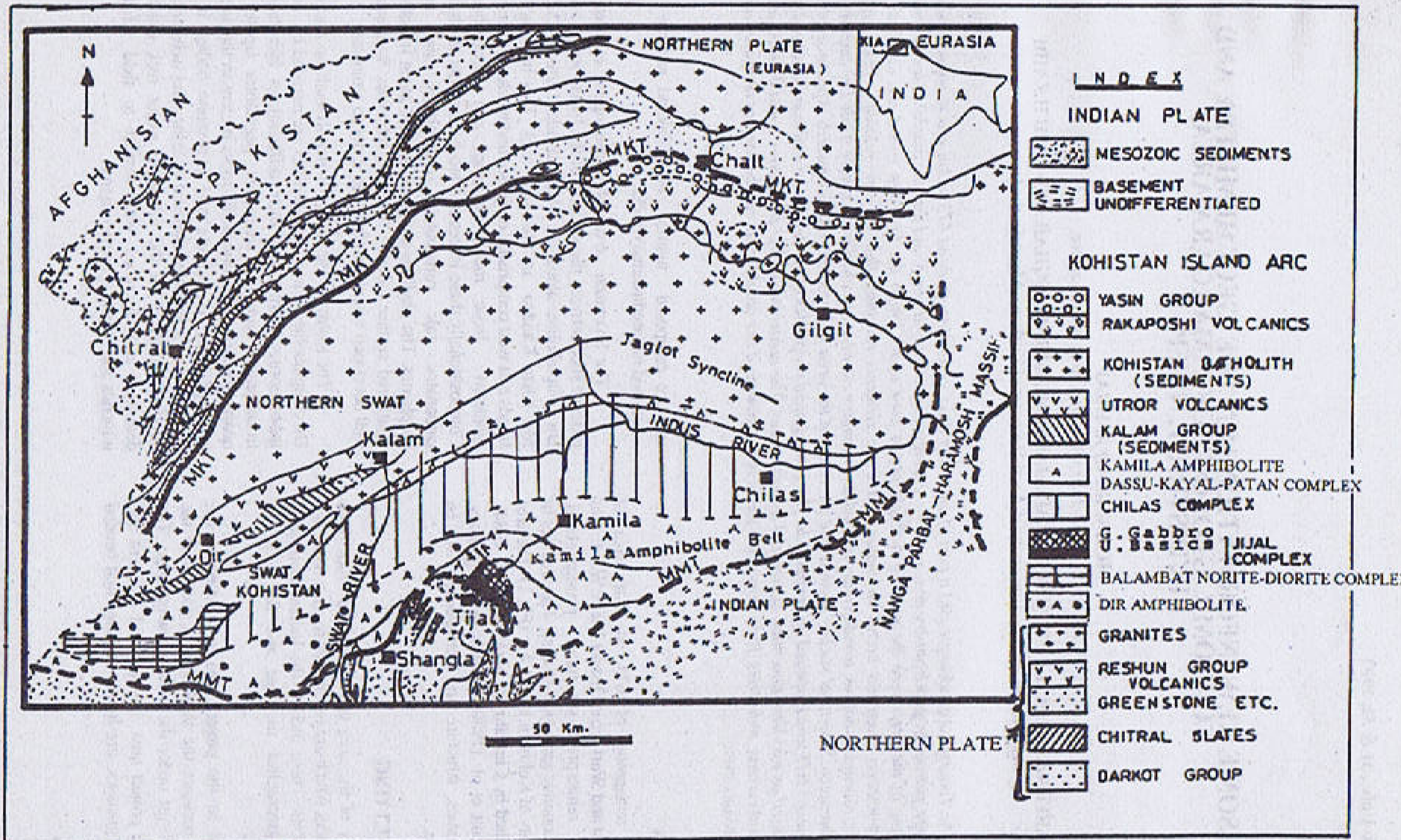



Fig. 1. Geological map of Kohistan Island Arc Complex showing occurrence of Komila Amphibolite Belt in Indus and Swat valleys and Dir Amphibolite in Timargara (modified after S. Hamidullah, 1992)

**Dir Tholeiitic Amphibolites**

The amphibolites exposed in the southern and northern extreme of the mapped area were the parts of a single ocean floor under which the arc was built. These amphibolites were formed by the metamorphism of basic volcanics and pillow lavas of tholeiitic affinities, with subordinate interlayered sediments of argillaceous, arenaceous and carbonate composition. The sediments were deposited on the ocean floor along with lavas at mid oceanic ridge(MOR). The concentration of metasediments in the southern exposure is relatively less and thin (due to nearness to Dargai MOR) as compared to northern part of amphibolites where thick piles of these sediments were evident. The amphibolites exposed in the project area are different from Kamila amphibolites which were formed by the metamorphism of basic plutonic rocks (Loucks et al., 1992). These plutons sucessively underplated the Dir amphibolites, e.g., the Dassu basic complex, Kayal basic complex and the Patan basic/ultrabasic complex. The Dassu complex is highly deformed, polymetamorphosed isoclinally folded banded amphibolite gneisses. The next in succession is Kayal complex which is possibly equivalent to Chilas complex. The Kayal complex is on the southern limb of the Kamila syncline and Chilas on the north. It consists chiefly of garnet-epidote amphibolite with generally strong foliation but only rarely gneissic segregation banding. Relict igneous layering and igneous pyroxene and hornblende are preserved locally in weakly deformed exposures. The Patan complex consist of massive to modally layered and locally crossbedded in the lower part grading to hornblende gabbronorite and diorite in the upper part. The upper part is weakly and locally amphibolitized but becomes increasingly amphibolitized and foliated southwards near the basal boundry fault i.e., the Patan strike slip fault. The basal ultramafics cumulate sequence consisting of serpentinized dunite, wehrlite and clinopyroxenite are exposed in the Dubair village. The contact of Patan complex with Kayal-Chilas complex is an igneous intrusive contact exposed in the village of Khawazakhela in Swat and along the KKH 9 km north of Patan village. The roof of the Kayal-Chilas complex intrudes the gneissic Dassu complex in upper Swat 18 km north of Bahrain and along the KKH 31 km north of Patan and in Khiner Gah 5 km north of Chilas town.

The Kamila amphibolites represent the base of Kohistan Island Arc and are exposed near or around Nangaparbat Syntaxis due to uplifting and uncovering of base rocks. Whereas Dir amphibolites represent the supra crustal material of Kohistan Island Arc under which the arc was built.

The southern part of Dir amphibolites are dominantly composed of fresh and altered plagioclase 20 to 38% (altered to sericite, kaolinite, epidote and chlorite), amphiboles (hornblende 10 to 61%, actinolite 1.5 to 15.5%, tremolite 1 to 5%, cummingtonite 1 to 6% but in shear zones its amount is 17 to 30%, and anthophyllite 1 to 5%) and quartz (2 to 50%). Carbonate metasedimentary layers within these amphibolites contain calcite (10 to 25%) and siderite (18%). Whereas biotite (18%) and garnet (6%) is found in meta argillaceous and arenaceous layers.

The northern part of Dir amphibolites are mainly composed of fresh and altered plagioclose 3 to 47%. (altered to sericite, kaolinite, epidote and chlorite), amphiboles (dominantly hornblende 1 to 68%, actinolite 2 to 52.5% and quartz (3 to 65%). The carbonate metasediments interbeds in these amphibolites contain 8 to 20% calcite, whereas biotite is 0.52 to 31% and garnet is 30 and 33% (In two samples).

From the geochemical studies of Dir amphibolites the major elements which were determined are $SiO_2$ (38.06 to 64.26 wt%), $TiO_2$ (0.07 to 1.3), $Al_2O_3$ (3.34 to 19.54), $Fe_2O_3$ (5.25 to 12.56%), MnO (0.16 to 0.28%), MgO (0.84 to 15.50%), CaO (5.58 to 20.70%), $Na_2O$ (0.03 to 5.0%), $K_2O$ (0.17 to 1.44%), $P_2O_5$ (0.01 to 0.20%) and $Cr_2O_3$ (0.01 to 0.41%). The trace elements in ppm are Ba (38 to 120), Ni (42 to 138), Sr (116 to 182), Zr (25 to 66), Y (12 to 20), Nb (10 to 24) and Sc (24 to 31).

The field and petrographic observations have proved that Dir amphibolites are mainly metavolcanics alongwith interbeds of metasediments. In the discrimination diagrams (Cox and Panhurst, 1979) $SiO_2$ and total alkalies of the amphibolites formed from relict flows and pillows, plot in basaltic field which shows that basaltic nature of the parent material of Dir amphibolites. The $K_2O$-$TiO_2$-$P_2O_5$ diagram (after Pearce et al., 1975), plots of Dir amphibolites show mainly oceanic floor volcanic nature (Fig.2). In AFM diagram

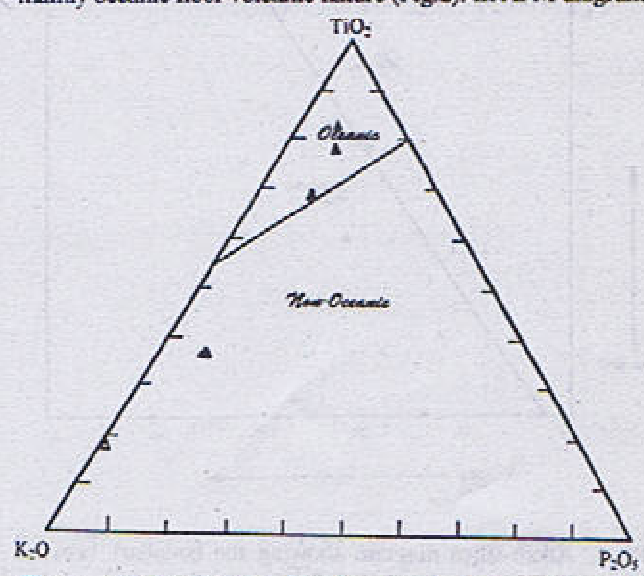



Fig. 2. Discrimination diagram showing the plots of Dir amphibolites falling mostly in oceanic field and rarely in non-oceanic field (after Pearce et al., 1975).

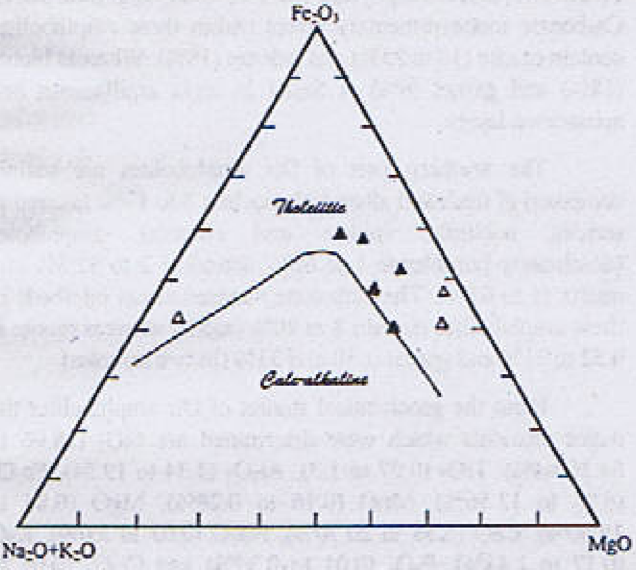



Fig. 3. AFM diagram showing the tholeiitic to calc-alkaline nature of Dir amphibolites (after Irvine & Baragar 1971).

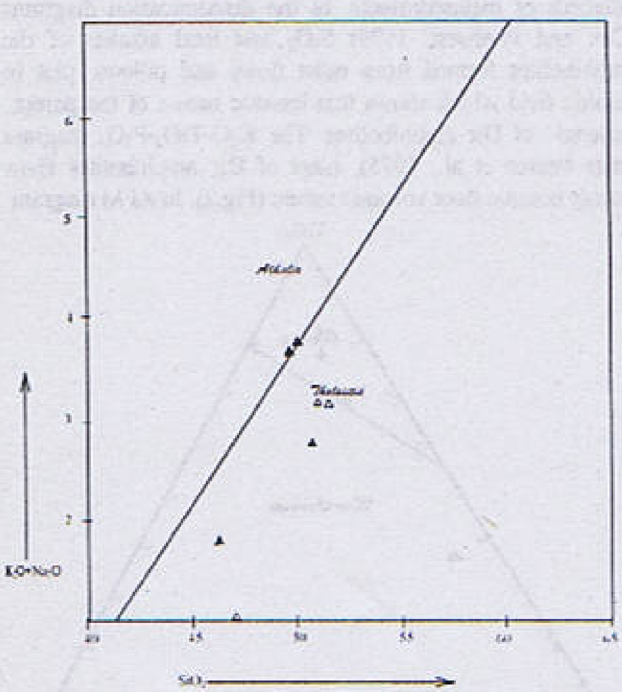
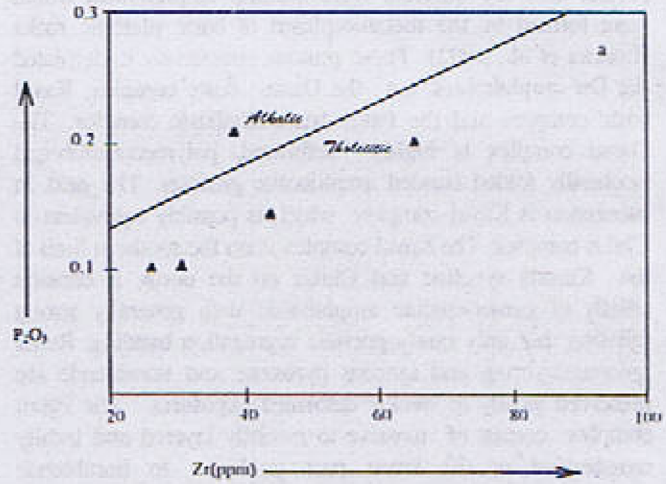


Fig.4. Alkali-silica diagram showing the boundary between tholeiitic and alkalic field. All the plots of Dir amphibolites fall in tholeiitic field (after Mocdonald & Katsura 1964).

(after Irvine and Baragear, 1971) most of the Dir amphibolites plot in tholeiitic field (Fig. 3).The tholeiitic nature of the Dir amphibolite was also proved by alkali- silica diagram plots (Fig. 4) of MacDonald and Katura(1964). The trace elements plots like $P_2O_5$ vs Zr and $TiO_2$ vs $Zr/P_2O_5$ (Winchester and Floyd 1976) show tholeiitic nature of Dir amphibolite(Fig.5) while Cr vs $TiO_2$ plots after Leake,1964) show ortho and para nature of amphibolites. The spider diagram of trace elements of Dir amphibolites shows a positive trough for Sr, K, Ba, Nb, P, Ni and Cr for most of the samples with respect to standard values of Pearce (1983) for MORB.



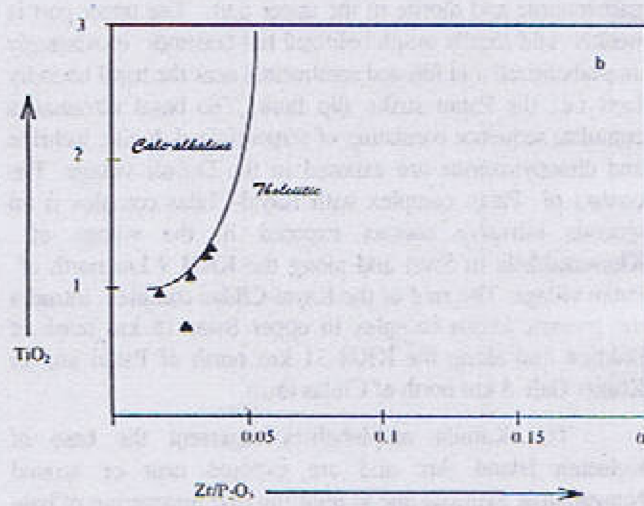




Fig. 5. (a) $P_2O_5$ (wt %) plotted vs Zr (ppm), showing the thleiitic nature of parent basalt of Dir amphibolites.

(b) $TiO_2$ vs $Zr/P_2O_5$ plot also showing tholeiitic nature of parent basaltic material of Dir amphiblites (after Winchester & Floyd 1976).

**The Calc-Alkalic Plutonic Rocks**

The major plutonics rocks exposed in the area consist of norite, gabbronorite, diorite, tonalite, trondhjemite, adamellite/ granite, whereas minor igneous bodies such as quartz porphyries and aplites/pegmatites are intruded in the Dir amphibolites and were exposed due to uplifting and uncovering of amphibolites. But the presence of small and large roof pendant of amphibolite over these plutonic rocks (which previously were called xenoliths and screens of amphibolites) evident the underplating beneath amphibolites by arc related rocks mentioned above.

The petrographic studies of plutonic rocks shows that there is gradational change in mineralogy from norite/gabbronorite towards diorite etc. The amount of quartz increases further from diorite (13.40%), tonalite (20%), trondhjemite (51.5%) to granitě (54.1%) and adamellite (59.3%). This gradational relationship shows that these rocks are not similar to the rocks of Chilas complex. The only difference is that the Dir plutonic rocks are mostly norite/diorite with minor associates of gabbronorite and are more evolved as shown above and are present near to the roof i.e., below the oceanic crust ( Dir amphibolite) of the Neothethys and are of not Chilas magama type, as the Chilas magma type rocks are dominantly gabbronorites with layered ultramafic associates ( Khan et al., 1989 ; Ashraf, 1997 and Ashraf & Ozair, 1997). Some other important features of the Chilas complex as advocated by Khan et al.,(1989) are that the rocks of Chilas crystallized from a single magma chamber. Whereas we believe that the origin of magma for Chilas complex may be of same type but it was feeded from different magma chambers which were formed due to development of Kohistan Island Arc. The Balambat norite / Timargara gabbronorite magma type was however was still different.

The amount of major elements determined by chemical assaying varies from norite/gabbronorite to acidic bodies as $SiO_2$ (52.78 to 70.54 wt%), $Fe_2O_3$ (9.62 to 1.53), MgO (6.08 to 0.59%), CaO (8.06 to 2.7%), $Na_2O$ (2.47 to 3.34%), and $K_2O$ (0.51 to 3.82 %). Whereas $TiO_2$ , $Al_2O_3$ and $Cr_2O_3$ does not show any remarkable variations. MgO, $Fe_2O_3$, CaO and $Al_2O_3$ decreases with increase of $SiO_2$ towards acidic bodies and $Na_2O$ and $K_2O$ increases with the increase of $SiO_2$ towards tonalite and acidic bodies.

AFM diagram(Fig. 6) for plutonic rocks (norites gabbronorites, diorites, tonalite, granites, adamellites, aplites and quartz porphries) display a calc-alkaline nature of these rocks. In Irvine and Baragar(1971) diagram $Al_2O_3$ vs An (Fig. 7) reveal calc-alkaline nature for plutonic rocks. The Bebien (1980) diagram plots $TiO_2$ vs FeO/MgO (Fig. 8) for Dir plutonic rocks classifying them as orogenic rocks showing emplacement of plutonic magma during collision, underplating the Dir amphibolite oceanic crust (of MORB nature).

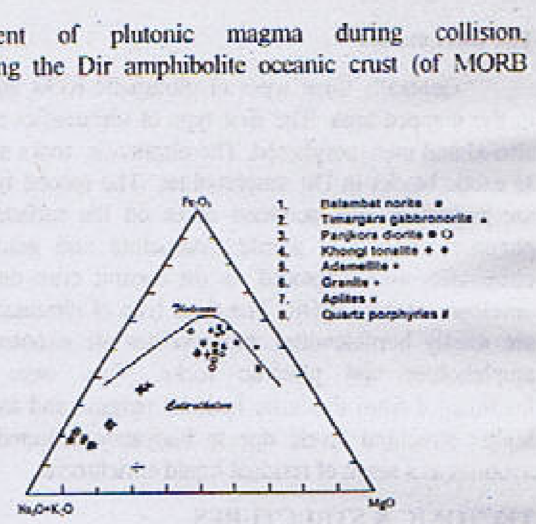



Fig. 6. AFM diagram showing calc-alkaline trend of plutonic rocks of Timargara-Lal Qila area (after Irvine & Barager 1971).

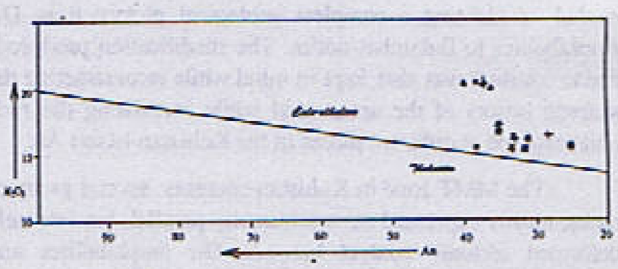



Fig. 7 Discrimination diagram showing plots of plutonic rocks of Timargara-La Qila area in calc-alkaline field (after Irvine & Baragar 1971).

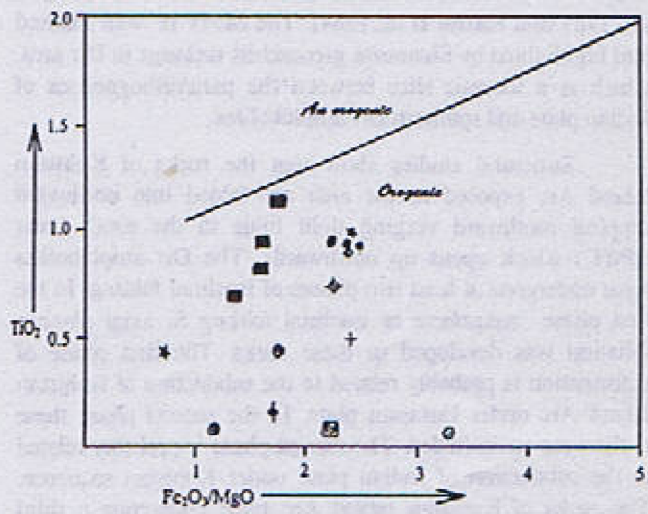



Fig. 8 Location of the plutonic rocks of Timargara-Lal Qila area in Bebien's diagram. All the plots of plutonic rocks fall in the orogenic field of the diagram (Bebien, 1980).

### The Ultramafics

Generally three types of ultramafic rocks are exposed in the mapped area. The first type of ultramafics are highly altered and metamorphosed. The ultramafic rocks are present as exotic blocks in Dir amphibolites. The second type which are present as roof pendents occur on the surface of some plutonic rocks (i.e., diorite, adamellite and granite). The ultramafics were emplaced in the oceanic crust during their development near MOR. The third type of ultramafics which are mostly hornblendites and scyelites are exposed both in amphibolites and plutonic rocks. They were probably fractionated from the basic hydrous magma and ascended to higher structural levels due to buoyancy acquired by their magmas as a result of residual liquid enrichment.

## TECTONIC & STRUCTURES

The collision of Indian plate with Kohistan block has formed most of the structures. The intensity of deformation, uplift and metamorphism is different at different places along the suture therefore, different rocks present at different structural levels are exposed. Most of the cover rocks were eroded evidenting a complete geological picture from Dir amphibolites to Balambat norite. The modification produced due to collision was also kept in mind while reconstructing the tectonic history of the area, and while correlating the rock units exposed at different places in the Kohistan Island Arc.

The MMT zone in Kohistan contains several group of rocks, mostly expressed as a schistocity parallel, but intensely deformed tectonic contact between Dir amphibolites and Indian mass, amphibolites of the Kamila belt and para/orthogneisses of Indian Plate with ophiolitic, layered ultramafics, blue schist and greenshist melanges are at different places along the suture zone ( Ashraf, 1997, Ashraf et al., 1989 and Kazmi et al.,1984). The MMT is well marked and highlighted by Shamozai greenschist melange in Dir area, which is a tectonic slice between the para/orthogneisses of Indian plate and southern Dir amphibolites.

Structural studies show that the rocks of Kohistan Island Arc exposed in the area are folded into northward dipping southward verging tight folds in the south (near MMT.) which opens up northwards. The Dir amphibolites have undergone at least two phases of isoclinal folding. In the first phase recumbent or isoclinal folding $S_1$ axial planner foliation was developed in these rocks. The first phase of deformation is probably related to the subduction of Kohistan Island Arc under Eurasian plate. In the second phase these rocks were again folded. The second phase is probably related to the subduction of Indian plate under Kohistan sequence. The rocks of Kohistan Island Arc have undergone a third phase of deformation resulting into shear zones and consequent retrograde metamorphism of the amphibolites rocks to chloride grade.This phenomenon is most probably related to the collision of Indian plate with Kohistan Island Arc.

The southern part of Dir amphibolites near MMT mostly trend E-W and dips $65^0$ to $80^0$ northwards, which is almost parallel to the trend of MMT. In the central portion of the mapped area, the Kohistan Arc plutonic rocks trend NE to SW and their dips varies from $40^0$ to $70^0$ NW and SE. Most of the fold axes in plutonic sequence are parallel to each other which mostly trend NE to SW and plunges from $12^0$ to $50^0$. The northern part of Dir amphibolites mostly trend NE and dips $50^0$ to $60^0$ SE.

## ECONOMIC GEOLOGY

In this section are discussed the mineral showing and small minerals deposits of industrial importance. We will discuss the use of different rocks as building materials and dimension stones along with their engineering and geotechnical properties.

Geotechnical properties of Balambat norite, Panjkora diorite and hornblendite were obtained having absorption capacity 0.59 to 1.01wt%, soundness 0.85 to 1.05wt%, unconfined compressive strengh 6483 to 8644 PSI and showing very good to excellent degree of polishing. This shows that these rocks could be used as dimension stones as well as aggregates.The best aggregates can be obtaied from the hornblendites which are least altered and with no deletarious associated minerals whereas Balambat norite, Timargara gabbronorite and Panjkora diorite contain most variable amounts ( 5 to 20%) of sericite, kaolinite, etc.The amount of quartz Is about 2 to 10% in norite and gabbronorite but higher amount in diorite. Therefore it is not recommended to use the latter rocks as concrete aggregate.

The chemical composition of the acid minor bodies indicate that such aplites and quartz porphyries can be used in the glass and ceramic industries as such and some after little benficiation.

Geologically the mapped area consist of three distinct petrotectonic epochs and province which are juxtaposed to each other due to collision of Indian plate with Kohistan Island Arc, these includes I) Indian Mass, ii) Melange Zone and iii) Kohistan Island Arc.

These three petrotectonic rock units originated in different environment in which different ores and minerals of economic importance crystallized.

### Indian Mass

The Indian mass consist of metasediments and granite gniesses, they are exposed in the south western part of project area. Pegmatites were observed in these rock units. The main useful minerls in these pegmatites are microcline, muscovite books and blue beryl. The microcline can be used in glass and ceramics manufactue, muscovite in electrical industry and blue beryl as semi-precious stone.

**Shamozai Greenschist Melange**

Shamozai greenschist melange is mapped along the MMT in the area for the first time. It consist of phyllite, wehrlite, pyroxenites, serpentinites, talc carbonate and carbonates. Nickel mineralization was found associated with the wehrlite and serpentinites of melange zone. The nickel sulphides are disseminated as fine grains in these rocks. This melange zone is about 50-70 meters thick and about 10 km long in the area under investigation.

Chromite floats were also observed in a local stream running along the MMT but no in situ occurrence was observed. It was probably associated with the serpentinized ultramafic of melange zone.

The occurrence of talc carbonate in the melange zone may contain *emerald mineralization* as the environment of talc carbonate and the Shamozai melange resemble with the talc carbonate present in Mingora melange (Kazmi et al., 1984) Baleja ophiolitic melange (Baig et al.,1989) and Barang melange (Hussain et al., 1989). Some reports of emerald mineralization were also passed on to us, associated with Shamozai melange zone. Some local tribe own these mines through which emerald was exploited in the past but no live mine was observed in the area. More detailed exploration work is required in this connection.

**Mineral Showing in Dir Amphibolites**

The amphibolites mainly consist of metavolcanics and metasediments which were deposited in an ocean floor. The depositional environment of these rocks is favourite for the precipitation of metals like iron, copper and zinc with minor amount of manganese, gold, nickel, titanium and silver.

Nickel mineralization was reported near Bandagai by Engineers Combine Limited (ECL 1977) in southern part of Dir amphibolite. Nickel mineralization is also reported near Manial 5 km. north west of Lal Qila in northern part of Dir amphibolite. Anomalous gold mineralization (105 ppb) was observed in pan concentrate sample (No. 1027A) collected from Shagokas Khwar 10km south west of Timargara. This stream drains amphibolites present in the southern extreme of mapped area along the MMT. The sample was analysed by SDA (Nawaz personal communication). Weak traces of gold (50 ppb) was also observed from Khongi Khwar and from Tangi Darra (No. 1026A). The Khongi Khwar' is about 2 km. south east of Timargara while Tangi Darra is in the centre of city. The former stream drain amphibolites and tonalites and the later stream has mainly amphibolites in its catchment.

Copper (300 pmm) is reported in southern part of Dir amphibolites at various places for example in Khongi Khwar (pan concentrate sample 1026A) and in Rabat Aseagai Khwar 15 km.. Nickel mineralization near Bandagai (north-east of Timargara) area reported by ECL is also evident from our geochemical analysis containing 137ppm of Ni.

**Mineral Showings in Calc-Alkalic Plutonic Sequence**

The plutonic rocks appear to underplate the amphibolites due to the development of arc related magma. It is an environment favourable for the precipitation of base metal sulphides like copper, nickel, cobalt, lead, silver etc. Nickel mineralization is reported in norite near Balambat and Malakand 6 km. north west of Timargara by ECL (1977). While pan concentrate sample collected by SDA show anomalous lead (200ppm) and silver (125ppm) from Sangoli Darra (sample No. 1051B). Sangolai Darra is about 20 km. north of Timargara. This stream mainly have diorite in its catchment area. Qalagai Darra also shows anomalous amount of lead which is about 145 ppm, this Khwar is about 3km. north west of Timargara. It also drain diorites. Lajbok Darra is found anomalous in chromium (165ppm). It also has diorite in its catchment. Three huge bodies of hornblendite and pendants of amphibolite are also present in the catchment area.

The mineral showing and anomalies in geochemical prospecting only indicates the presence of metals in the rocks of the area but the discovery of some metallic ore deposit of economic value require further detail geochemical, geophysical and geological surveys. Petrogenetic and geochemical evolutionary studies may also be helpful in this concern.

**Industrial Minerals**

Small mineral deposits of industrial importance like pottery stone and kaolinized rocks are present in different localities of the project area. These mineral deposits are mainly associated with the porphyries and aplites which are intruded in both amphibolites and plutonic rocks.

Quartz porphyries are mainly exposed in southern part of Dir Amphibolites. Most of these bodies trend east west which is also the trend of the amphibolites and the MMT. Aplites of economic significance containing feldspars are mostly exposed in the central and western part of project area. Texturally quartz porphyries are fine-grained groundmass of quartz (10-45%), plagioclase (15-

50%) and accessories minerals like muscovite, sericite, kaolinite, zoisite, chlorite, hornblende, magnetite (in decreasing order are 2-8%) with 1-3mm size phenocrytals of quartz (3-8%).

Mappable bodies of quartz porphyries and aplites were observed in four areas. Those bodies includes: i) Bandagai-Derai area, ii) Khongi-Kamrani area, iii) Koto Shahzada-Hayaserai area and iv) Nagotal area

*i)* ***Bandagai-Derai area***: The largest porphyry of the area crops out near Bandagai in the amphibolites, the body trends EW ranging in thickness from 30 m to 350 m and is about 6 km long. Generally this body has concordant relationship with the amphibolite, however discordant relationship was also observed at some localities. Roof pendants of amphibolites were also evident, which range in size from about 30 cm to ten of meters.

The porphyry shows snow white fresh colour and yellowish to grayish white weathered colour. The rock is medium hard to very hard at places. Pockets of soft white material probably containing kaolinite was observed in altered outcrops. Mineralogically the body is composed mainly of both feldspars ( plagiclase 30 to 35%, microcline 10 to 30%) and quartz (20%), while chlorite is present as minor constituents. Similar type of porphyritic bodies are observed near Dherai, Aju and Kuz Nagari. Chemically the rocks are $SiO_2$ 70 to 72%, $Al_2O_3$ 15 to 16%, $Fe_2O_3$ 1 to 1.6%, $Na_2O$ 3 to 4.6%, $K_2O$ 3.4 to 4.4%, MgO about 4%, and CaO 1.4 to 2.5%

*ii)* ***Khongi-Kamrani area:*** Six porphyry bodies were observed in area, which occurred in tonalite and amphibolite. These bodies range in length from 200 m to 400 m and 3 to 10 m in width. These bodies are mainly composed of both feldspars and quartz as phenocrysts and in ground mass. The feldspars are altered to soft white material the kaolinite. These bodies generally trend EW. Chemically $SiO_2$ 69 to 73%, $Al_2O_3$ 16 to17%, $Fe_2O_3$ 0.7 to 1.6%, MgO 0.02 to 1.2, CaO 0.4 to 2.4%, $Na_2O$ 3.6 to 5.2% and $K_2O$ 1.9 to 3.4%.

*iii)* ***Koto-Shahzada-Hayaserai area***: Both porphyries and aplites were observed in this area.

*a) Porphyries*: These bodies of various sizes and magnitude were found in this area ranging in length from 100m to 700m while thickness varies from 5 to 15m, most of these bodies were found altered along joint planes, and cracks, forming small pockets of white soft material. These bodies generally trends NE-SW and dips steeply towards north. Mineralogically these bodies are composed of both feldspars (plagioclase 20 to 35%, microcline 15 to 27%) and quartz (25 to 35%) which are present as well developed coarse crystals and in the groundmass. Other noticeable minerals are kaolinite (3 to 6%), chlorite (2 to 6%), epidote (1 to 5%) and magnetite and biotite in two samples only from 1 to 2%. Chemically $SiO_2$ 69 to 72%, $Al_2O_3$ 14 to 20%, $Fe_2O_3$ 1 to 2%, MgO 0.08 to 1.3%, CaO 2 to 3.5% and $Na_2O$ 2.4 to 4.4%.

*b) Aplites*: An aplitic body in this area extends from Kufar Darra to Koto and crops out in four discontinuous bodies in diorite. The cumulative length of these bodies is about 2 km and thickness ranging from 5-10m.

Mineralogically these aplites mainly consist of plagioclase 25 to 35%, microcline 12 to 23% and quartz 22 to 35% whereas kaolinite 1 to 8% is present as altered product along joints occurring as soft white material. Another aplitic body exposed near Naraitangi in Lojbok Darra, 10 km northwest of Timargara, is about 20 to 40m thick and 800m long discountinouly. It is intruded in diorite along with a body of hornblendite. It is white to dirty white on fresh surfaces and creamy to grayish white on weathered surfaces.

**iv) Nagotal area**

A mappable body of quartz porphyry was observed near Nagotal in the northern extreme of mapped area, the body trends NE and SW, exposed in an area of about 500 square meters. Its fresh colour is white to apple white while weathered colour is creamish white to greenish white. Petrographically is composed of feldspar and quartz which are present both as well developed crystals and ground mass like those mentioned above.

In addition to these bodies many small bodies of porphyries and aplites were observed at different localities in Malakand Darra, Lajbok Darra, Sangoli Darra, Lalu Khwar and Shigokach.

Mining of these porphyries and aplites have been noted at some localities which are evident by the presence of deep open pits. Whereas mining operation is still in progress at other localities. The material excavated from these bodies were mostly supplied to ceramic and glass industries, on the other hand compact blocks of some aplite and porphyries are also used as building material by locals.

**Gem Stones**

Ruby corundum mineralization is present in two pyroxenite bodies near Khongi which are intruded in amphibolite. Light pink to purple coloured corundum crystals are present in the host rocks as two zones. One zone is about 7m thick and 9m long. This zone is present in the upper level body on the peak. While second zone is about 70-80m down the slope in the second body, it is about 10m thick and 25m long. A local company is mining corundum from this zone.

The ruby corundum grains are usually disseminated in the host rock and are usually enveloped by a green coloured rim of margarite and white coloured rim of antigorite.The apparent shape of crystals may be square / tetragonal with size ranging from tiny specks to 2.5 cm, however the larger crystals are rare, but the usal size is about 5mm to 10mm. The percentage of corundum in the rich zones seems to be 2-3%.

The ruby corundum of this area is of semigem grade due to the presence of some micro-fractures in it. But some of the grains found here and there are of good quality red to pinkish red in colour with good transparency/ translucency. The portion of rock in which fine grained specks of corundum are present could be used as abrasive with minor processing.

## CONCLUSIONS

The Dir amphibolite exposed in the northern and southern parts of the area are orth-amphibolites with interbeds of para-amphibolites. These are the product of metamorphism of a single ocean floor containing basalts, basaltic pillows and oçean floor sediments.

The plutonic rocks in the area show complete differentiation trend from norite/gabbronorite to acidic minor bodies and were either intruded in amphibolites or underplated them. These plutonic rocks have agmatitic contact with the roof amphibolites at many places. These plutonic rocks are not related to Chilas magma type.

The Dir amphibolites extend to the east through Swat valley some what beyond Shahpur valley and are not exposed in the Indus canyon where we have Kamila amphibolites consisting of three metamorphosed plutons e.g. Dassu complex the oldest rocks in Kohistan, underplated by Kayal complex which is underplated by Pattan complex. These are plutonic complexes showing relict rhythmic and modal igneous layering.

The collision of Indian Plate with Kohistan Island Arc has formed most of the structures.

The MMT zone contains several group of rocks mostly expressed as schistosity parallel but intensely deformed tectonic contact.

Structural studies show that the rocks of Kohistan Island Arc exposed in the area are folded into northward dipping southward verging tight folds in the south (near MMT) which opens up northwards. The Dir amphibolites have undergone at least two phases of isoclinal folding. In the first phase recumbent or isoclinal folding $S_1$ axial planner foliation was developed in these rocks. The second and third phases deformations are related to subduction of Indian Plate under Kohistan sequence producing $S_2$ foliation and shear zones.

The Dir amphibolites near MMT trend E-W dipping at 65° to 80° northwards. The plutonic rocks of the Kohistan Island Arc trend NE-SW dipping at 40° to 70° NW and SE.

Geotechnical properties show that the rocks like Balambat norite/ Timargara gabbronorite and hornblendites can be used as exellent dimension stones as they get very good polish. All hornblendites and fresh norite and gabbronorite can be used as aggregate materials.

Quartz porphyries and aplites after carefull mining operation or with little beneficiation can be used as pottery stone and in colourless glass manufacture.

Ruby corundum of Timargara has potential as gemstone and as abrasive stone.

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# FACIES AND PALAEOENVIRONMENTS OF THE DUNGAN FORMATION, EASTERN SULAIMAN RANGE, PAKISTAN.

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**Abstract:-** The Dungan Formation of Paleocene-Early Eocene age is predominantly a carbonate sequence. It is characterised by eight microfacies including Peritidal Carbonate, Inner Lagoon, Oolitic, Outer Lagoon, Rhodolith Platform, Nummulitic, Larger Foraminiferal and Planktonic Foraminiferal. All these microfacies are interpreted to have been deposited on a windward side of a homoclinal ramp setting.

## INTRODUCTION

The present work deals with the study of Raghasan, Zinda Pir and Rakhi Nala sections of the Sulaiman Range (Fig. 1). The study was aimed to identify microfacie of the Dungan Formation and interpret their environments of deposition. As a part of this study, more than 130 stained and unstained thin sections was carried out with the help of binocular microscope, reflected light microscopy and scanning electron microscopy (SEM). Collectively, these facies are considered to represent deposition through time on a homoclinal windward ramp. The present study focuses on the stratigraphic relationships, lithological variations and microfacies interpretation of the Dungan Formation in the Sulaiman Range (Fig. 2).

## GEOLOGICAL SETTING

The Dungan Formation dominantly consists of nodular to massive limestone with subordinate shale, marl, sandstone and limestone conglomerates. The limestone is dark grey to brown and creamy white in colour, and weathers brown, grey and buff yellow colour. The dark blue grey, brown and olive shale which weathers grey or green becomes dominant in the southern Sulaiman Range. Beds of limestone conglomerate also occur within the formation which grade vertically into nodular and massive limestone. The conglomerate is composed of pebbles and cobbles of grey and brown limestone and marl, embedded in a matrix of soft, ash grey calcareous shale. Occasionally brownish green, coarse grained, calcareous sandstone beds are interlayered with shale. The Dungan Formation, mainly developed in the Sulaiman Range is about 300 m thick. It is however, characterised by variation in thickness in all the studied stratigraphic sections though its thickness changes rapidly from place to place.

The lower contact of the Dungan Formation is unconformable in most of the localities and "marks one of the major unconformities of the basin" (Williams, 1959). The upper contact with the Ghazij Formation is conformable. A rich fossil assemblage including foraminifers, gastropods, bivalves and algae are recorded by Davies (1941), Khan and Haque (in Lexique, 1956), Hunting Survey Corporation (1961), Latif (1964), and Iqbal (1969). The formation is Palaeocene to Early Eocene in age and is correlated with the Ranikot Group, the Rakhshani Formation of Axial Belt, and the Hangu-Patala sequence of the Kohat-Potwar Province.

## MICRO-FACIES

On the basis of detailed petrographic study eight microfacies are recognised within the Dungan Formation. These microfacies are Peritidal Carbonate Facies, Inner Lagoonal Facies, Oolitic Facies, Outer Lagoonal Facies, Rhodolith Platform Facies, Nummulitic Facies, Larger Benthonic Foraminiferal Facies and Planktonic Foraminiferal Facies.

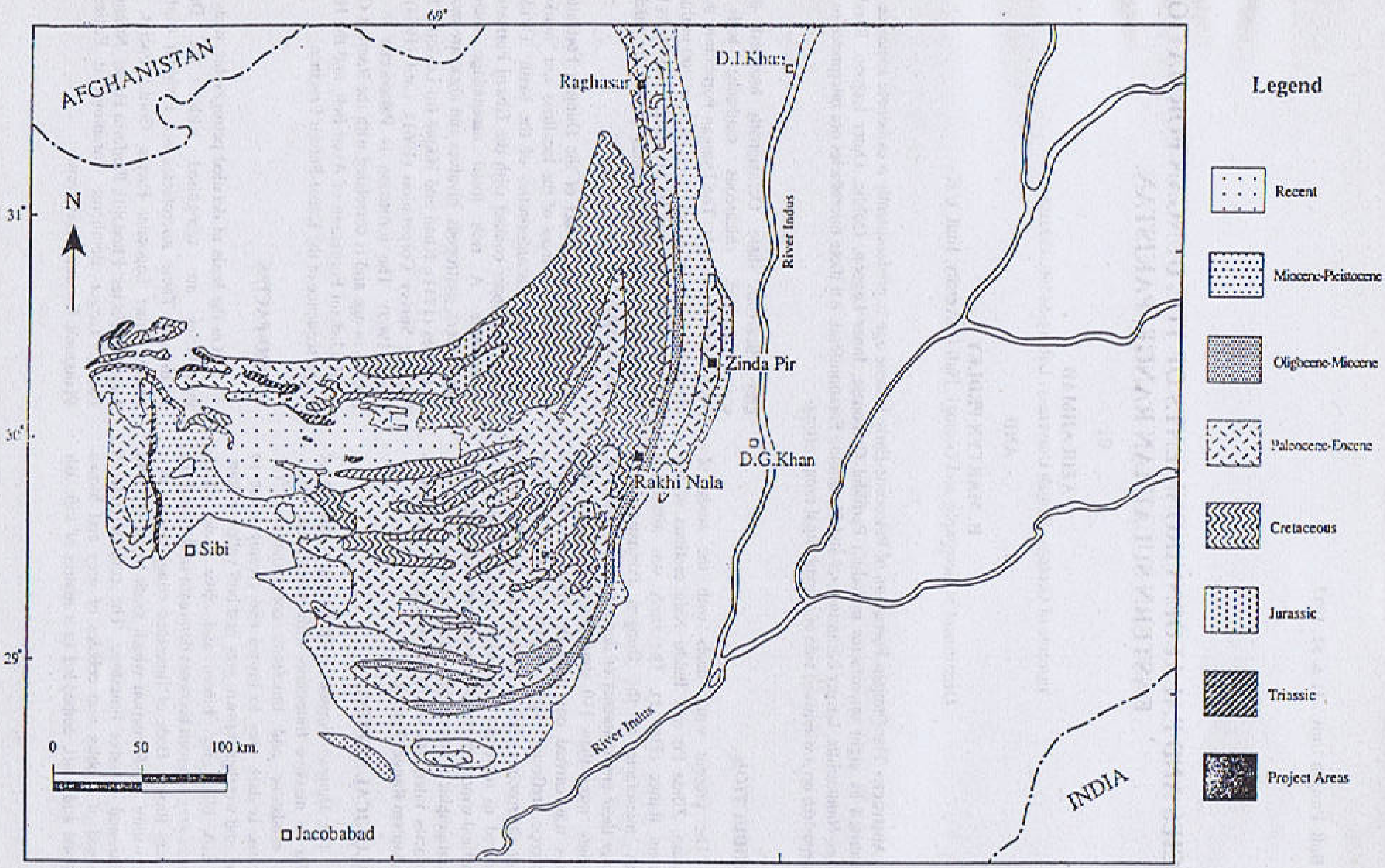



**Fig. 1** Generalized geological map of the Sulaiman Basin (modified after Bakr and Jackson, 1964).

### 1. Peritidal Carbonate Micro-Facies (F 1)

This microfacies is mainly encountered in the Rakhi Nala section in the southern part of the Sulaiman Range (Fig.1). It is characterized by medium to coarse grained grey, grey brown coloured quartz arenite with a sparry calcite cement, which is thick bedded (0.7 to 1.0 metre thick) and shows planar cross-bedding. The quartz grains are monocrystalline, well sorted medium grained and subangular to subrounded in shape. Most of the allochems are unidentifiable due to alteration. However, a few echinoid fragments (0.1%) are identified in this facies.

#### Interpretation

The peritidal carbonates are typical grainstone sediments and are commonly forming sheet-like grainstone units, reflecting the tendency of high-stand ramp shoreface sediments to migrate or prograde rapidly (Burchette and Wright, 1992). Peritidal carbonates are generally associated with low-energy tidal zones. They may accrete from the shorelines of land areas and from around islands (Ebanks, 1975; Pratt and James, 1986). The peritidal carbonates show bedding dipping at a low angle off-shore (surf-swash deposit) and on-shore from deposition on the backsides of beach berms. On-shore directed cross-bedding is produced by shoreface mega-ripples and wave-ripples. Cross-lamination also occurs. Burrows may occur in the low intertidal shoreface part (Tucker and Wright, 1990). The presence of well-sorted subangular to subrounded quartz grains and the thick and planar cross-bedding of the unit indicates deposition of this facies close to shore. So consequently this facies is deposited in a warm water near shore located below the supratidal zone at the depth of 3 to 5 metres.

### Inner Lagoonal Micro-Facies (F 2)

This facies is also encountered in the Rakhi Nala section (Fig.1). It is composed of dark grey to grey coloured quartz arenite with a sparry matrix. Beds are thin to thick bedded (0.2 to 1.00 metre thick) and show planar and trough cross-bedding. The quartz grains are poorly sorted, subangular to subrounded. The sediments are poor in skeletal grains of benthonic foraminifera (0.8% mean), with bivalves (1.0% mean) and echinoids fragments (0.7% mean; Table 1). The foraminifera include miliolids and agglutinated forams. Quartz grains are frequently present (Plate 1A). A few scattered pyrite crystals with dark brown to black insoluble residues (probably organic matter) are also present.

#### Interpretation

A wide range of compositions of carbonate sands and carbonate mud (Milliman, 1974; Flugel, 1982) is present in lagoons. The inner lagoonal sediments are fine grained and sandy, confined principally to tidal inlets. Sediment blown from barriers may be scattered throughout the lagoonal area and characterised by current ripples and internal small scale cross-bedding that may dip in either a landward or in a seaward direction. The sand is generally horizontal laminated but it may display ripple cross-lamination. The faunas that inhabit inner lagoonal environments are highly variable depending upon the salinity conditions but are generally characterised by low diversity. Under very arid conditions, inner lagoonal sedimentation may be characterised by the deposition of evaporites, which are mainly gypsum but may include some halite and minor dolomite. Under less hypersaline conditions, carbonate deposition prevails, particularly in a lagoon developed by barrier. Deposition in such lagoons may consist of carbonate sparite and associated skeletal grains, although oolites may form in more agitated parts of the lagoon.

This facies probably represents the subtidal deposit of a lagoon formed under reducing conditions. The dark grey colour is due primarily to the presence of organic matter and pyrite. The environment in which this facies was deposited was probably calm or with little agitation. It is likely that during calm periods the water within the sediment became stagnant and eventually reducing, hence, pyritic. Consequently, this facies is interpreted as having been deposited in the lagoon environments above the fair weather wave base at the depth of 5 to 10 metres.

### Oolitic Micro-Facies (F 3)

This facies is also found in the Rakhi Nala section (Fig. 1). It is represented by ooid wacke to packstone (ooids 6 to 34.0%; Plate 1B) dark grey to grey, brown olive colour and containing scattered quartz grains. The unit is thick bedded (0.5 to 0.9 metre thick), sometimes laminated. Fenestral structures are also present. The skeletal allochems are benthonic foraminifera (0.4 to 1.6%), fragmental infaunal bivalves and gastropods (0 to 11.2%) and echinoids (0.4 to 8.0%) with a few algal branch fragments (0 to 0.4%; Table 1). The forams includes miliolids and small rotaliids. The ooids are spherical to oval in shape, 0.1mm to 0.2mm in diameter, and their nuclei are the fragments of molluscs, abraded foraminifera or the quartz grains. Scattered pyrite is present.

#### Interpretation

The depositional characteristic features like presence of ooids, lamination and fenestral fabric present and the general paucity of fossils provide important clues to the depositional environment of this facies. Laminations, whether thick or thin, are one of the most

**Table 1**

**Thin section data of the Dungan Formation to illustrate mean, standard deviation, maximum and minimum values obtained by point counting.**

| Facies | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
|---|---|---|---|---|---|---|---|---|
| No. of Samples | 9 | 9 | 9 | 9 | 15 | 15 | 15 | 15 |
| | Mean | St.Dev. | Maxi. | Mini. | Mean | St.Dev. | Maxi. | Mini. |
| Algae | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.2 | 0 |
| Foraminifera | 0 | 0.1 | 0.4 | 0 | 0.8 | 0.6 | 2.4 | 0 |
| Echinoderms | 0.1 | 0.3 | 0.8 | 0 | 0.7 | 0.8 | 2.6 | 0 |
| Molluscs | 0 | 0 | 0 | 0 | 1 | 1.2 | 4 | 0 |
| Bryozoa | 0 | 0 | 0 | 0 | 0.3 | 0.4 | 1.2 | 0 |
| Coral | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0.4 | 0 |
| Total Allochems | 2.6 | 2.3 | 6.8 | 0 | 5.2 | 3.8 | 15.4 | 1 |
| Oolites | 0 | 0 | 0 | 0 | 1.8 | 2.4 | 5.6 | 0 |
| Cement | 17.8 | 7.6 | 34.8 | 11.6 | 32.6 | 15.6 | 57 | 12.8 |
| Matrix | 0 | 0 | 0 | 0 | 2.9 | 5.7 | 18.8 | 0 |
| Non-carbonate | 79.6 | 7.7 | 87.2 | 65.2 | 57.5 | 18.6 | 83.2 | 29.2 |

| Facies | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
|---|---|---|---|---|---|---|---|---|
| No. of Samples | 11 | 11 | 11 | 11 | 10 | 10 | 10 | 10 |
| | Mean | St.Dev. | Maxi. | Mini. | Mean | St.Dev. | Maxi. | Mini. |
| Algae | 0.1 | 0.1 | 0.4 | 0 | 1.8 | 4.7 | 15 | 0 |
| Foraminifera | 0.9 | 0.4 | 1.6 | 0.4 | 3.1 | 3 | 8 | 0.4 |
| Echinoderms | 2.2 | 2.3 | 8 | 0.4 | 6.4 | 4.6 | 16.8 | 2 |
| Molluscs | 2.6 | 3.4 | 11.2 | 0 | 5.7 | 3.7 | 10.8 | 0.6 |
| Bryozoa | 1.1 | 1.7 | 5.6 | 0 | 2.4 | 5.2 | 17 | 0 |
| Coral | 0.3 | 0.4 | 1.2 | 0 | 0.3 | 0.4 | 1 | 0 |
| Total Allochems | 14 | 10.1 | 31.4 | 3.2 | 30.7 | 7.4 | 41 | 16.8 |
| Oolites | 17.4 | 10.9 | 34 | 6 | 1.3 | 2 | 5 | 0 |
| Cement | 32.7 | 6.3 | 43.6 | 22.4 | 43.5 | 11.1 | 62.8 | 22.4 |
| Matrix | 2.1 | 6 | 20 | 0 | 11.6 | 15.8 | 40.2 | 0 |
| Non-carbonate | 33.8 | 9.5 | 48.4 | 21.8 | 12.8 | 11.1 | 27.8 | 0 |

| Facies | 5 | 5 | 5 | 5 | 6 | 6 | 6 | 6 |
|---|---|---|---|---|---|---|---|---|
| No. of Samples | 31 | 31 | 31 | 31 | 29 | 29 | 29 | 29 |
| | Mean | St.Dev. | Maxi. | Mini. | Mean | St.Dev. | Maxi. | Mini. |
| Algae | 20.1 | 9.2 | 39.2 | 2.8 | 11.7 | 9.7 | 36.4 | 1.2 |
| Foraminifera | 10.4 | 9.3 | 33 | 0.4 | 30.8 | 23.1 | 70 | 0.2 |
| Echinoderms | 5.1 | 2.8 | 12.4 | 0.8 | 4 | 3.4 | 14.4 | 0.6 |
| Molluscs | 0.3 | 0.3 | 1 | 0 | 0.2 | 0.3 | 1.2 | 0 |
| Bryozoa | 3.1 | 2.7 | 9 | 0 | 2.4 | 4.1 | 21.6 | 0 |
| Coral | 0.5 | 1.3 | 5 | 0 | 0.5 | 1.4 | 6.8 | 0 |
| Total Allochems | 39.5 | 10.2 | 67.6 | 24.6 | 50.4 | 15.4 | 76.6 | 22.2 |
| Oolites | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cement | 35.3 | 14.3 | 60.8 | 6.8 | 26.4 | 6.9 | 42 | 14.6 |
| Matrix | 25.2 | 10.3 | 45.6 | 4.8 | 22.8 | 12.9 | 48.6 | 4.8 |
| Non-carbonate | 0.1 | 0.2 | 0.8 | 0 | 0.4 | 0.7 | 3.2 | 0 |

| Facies | 7 | 7 | 7 | 7 | 8 | 8 | 8 | 8 |
|---|---|---|---|---|---|---|---|---|
| No. of Samples | 13 | 13 | 13 | 13 | 12 | 12 | 12 | 12 |
| | Mean | St.Dev. | Maxi. | Mini. | Mean | St.Dev. | Maxi. | Mini. |
| Algae | 4.8 | 4.9 | 17.2 | 1.2 | 0 | 0.1 | 0.4 | 0 |
| Foraminifera | 56.3 | 20.9 | 77.6 | 6.6 | 9.4 | 5.1 | 17 | 3.4 |
| Echinoderms | 2.6 | 1.8 | 5.4 | 0.4 | 0.7 | 0.7 | 2.6 | 0 |
| Molluscs | 0.3 | 0.3 | 1 | 0 | 0.3 | 0.3 | 0.8 | 0 |
| Bryozoa | 0.5 | 0.5 | 1.8 | 0 | 0.1 | 0.2 | 0.8 | 0 |
| Coral | 0 | 0.1 | 0.4 | 0 | 0 | 0 | 0 | 0 |
| Total Allochems | 64.9 | 17.9 | 80.4 | 23.6 | 11 | 4.9 | 19.6 | 5.4 |
| Oolites | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cement | 20.3 | 5.3 | 33.4 | 12.8 | 10.8 | 3.8 | 17.8 | 5.4 |
| Matrix | 14.2 | 16.5 | 57.6 | 1.8 | 77.8 | 5.4 | 89.2 | 69.6 |
| Non-carbonate | 0.6 | 0.6 | 2 | 0 | 0.5 | 0.4 | 1.2 | 0 |

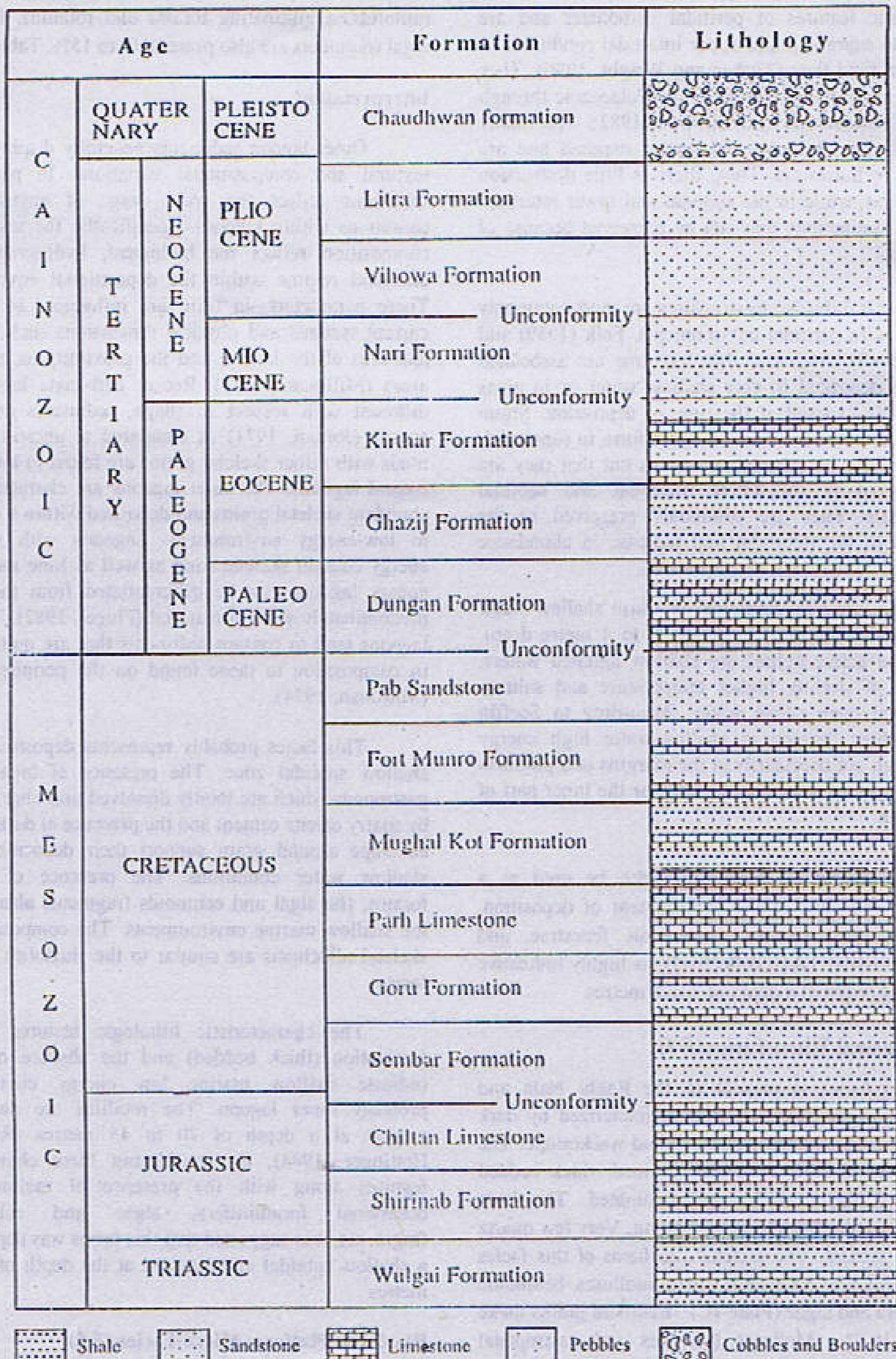



Fig. 2 The stratigraphic sequence of the Sulaiman Basin (after Shah, 1977).

characteristic features of peritidal carbonates and are restricted to supratidal and upper intertidal conditions in the modern tidal flats (Tucker and Wright, 1990). They are found in similar positions in late Palaeozoic through Cainozoic sedimentary rocks (Shinn, 1982). The tidally influenced areas are more frequently exposed and are unsuitable to burrowers. Thus, there is little destruction of lamination, while in the subtidal and lower intertidal areas, the laminations may not be preserved because of bioturbation.

Fenestral (birdseye) structures are most commonly associated with peritidal environments. Folk (1959) and Laporte (1967), suggested that fenestrae are associated with rocks deposited in very shallow water or in areas intermittently exposed at the time of deposition. Shinn (1968, 1982) noted that these features form in supratidal, intertidal and even subtidal sediments but that they are not preserved in the lower intertidal and subtidal environments. They are commonly preserved in the upper part of the intertidal and increase in abundance through the transition of the supratidal.

Ooids are best developed in warm shallow water (tropical and subtropical, normally 0 to 4 metre deep). The sites of active oolites are shallow agitated waters, commonly of slightly higher temperature and salinity than normal open ocean water. According to Scoffin (1987), oolites develop in shallow-water high energy zone, though not necessarily at the margins of a platform but may be on a gently sloping ramp or the inner part of the platform.

The paucity of fossils can also be used as a supporting indicator of the environment of deposition. All the evidence (oolites, lamination, fenestrae, and paucity of fossils), taken collectively, is highly indicative of intertidal origin at a depth of 5 to 8 metres.

**Outer Lagoonal Micro-Facies (F 4)**

This facies is present in the Rakhi Nala and Raghasar sections (Fig. 1). It is characterized by dark grey and brown coloured packstone and wackestone. The biomicrite is medium to course grained, thick bedded (0.5 to 1.0 metre thick) and laminated. The beds occasionally show trough cross-bedding. Very few quartz grains are present. The skeletal allochems of this facies are predominantly echinoderms with molluscs, benthonic foraminifera and algae (Plate 1C) . Echinoid grains make up 2 to 16.8%. Molluscs (bivalves and gastropods) comprise 0.6 to 10.8%. They are replaced by non-ferroan sparry calcite cement. The forams (0.4 to 8%) are miliolids, agglutinating forams and rotaliids. Coralline algal fragments are also present, (0 to 15%: Table 1).

**Interpretation**

Outer lagoon sediments generally display greater textural and compositional variations. In part, these variations reflect the wide range of environmental conditions within lagoons. Specifically, the texture and composition reflect the biological, hydrographic and chemical regime within the depositional environment. These parameters, in turn, are influenced by climate, current systems and physical dimensions such as depth and area of the lagoon and the proximity to peripheral areas (Milliman, 1974). Recent carbonate lagoons are different with respect to shape, sediments and water energy (Jordan, 1971) as compared to ancient . Lime-muds with minor skeletal grains are found in low-energy coastal lagoons. The outer lagoons are characterised by abundant skeletal grains and deposited within a moderate to low-energy environment. Lagoons with moderate energy contain skeletal sand as well as lime mud. Low-energy lagoons can be differentiated from those with predominately skeletal material (Flugel, 1982). The open lagoons tend to contain sediments that are quite similar in composition to those found on the peripheral areas (Milliman, 1974).

This facies probably represents deposition in the shallow subtidal zone. The presence of bivalves and gastropods which are totally dissolved and later on filled by sparry calcite cement and the presence of dark micritic envelope around grain support their deposition under shallow water conditions. The presence of abraded forams, the algal and echinoids fragments also indicate the shallow marine environments. The composition and skeletal allochems are similar to the rhodolith platform facies.

The characteristic lithologic features such as lamination (thick bedded) and the absence of oolites indicate shallow marine low energy environment, probably inner lagoon. The rotaliids are dominantly present at a depth of 20 to 45 metres (Reiss and Hottinger, 1984). By considering these characteristic features along with the presence of molluscs with occasional foraminifera, algae and echinoderm fragments, it is suggested that this facies was deposited in a shallow subtidal environment at the depth of 8 to 35 metres.

**Rhodolith Platform Micro-Facies (F 5)**

This facies is found in the Raghasar section (Fig.1). It is represented by dark grey to brown and creamy white wackestone to packstone weathering to brown, grey and buff yellow. These biomicrites are fine to medium grained, thick bedded to massive (1.0 to 1.8 metre thick) and are occasionally nodular. Bioturbation is common. The skeletal allochems are predominantly algae, benthonic foraminifera, isolated coral heads, encrusting bryozoa, echinoderm fragments; and occasional mollusc fragments. The algae are mainly the red coralline (2.8% to 39.2%; Table 1), the main genera being Lithothamnium, Archaeolithothamnium, Lithophyllum, Mesophyllum, Lithoporella and Jania. Green algae are Trinocladus, Neomeris, Clypeina and Acicularia. These are very well preserved in thin section. Spheroidal and ellipsoidal structures of densely branched type Rhodoliths are frequently present (Bosence, 1983a). Few of them are of large size (greater than 2cm in diameter). They are predominantly densely branched, spheroidal to ellipsoidal in shape (Plates 2A & B). Coralline algal debris is commonly present in this facies. The rhodoliths are mostly abraded. Foraminifera (0.4 to 33%) are mainly rotaliids and to lesser extent miliolids. Corals constitute 0 to 5% of the rocks. The echinoderms (0.8 to 12.4%) are dominantly echinoids with few asteroids (starfish).

**Interpretation**

Red coralline algae are important rock builders, in clear, shallow, warm waters rich in lime. These algae may grow rapidly and contribute appreciably to the formation of limestone.

The ecology of living crustose corallines has been summerized by Adey and Macintyre (1973). Principal factors controlling the distribution of corallinaceae are the temperature, depth, salinity, substrate type and energy.

According to Johnson (1961), most of the Tertiary limestones in the Mediterranean region, the West Indies and around the islands of the tropical Pacific contain coralline algae. Algal foraminiferal limestone are especially abundant in the Cenozoic rocks of the Tethyan Sea.

Rhodoliths are developed from crustose corallines in some unstable substrate environments ( Bosellini and Ginsburg, 1971). A delicate balance between water motion and light conditions, which permits essentially continuous growth on all surfaces of the nodule, is required for rhodolith development. According to Adey and Macintyre (1973), branched species of Lithothamnium are the dominant rhodolith forms, although Archaeolithothamnium and Lithophyllum are also contributors to the construction of these kinds of algal structures.

Archaeolithothamnium and Lithoporella are common in rhodolith platform facies but are restricted to tropical and sub-tropical waters. Mesophyllum and Lithothamnium do occur in lower latitudes (warm water) regions in slightly deeper environments. According to Adey and Adey (1973), light is the primary factor controlling the depth distribution of coralline algae. These algae cannot survive in very low intensity light conditions. Consequently they are of shallow water tropical environments. Jania occurs widely in tropical and sub-tropical seas at shallow depths of less than 10m and in the intertidal zone in high energy regimes.

Montaggioni (1979), describes abundant rhodolith genera from depth of 25 to 60 metres on the fore-reef slopes of the Mascarene Is. His studies show that the rhodolith structures are constructed mainly by the Lithophyllum and Lithoporella but with minor amounts of Porolithon, Lithothamnium, Hydrolithon and encrusting foraminifera. According to Adey and Boykin (1982), abundant rhodolith structures are developed by Archolithothamnium, Lithothamnium, and Mesophyllum in depths of 60 to 90 metres.

Rhodoliths have a wide variety of size, internal morphology and structure (Bosence and Pedley, 1982). Bosence (1976, 1983a), described the classification of rhodoliths and illustrated spheroidal ellipsoidal and discoidal shapes with open to dense branched types. Bosence (1983b) also studied the ecology of the rhodoliths and concluded that rhodoliths may occur in a wide range of environments. The idea that rhodoliths indicate shallow warm water environment (Adey and Macintyre, 1973) is not correct. The external morphology (shape and branch types) of rhodolith gives a good indicator of hydraulic energy.

Bosence and Pedley (1982) and Bosence (1983b), studied growth variations, morphology and the environment setting of rhodoliths and concluded that the commonest shapes are ellipsoidal and spheroidal showing no obvious pattern of distribution. Discoidal forms are concentrated on sand, substrates. The branching density classes illustrate a close correlation with exposure of ripples. Their observations suggest that the ellipsoidal forms are more easily transported than the spheroidal forms and the discoidal forms are the most stable. Open branched forms are found to be more stable than densely branched forms of the same shape and size.

The distribution of the coralline algae is mainly controlled by temperature and light in marine setting (Adey 1966, 1970; Adey and McKibbon 1970; Adey and Adey 1973). Within the ecological restraints of light and temperature, rhodolith occurence will be controlled by substrate and hydraulic energy. Suitably sized grains for spore settlement must be present to develop a rhodolith bed. However, once rhodoliths are established, future recruitment is probably by breakage and overgrowth of rhodoliths. An exposure of moderate hydraulic energy is required to overturn crests and branched growths of newly settled corallines which results in the concentric (crustose) and radial (branching) growths characteristics of rhodoliths (Bosence. 1983b).

If the hydraulic energy is too high, then the rhodoliths are broken down into coralline gravels composed of branches and crusts. This erosion can be recorded within the rhodoliths which are smaller, densely branched or crusting with erosion surfaces are fractures (Bosence and Pedley, 1982). The densely branched and laminar rhodoliths are the result of frequent turning and high energy conditions. Apical abrasion occurred during turning appears to lead to intercalary branching or lateral filament growth below the apex. This results in branches joining laterally. Subsequent growth in high energy environments may be recorded by concentric laminar growth. Bosellini and Ginsburg (1971) suggested that columar growth form from stabilised rhodoliths but Bosence and Pedley (1982) found columar growths on rhodoliths that have been turned and the columns may show the same lateral growth in response to apical abrasion.

According to Illing (1954), the two dasycladacean genera Acicularia and Neomeris occur on the Bahama Banks but are not common. A similar observation was made in the same area by Cloud (1961), who stated that these algae inhabit tidal lakes. Johnson (1961) summarised the ecology of Dasycladaceae, a group that occurs at depths ranging from low tidal down to 10 metres but with the most luxuriant growth being confined to waters shallower than 5 or 6 metres (Johnson, 1960). Recent forms of this group are dominantly marine and are limited to tropical and warm temperature seas. In earlier observations Johnson (1957) concluded that these dasycladacean algae are present where the bottom is muddy or silty. The maximum depth is reported to be 30 metres (Cloud. 1952).

Many references point out the occurrence of dasycladacean algae in ancient limestones. Newell et al. (1953) and Newell (1957) report them from the back-reef region immediately behind the Permian Reef of the Guadalupe Mountain region. Schlanger (1963) considered the subsurface Eocene limestone of Eniwetok Attol containing them. are of shallow lagoon. Wolf (1965), from his work on the Devonian algal limestone of Australia. concluded that the favoured habitats of these algae are in protected pools, crevices and local lagoons. According to Jamieson (1969). Devonian Dasycladaceae thrived best in shallow, calm muddy lagoonal areas subject to change in salinity and Eh (Wray, 1969). Both the authors stress the role of this group as a sediment contributor. In the Eocene Reefs of Northeast India.

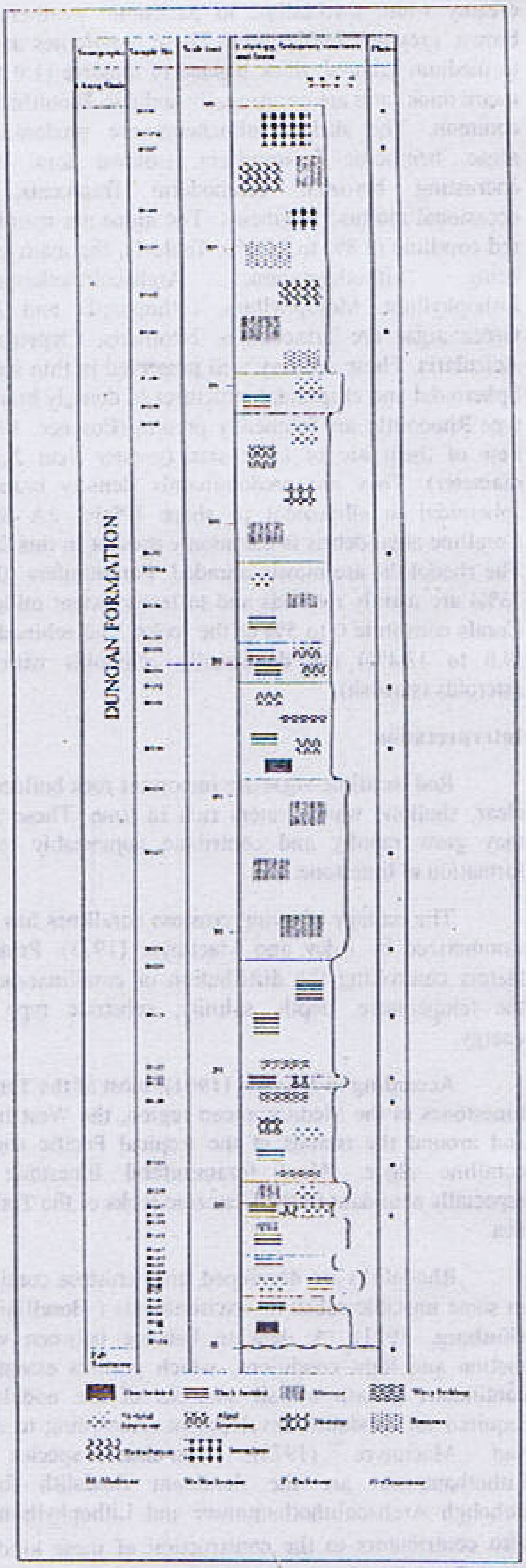



Fig. 3 Lithologic log of Reghasar section

abundant skeletons of dasycladacean algae are present in limestones interpreted to have been formed from sediments deposited in the back-reef region close behind the reef core. From the above discussion it may be concluded that abundant dasycladacean algae indicate a shallow environment and a tropical to warm subtropical climate.

In this facies the foraminifera are dominantly rotaliids, which normally occur between 20 to 45 metres depth (Reiss and Hottinger, 1984).

On the basis of above discussion it is concluded that the coralline algae are deposited in a wide range of environments, and that their distribution was dependent on temperature, depth, salinity, substrate and hydraulic energy. This facies has both coralline algae such as Lithothamnium, Archeolithothamnium, Lithophyllum, Mesophyllum, and Lithoporella and Articulated coralline algae such as Jania with few green algae such as Trinocladus, Neomeris, Clypeina and Acicularia. Most of the coralline algae are densely branched, spheroidal and ellipsoidal in shape (rhodolithic growth form). All these algae and the rotaliid foraminifera occur in water of normal marine salinities and at shallow depth. By considering them collectively it is suggested that this facies is deposited in the shallow sub-tidal ramp environment at a depth of 40 to 70 metres in a moderately open marine tidal situation.

**Nummulitic Micro-Facies (F 6)**

This facies is encountered in the Raghasar and the Zinda Pir sections (Fig. 1). It is characterised by dark grey to grey coloured wackestones and packstones. The bioclastic packstone is fine to medium grained, thick bedded (0.5 to 1.0 metre thick) and bioturbated. The skeletal allochems are predominantly benthonic foraminifera with red algae and isolated coral heads. Very few encrusting bryozoa (0 to 21.6%; Table 1) and echinoderm fragments (0.6 to 14.4%) are present. The benthonic foraminifera are dominated by entire to fragmental Nummulites with Operculina, Assilina, Lockhartia and Ranikhothalia (Plates 2C, 3A). The algae are mainly the red coralline developed as small rhodoliths fragments, particularly out of Lithothamnium, Archaeolithothamnium, Lithophyllum, Mesophyllum, and Lithoporella. Lithothamnium and Mesophyllum frequently are dominant. In this facies the coralline algae ranges from 1.2 to 36.4% of the total rock and the benthonic foraminifera are 0.2 to 70%.

**Interpretation**

Several authors have made attempts to explain the mechanisms governing nummulites distribution and accumulation in different geologic settings (Arni, 1965; Aigner, 1983, 1985; Bernasconi et al., 1984). Since nummulites are extinct, and their ecological parameters are not clearly known, hence their use in the sedimentological interpretation in the stratigraphic record becomes rather uncertain. Several comprehensive studies have, however, been done by a number of authors during the last three decades and different sedimentological models have been proposed which are of great importance in understanding the depositional environments of nummulitic facies.

The following is a brief historical review concerning deposition and accumulation of nummulitic facies.

Arni (1965), subdivided the nummulitic rock suite of Palaeogene of Libya into different facies related to bank formation and each nummulitic facies was distinguished from others by its own characteristic fossil assemblage. The fore-bank setting was characterised by enrichment of fossil debris and the presence of Assilina and Operculina. The bank setting was associated with Assilina, Operculina and Nummulites and the back-bank setting was characterised by the dominance of Alveolina and Orbitolites. According to his view, during the deposition of nummulitic bank facies, a submarine relief was formed almost as a consequence of the high biological productivity of the nummulites. He also interpreted the nummulitic bank facies in terms of insitu reworking phenomena and stated that the northern African continental platform was an ideal geological province for nummulitic facies developments. He did not, however, indicate the water depth of the formation of nummulitic bank but suggested a maximum depth correspond to the wave base.

Fournie (1975) has studied the Tunisian nummulitic facies of the El Garia Formation and interpreted its depositional setting as outer platform. According to him, the water depth of the nummulitic bank ranges from wave base to the low tidal level. He also mentioned that this nummulitic bank became subject to reworking when it entered a high-energy environment as he recognised diagnostic sedimentary structures of cross-lamination type.

Aigner (1983), in his study of the Egyptian nummulitic facies of Mckattan Formation, related the formation of the nummulitic bank to several factors which can be summarised as "deposition of the nummulites on a pre-existing topographic high situated in the photic zone. Currents and wave action, lead to in situ reworking and mechanical or hydrodynamic concentration of the nummulitic shells with upward shallowing phenomena".

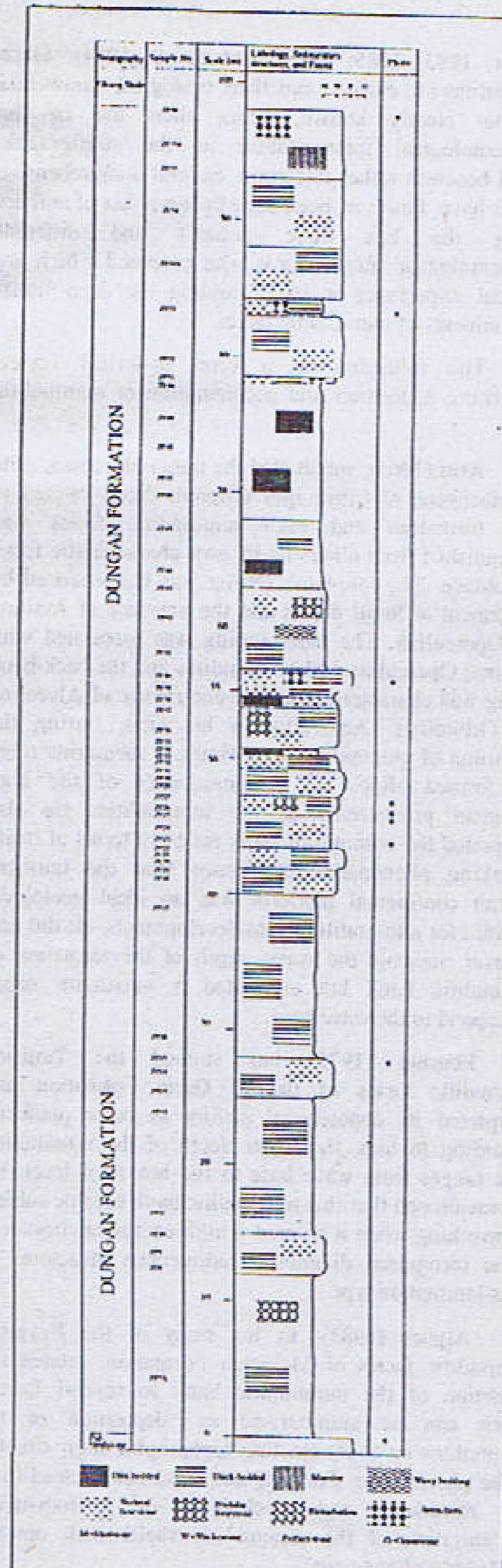



**Fig. 4** Lithologic log of Zinda Pir section

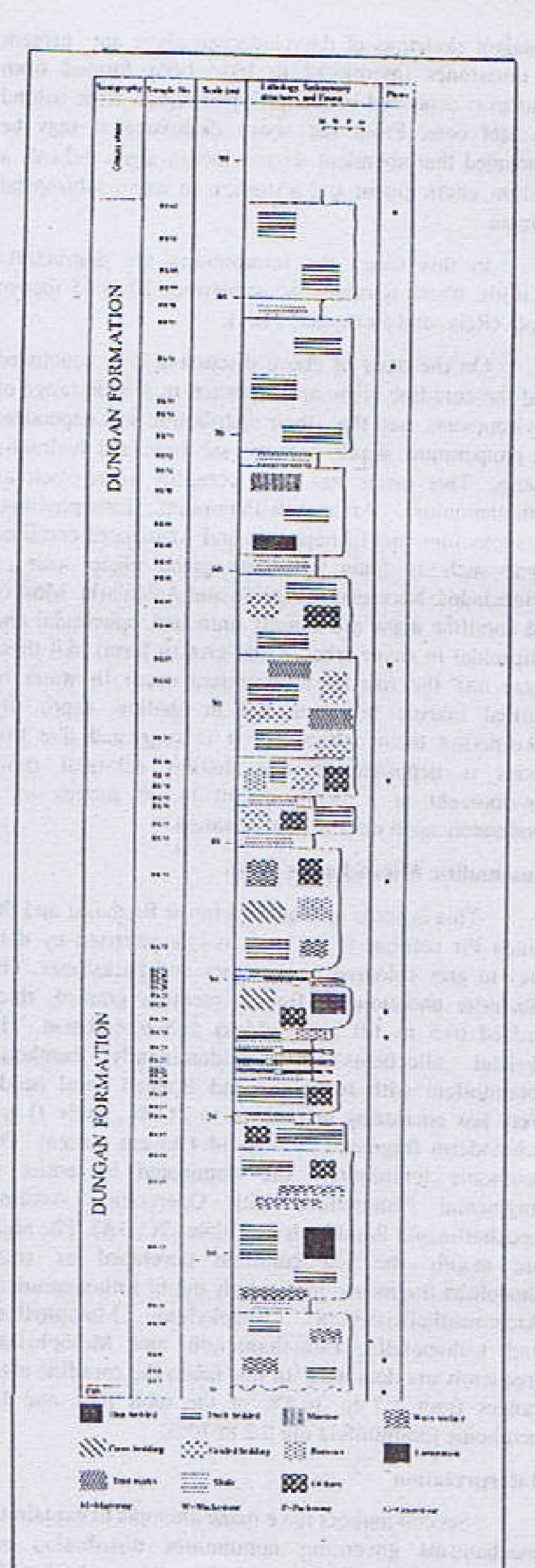



**Fig. 5** Lithologic log of Rakhi Nala section

Bernasconi et al. (1984), on the basis of studies of the nummulitic bank and the seismic lines at the Bauri Oilfield, drew the conclusions that the nummulitic bank was deposited on a substratum consisting of restricted shallow platform packstones. The presence of petrographic structures typical of intertidal zone suggest that the banks were formed in a high-energy environment. During the growth of the nummulitic bank it entered the intertidal conditions and became subjected to reworking. The water depth of the formation of the banks could not have exceeded the wave-base.

Aigner (1985), has published a paper describing the major nummulitic biofabric types in the middle Eocene limestone of Cairo, Egypt. Based on the ratios of the smaller nummulites (A-forms) to the larger or (B-form), he classified the nummulitic biofabrics of the Cairo bank into four main assemblages and evaluated their hydrodynamic mechanism. The main characteristics of these biofabrics can be summarised as follows,

Relatively undisturbed assemblages: These are inferred when small nummulites dominates in matrix-supported lithologies. This nummulitic facies is very common in the back-bank environments.

Paraautochthonous assemblages: The small nummulites are dominate with edge-wise imbrication of nummulites tests suggesting in situ reworking caused by a wave winnowing hydrodymanic mechanism.

Residual assemblage: This can be inferred when large nummulites are dominant and oriented parallel to bedding. The dominance of large nummulites suggest selective removal of the smaller ones.

Allochthonous assemblage: This can be inferred for layers composed entirely of small nummulites which suggest hydraulic sorting and separation of the bioclasts during lateral transport.

Gardiner (1906) and Mc Kee et al. (1959), studied the depositional environment of Operculina. According to their study, the Operculina has been reported from the deeper parts of lagoons where the water is quiet. Maxwell et al. (1961), reported them on channels on reef flats, whereas Collins (1958), Jell et al. (1965), and Maxwel (1968), reported them on shelf areas. They have also been reported from the subsurface reef limestones of Bikini (Cole, 1954), the Miocene reefs of Louisiana, where it is supposed to have lived in the sublittoral zones of the reef-flat environment (Squires and Sachs, 1957), and the Tertiary offshore carbonate bars of Libya along with Nummulites (Bebount and Pendexte, 1975). Both Henson (1950) and Schlanger (1963) state that Nummulites and Operculina, especially the larger one, lived in fore-reef shoal areas. On the other hand, Phleger (1960) grouped them with back-reef forms. Cushman et al. (1954) from their work on Bikini Attol, reported that these forms are rare in deeper water but are present in lagoons. Cloud et al. (1956) are of the view that they are associated with bank deposits.

Levin (1957), studied the depositional environment of Miscellanea. According to his studies, Miscellaneae associated with Lockhartia, indicate a warm shallow water environment of deposition.

The nummulitid species are usually bottom dwellers throughout their life. They occur at depths of 20 to 130 metres (Reiss and Hottinger, 1984). The perforated nummulites are normally deposited at the depth of 60 to 70 metres, the Alveolinids occur below 60 metres. The distribution of foraminifera with depth is studied by a number of workers. Dario Sartorio and Sandro Venturini (1988) gave a chart for the distribution of foraminifera with depth for the Tethys.

Apart from the presence of Nummulites, the coralline algae (melobesiid algae) are important not only as frame-builders but also sediment binders and sediment contributors (Cloud, 1952). Important genera of this group include Archaeolithothamnium, Lithothamnium, Lithophyllum and Lithoporella. There are numerous references to the different genera of crustose coralline algae in Recent reefs. Emery, 1948; Tracey et al., 1948; Wells, 1957; Chevalier, 1973; Doty, 1974; Litter and Doty, 1975; Maxwell et al., 1961,1964; Lewis and Taylor, 1966; Maxwell, 1968; Maiklem, 1968; Lewis, 1969; Kendall and Skipwith, 1969; and Vasseur, 1974; all suggest that the coralline algae occur mainly in the shallow water environments. Illing (1954), stated that crustose coralline algae (Lithothamnium and Lithophyllum) are quantitatively important on the Bahama Banks. Ginburg (1956), reported that they are abundant on reef edges and in areas immediately in front of reefs in Florida but they are not common in the back-reef region. In the same area Lithothamnium has been found to encrust dead corals. Coralline algae have been found to construct reef frame-works along with foraminifers (Garrett et al., 1971; Ginburg et al., 1971; Jordan, 1973). Logan (1969) and Milliman (1973) recorded the presence of these algae (Lithothamnium, Lithophyllum and Lithoporella) from Yucatan Shelf off Mexico. From the Alacran Reef-Complex of the same region branching forms of Lithothamnium have been reported by Kornicker and Boyd (1962).

Johnson (1957), while discussing the paleoecology of algae occurring in the limestones of Spain and Mariana Island, stated that coralline algae live at depths between tide level and 100 metres (in some cases upto

200 metres) but long-branching forms thrive within 10 to 15 metres. Later. Johnson (1961), summarised the ecologic distribution of coralline algae stating that, in general. they are widely distributed from cold temperate to warm tropical seas. They can live at depths ranging from the intertidal zone down to 156 metres. They grow on practically any surface and do not necessarily require strong light. They can withstand strong current and surf action and are euryhaline (see Jamieson, 1969). This would indicate that the remains of coralline algae cannot be effectively used for making palaeoenvironmental interpretations. which is not true. His discussion also shows that they are most diverse (as regards species) and abundant in shallow, warm, strongly agitated tropical waters. Moreover, certain genera (e.g. Archaeolithothamnium) are confined to this particular environment. Though Lithothamnium is now found mostly in cool waters, numerous species of this genus lived in the tropics during the Late Cretaceous and the Eocene and developed a variety of growth forms (Johnson, 1961). Adey and Macintyre (1973), have drawn attention to the same facts. They say that Archaeolithothamnium and Lithoporella are exclusively tropical genera. Archaeolithothamnium and Lithophyllum may grow in the intertidal zone but the latter requires stronger light than the former.

The following conclusions can be drawn regarding the ecology of the crustose coralline algae:

Limestones mostly constituting skeletons of crustose coralline algae are deposited in a wide range of depth. High species diversity and abundance indicate a shallow, warm, tropical environment.

They construct the main platform together with corals and foraminifers. They may construct alone by binding loose sediments into a coherent mass.

Their abundance increases towards the outer edges of the main platform.

They can grow on any surface.

In summary, this facies has the coralline algae Lithothamnium, Mesophyllum, Archaeolithothamnium, and Lithoporella which can survive in deeper environments as compared to other crustose coralline algae. The nummulites are dominantly deposited below the depth of 60 metres.

This facies has a large association of foraminifera; Nummulites, Assilina, Operculina, Ranikothalia, Lockhartia alongwith the coralline algae, Lithothamnium, Mesophyllum, Archaeolithothamnium, and Lithoporella. The genera Lithothamnium and Mesophyllum are dominant in this facies and can survive in slightly low intensity light conditions and deeper environments as compared to other crustose coralline algae.

This facies shows deposition in a shallow ramp environment at depths of 60 to 80 metres by considering the presence of benthonic foraminifera and the crustose coralline algae.

**Larger Foraminifera Micro-Facies (F 7)**

This facies is encountered in the Zinda Pir section (Fig. 1). It is mainly characterised by grey to dark grey weathering buff, yellow coloured wackestone. The biomicrite is fine to medium grained and the unit is thin to thick bedded (0.3 to 0.8 metre). Skeletal allochems are predominantly benthonic foraminifera (6.6 to 77.6%; Table 1) with occasional planktonic foraminifera. Few bryozoa (0 to 1.8%), coralline algal (1.2 to 17.2%) and echinoid fragments (0.4 to 5.4%) are also present. The benthonic foraminiferas are mainly represented by larger Nummulites, Discocyclina, Athecocyclina, Actinosiphon, Alveolina, and Assilina (Plate 3B). Pressure solution phenomena are developed and mainly restricted to low amplitude, parallel to bedding and the stylolites are of simple type. The skeletal grains are slightly deformed which indicate post depositional compaction. Some veins are also present which are filled by sparry calcite cement.

**Interpretation**

Ranikothalia a Palaeocene genus has a worldwide distribution in shallow water facies from Cuba through West Africa and southern Europe to Tibet and Borneo(Fleury et al., 1985). Alveolinids are, in general, shallow water neritic forms (Reichel, 1964) and indicate a littoral and reefal facies. The recent Alveolinella, which may be regarded as the ecologic descendants of the Eocene genus Alveolina, lives in tropical seas at depth of 10 to 80 metres. A study of the distribution of this genus in Recent reefs (Ghose, 1977), clearly shows that it lives in both fore-reef and back-reef zones. Henson (1950), also concluded that this genus was characteristic of reef areas with clear water having little or no deposition of clastic sediments. Discocyclina is supposed to be a typical fore-reef form (Henson,1950). In addition, together with other foraminifers they formed bank and off-shore bar deposits (Cloud et al., 1956; Bebout and Pendexter, 1975). Thus, it may be concluded that the paleoecology of Discocyclina is similar to that of Nummulites. Myers (1943) suggested that the presence of Discocyclina indicates a deeper water environments.

According to Ghose (1977), Heterostegina is a long ranging foraminifera (Eocene to Recent) and has obvious advantages from a paleoecological point of view.

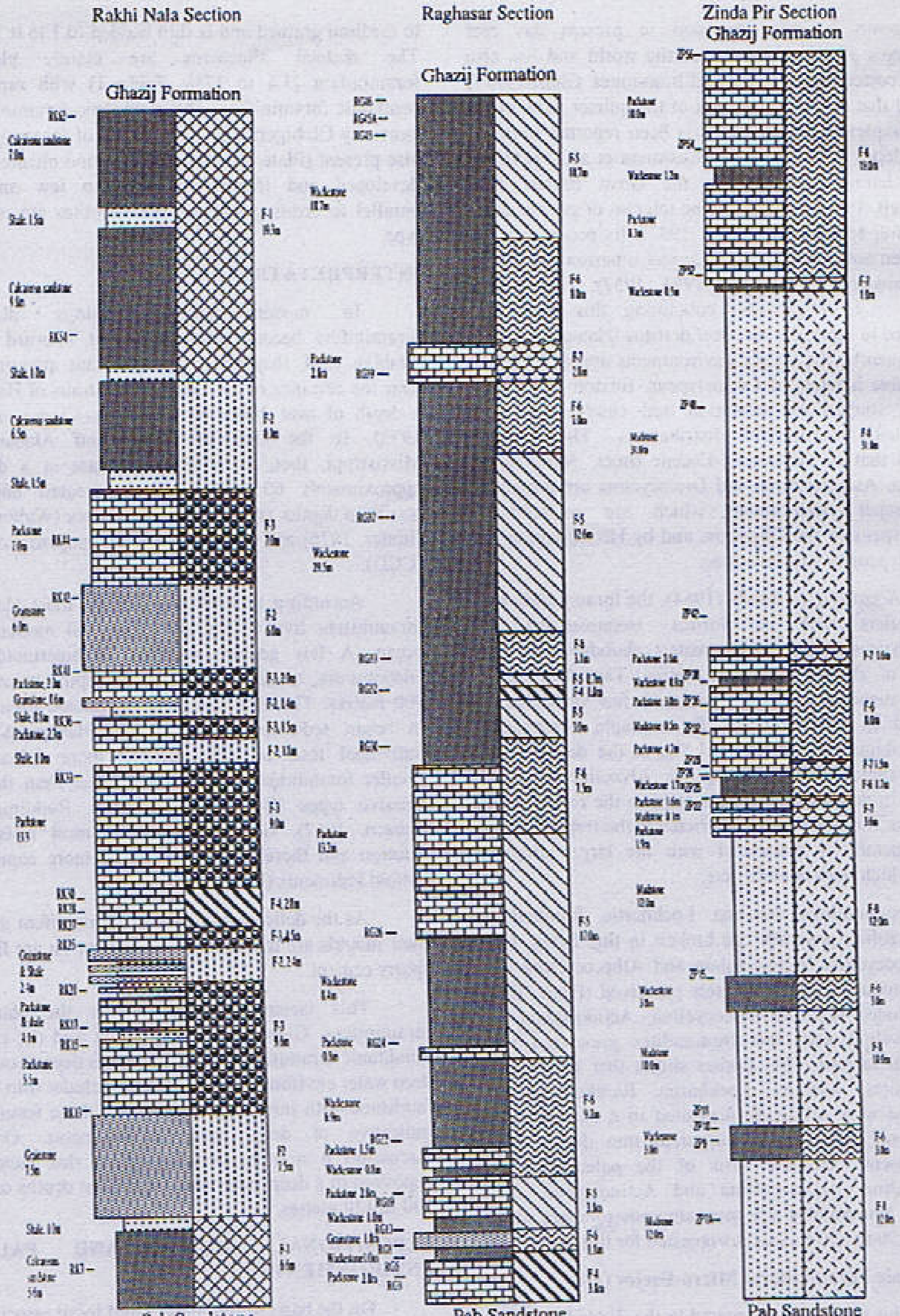



**Fig. 6** Distribution of lithology and facies types in three studied sections of the Dungan Formation

This genus is quite common in present day reef complexes of different parts of the world and has also been reported from ancient reef limestones. Ghose (1977) showed that it is an inhabitant of the quieter parts of the reef complex. Cycloclypeus, has been reported from the outer slopes of Bikini Attol (Cushman et al., 1954) and from channels adjacent to the Great Barrier Reef (Maxwell, 1968). It is said to be tolerant of greater depth and lower temperature (Cole, 1957). Its occurrence has also been noted from subsurface reef limestones of Bikini and Eniwetok atolls (Cole, 1954, 1957). The Tertiary limestone of Micronesia containing this genus are supposed to represent fore-reef detritus (Hanzawa, 1957). Consequently, the deeper environments appear to be the favourable habitats of Cycloclypeus. Buxton and Pedley (1989), studied the evolution and changes in ramp associated foraminiferal distributions. Their studies showed that in Palaeocene-Eocene times, Nummulites, Assilina, Asterocyclina, and Discocyclina are present in the deeper environment which are replaced by Spiroclypeus in the Oligocene and by Heterostegina and Cycloclypeus by Miocene time.

According to Bandy (1964), the foraminifera with chamberlets such as Sorites, Heterostegina and Cycloclypeus, attain their greatest abundance between depths of about 20 and 80 metres. They live on the deeper anchored types of seaweed. A few variations are reported in deeper waters for example, Amphisorus occurs abundantly in the Red Sea at the depth of 941 metres (Said, 1949). The genus Alveolinella is also present in depth of 20 to 80 metres in the region of the Sulu Sea. It is stenohaline restricted to the tropical waters and generally is associated with the larger discoidal forms which have chamberlets.

Nummulites, Assilina, Lockhartia, Ranikothalia and Alveolina generally are broken in this facies. Only the Discocyclina, Actinosiphon and Athecocyclina with few Nummulites are completely preserved (Plate 3B). It is concluded that the Discocyclina, Actinosiphon and Athecocyclina with few Nummulites grew and were preserved in situ. This studies shows that most of the Nummulites, Assilina, Lockhartia, Ranikothalia and Alveolina were originally deposited in a shallow ramp setting and then were transported into deeper ramp environments. On the basis of the paleoecology of Discocyclina, Athecocyclina and Actinosiphon along with the Nummulites a deeper ramp environment with a depth of 70 to 100 metres is suggested for this facies.

#### Planktonic Foraminiferal Micro-Facies (F 8)

This facies is encountered in the Zinda Pir section (Fig. 1). It is characterised by dark grey to grey coloured mudstone interbedded with shale. The biomicrite is fine to medium grained and is thin bedded (0.1 to 0.3 metre). The skeletal allochems are mainly planktonic foraminifera (3.4 to 17%; Table 1) with rare larger benthonic foraminifera. The planktonic foraminifera are generally Globigerinids. The moulds of foraminifera are also present (Plate 3C). Pressure solution phenomena are developed and mainly restricted to low amplitude, parallel to bedding and are the stylolites are of simple type.

### INTERPRETATION

In modern marine settings, planktonic foraminifera become more abundant seaward. In the Arabian Gulf, they occur in significant quantities only near the entrance of the Gulf in the Straits of Hormuz at a depth of over 100 metres (Hughes-Clarke and Keij, 1973). In the Gulf of Mexico off Alabama and Mississippi, there is a sharp increase at a depth of approximately 60 metres. Their greatest abundance occurs in depths greater than 200 metres (Walton, 1964; Hunter, 1976) and above the calcite compensation depth (CCD).

According to Milliman (1974), most planktonic foraminifera live within the upper 100 metres of the ocean. A few genera, such as Globigerinoides and Globorotalia, however, can live at depths greater than 500 metres. The distribution of planktonic foraminifera in ocean sediments depends upon the resistance of individual tests to solution. The more delicate and smaller foraminifers will dissolve faster than the more massive types (Berger, 1967, 1968; Ruddiman and Heezen, 1967). Globorotalia is the most resistant to solution and therefore appears to be more common in bottom sediments (Parker, 1971).

As the delicate and smaller foraminifera dissolve, their moulds are left behind, which later on are filled by sparry cement.

This facies comprises mainly the planktonic foraminifera, Globigerina/Globorotalia and the casts of planktonic foraminifera which indicates deposition in the deep water environment. This facies includes thin bedded mudstone with interbedded shale. All these features are indicative of deep water environments. On this discussion it may be concluded that this facies was deposited in a deep water environment at depths of about 100 to 120 metres.

### DEPOSITIONAL MODEL AND PALAEO-ENVIRONMENTS

On the basis of lithological and fossil associations, the Dungan Formation is interpreted as having been deposited in the carbonate ramp environments.

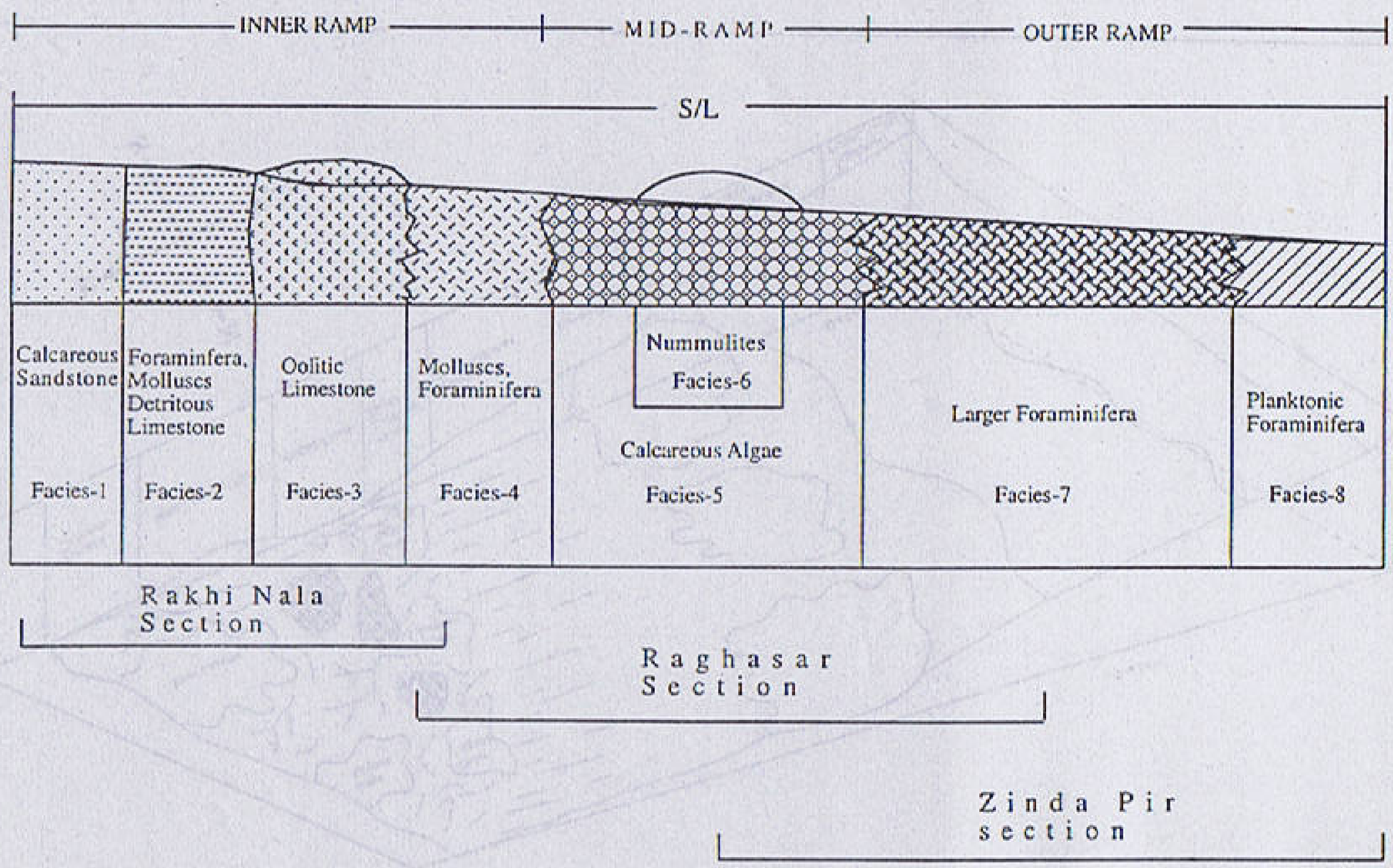



Fig. 7 Ideal Homoclinal Ramp Profile showing down-ramp distribution of facies in this study

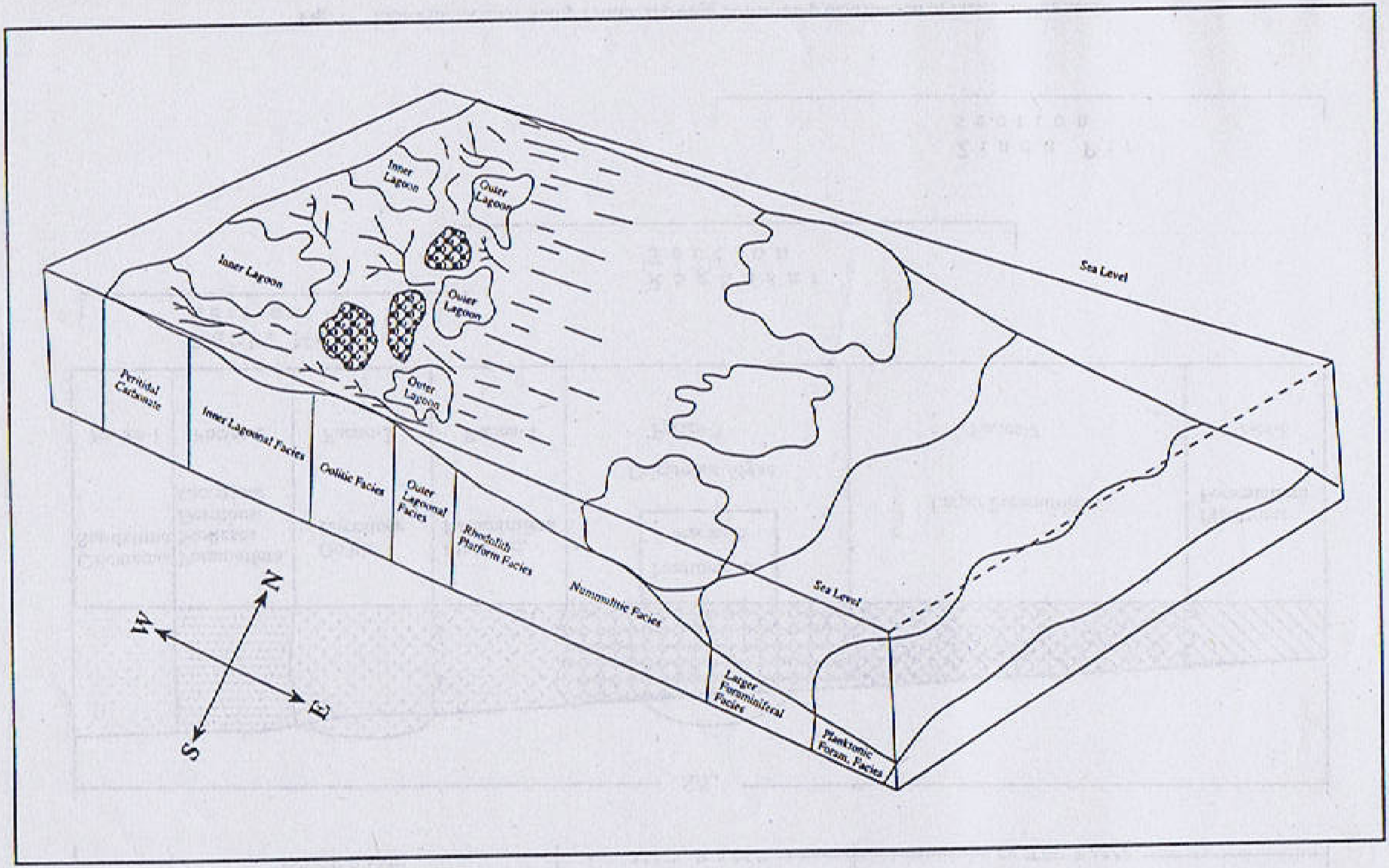



**Fig. 8** Idealized block diagram of proposed homoclinal ramp model facies and sedimentary environment of eastern Sulaiman Range, Pakistan.

The ramp-model as given by Ahr (1973), is "a sloping surface connecting two levels". There is no break in slope. According to him, grainstone and packstone are landward facies and the sediments become muddy in the basinward direction.

Read (1982, 1985), elaborated the ramp model and described two types of ramps.

The homoclinal ramp has a relatively uniform slope (one to a few metres per kilometre) into the basin and generally lacks significant sediment gravity flow deposits and slumps in deep water facies. It includes coastal clastics, cyclic lagoon and tidal flat carbonates and coal/evaporites. These pass seaward into nearshore ooid/peloid sands or skeletal sheets and buildups; deep ramp argillaceous lime wackestone/mudstone, containing open marine diverse biotas and slope and basin deep water pelagic muds or periflatform muds and shale interbeds.

The distally steepened ramp shows a marked increase in slope at the seaward edge of the deep ramp and abundant slumps, slope breccias and turbidites. It includes coastal clastics, cyclic lagoon, tidal flat carbonate, ooid/peloid sand or skeletal sheet and buildups; deep ramp sub-wave base, nodular burrowed lime wackestone, mudstone, with open marine biota; may also have slumps, breccias and turbidites along basin margin; and even-bedded grey to black lime mudstone and lesser wackestone, may be argillaceous or shaly, laminated, unburrowed, abundant intraformational truncation surfaces, and contain slumps and breccias with clasts of slope facies. The facies reflect relatively high (several degrees) slopes into the basin.

Buxton and Pedley (1989), gave emphasis to a ramp model for Tethyan Tertiary carbonate rocks. According to their study on Cenozoic carbonate rocks in Malta, Sicily, Tunisia and Antigua, they grouped the peritidal carbonates, lagoonal, unstratified (grainstone) barrier/beach facies, protected embayment (gastropod-sea-grass) facies and rhodolith platform/pavement facies into the inner ramp. For the outer ramp they suggested the coralgal patch-reef belt, larger orbitoidal foraminiferal facies and planktonic foraminiferal facies.

Burchette and Wright (1992) described the carbonate ramp and subdivided it into inner, mid and outer ramp. The inner ramp is the zone above fair-weather wave base, dominated by sand shoals or organic barriers and shoreface deposits and back-barrier peritidal areas. The mid ramp is the zone between fair-weather wave base and storm wave base. Sediments show evidence of frequent storm reworking. A variety of storm-related features typically occur, including graded beds and hummocky cross-stratification. Proximal-distal trends can commonly be recognised in ancient mid-ramp deposits (Aigner 1984; Burchette 1987; Faulkner 1988). The outer

ramp is the zone which extends from the depth-limit to which most storms influence the sea floor to the basin plain. Sediments show little evidence for direct storm reworking but a variety of storm related deposits such as sparse, graded, distal tempestites may occur in the upper part (Aigner 1984; Calvet and Tucker 1988). Their studies show that a wide variety of organisms have constructed mounds in mid and outer ramp environments, and that ramps develop mostly on cratonic interior basin margins, passive continental margins and foreland basins margins. The windward ramps are wave and storm dominated and have more grainstone facies in the inner ramp area. The leeward ramps show stronger progradation or even lower slope angles, with a tendency towards more tabular geometries, and less abundant grainstone than those in windward settings.

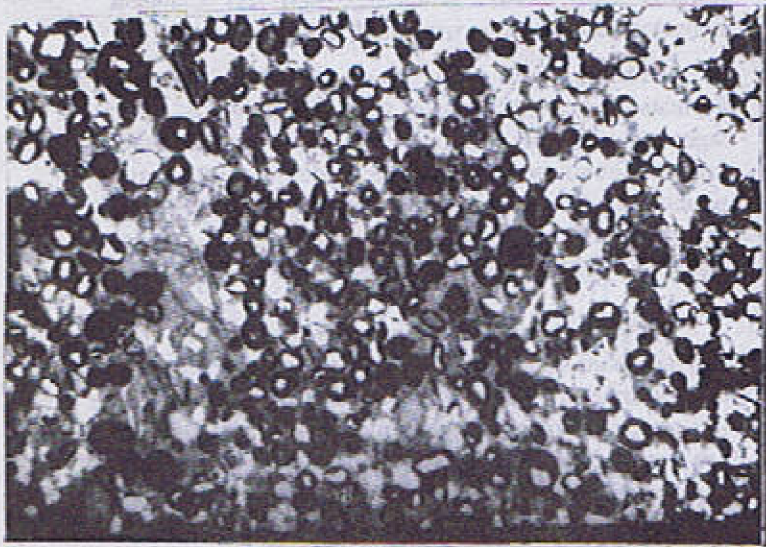
The present study shows that the Dungan Formation has a lithofacies of peritidal carbonates, inner lagoon facies, oolitic and outer lagoon facies in the inner ramp environment (Fig. 7). The rhodolith platform and nummulites facies are the mid ramp facies. The larger foraminifera and planktonic foraminiferal facies represent the outer ramp facies (Fig. 7).

The inner ramp facies show abundant grainstone and dominant sand shoal and high energy environments. The sediments may be removed from the coastal environment by longshore drift or wind deflation of beaches or shoal. The inner ramp facies also show oolitic units which may be assumed that the sediments removed by deflation from beach and shoal along the windward direction (Fig. 8).

The mid ramp facies are mainly thick-bedded to massive wackestones and packstones. They are bioturbated, slumps, and turbidites are rare in the mid ramp facies. The main skeletal allochems in this facies are red coralline algae and foraminifera. The red coralline algae are in the form of rhodoliths. As discussed above these rhodoliths include cool water (deeper) and shallower forms. In the higher latitudes they are in the shallow depth of cool water whereas in the low latitudes they shifted to the deeper depths (cool water). Similarly the presence of Assilina, Operculina and Nummulites in this facies show the deeper depth. Consequently it is concluded that the mid ramp facies accumulated in depths of 50 to 80 metres (Fig. 8).

**PLATE – 1**

A Inner Lagoon Facies 200μm



B Oolitic Facies 1000μm

C Outer Lagoon Facies 1000μm

**PLATE 2**

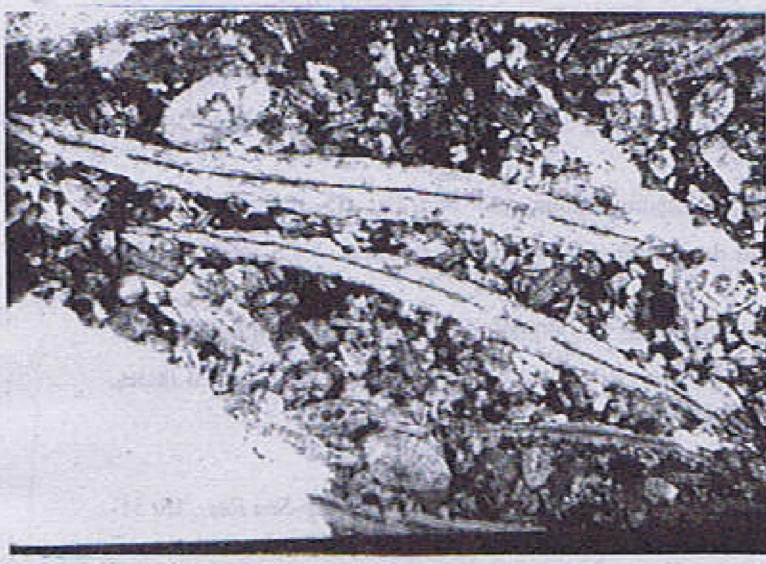
A Rhodolith Platform Facies 1000μm

B Boring Algae in Rhodlith Platform Facies 1000μm

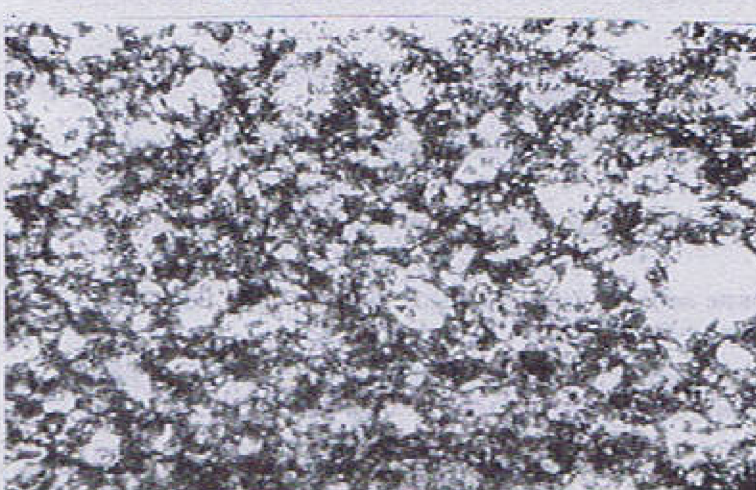
C Nummulitic Facies 1000μm

PLATE 3

A Nummulitic Facies 1000μm



B Larger Foraminiferal Facies 1000μm



C Planktonic Foraminiferal Facies 200μm

The outer ramp facies are mainly thin bedded lime mudstone, interbedded with shale. Truncation surfaces are rare. Few breccias and reworked sediments are present. The skeletal allochems in outer ramp facies are mainly Discocyclina, Athecocyclina, larger Nummulites, and Assilina, and Globigernia, and Globorotalia. As discussed earlier, the presence of these foraminifera indicate the deeper environment of deposition. It is concluded the outer ramp facies accumulated in depths of 70 to 120 metres (Fig. 8).

On the basis of this discussion, it is concluded that these facies are deposited on a ramp with a slope of about 1°. The ramp is homoclinal, and the facies are deposited on the windward side of the ramp.

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# TECTONIC MODELLING OF WESTERN HIMALAYA IN NORTHERN PAKISTAN BASED ON GRAVITY STUDY

BY

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**Abstract:-** *Gravity data in the Hazara and its adjoining areas of northern Pakistan have been incorporated for the interpretation of the gross crustal structure of the Hazara-Kashmir Syntaxis in western Himalayas. In this region two types of deformation have been observed. One is in the crystalline basement and other is in the sedimentary wedge. The crystalline crust of 38Kms thickness faulted into blocks in the northeast of Taxila and Abbottabad. These faults are Hazara Lower Seismic Zone and Bagh Basement Fault. These predeveloped faults have been reactivated after collision of Indian and Eurasian Plates.*

*Some of the normal faults trending in the NE-SW, also appeared to exist in the upper crystalline basement near Rawalpinidi. These faults were developed by the extensional stresses, which are caused by the bending of Indian crystalline basement.*

*In the sedimentary wedge the thin-skin structures have been developed by the southward migration of the sedimentary wedge. In the area under study the thin-skin structures consist of thrust faults, strike slip faults and the salt/incompetent state (decollement). In the eastern limb of Hazara Kashmir Syntaxis there is strong coupling between sediments and basement consequently the materials is uplifted. In Pakistan Late Precambrian to Early Cambrian age strata constitute the uplifted zone of decollement. Over this decolloment the western limb of Hazara-Kashmir Syntaxis move southward between Jhelum and Kalabagh strike slip faults.*

## INTRODUCTION

The Hazara-Kashmir Syntaxis (HKS) in the western Himalayas in northern Pakistan is the most prominent geological structure of the area. The western limb of Hazara-Kashmir Syntaxis consist of a complete series of over lapping nappes made up of various predominantly red brown coloured classic sediments, the Murree Formation of Tertiary age (Bossart et at. 1988). Two major Himalayan age thrust faults are wrapping around the HKS, northern one is the Panjal Thrust (PT) and the southern one is the Murree Thrust (Wadia, 1931). In the western limb, the Panjal and Murree faults have been subdivided the region into three tectonic elements. The tectonic element below the Murree Thrust in the core of HKS is mainly composed of Tertiary red and green sandstone and shales of Murree Formation. Thus Sub-Himalayas structurally the lowest element is characterized by and intensive folding associated with the formation of the Muzaffarabad Anticline. Along the hinge of anticline carbonates of Paleozoic and Cambrian age exposed.

The tectonic elements between Murree and PT mainly consist of Jurassic to Eocene Limestone and Hazara Slates of Precambrian age in the Main Boundary Thrust Zone (MBTZ) to the west. In the north of PT the upper most tectonic units are formed by Tanol and Salkhala Formation of Precambrian age intruded by Cambrian age rocks of Mansehra Granite (Le Fort et al. 1980). The geology and tectonics of western limb of HKS in northern Pakistan are most complicated as compared to the eastern limb. For further tectonic sub-division of the western limb into separate rock units, gravity survey was carried out in the study area.

The study area spread over northern Potwar and southern Hazara (Fig.1). Gravity measurements were taken with Worden Gravimeter (Model III) along the available metalled and unmetalled roads which generally cross the regional geological structures. The station or measurements interval was selected 1 Km. The gravity data was reduced to mean sea level applying conventional correction such as drift, free-air, Bouguer (with surface density 2.65 gm/cc), latitude and terrian correction. Cross sections A-A′ and C-C′ were taken for gravity modelling across the basement and sedimentary structures of the western limb of HKS (Fig.2).

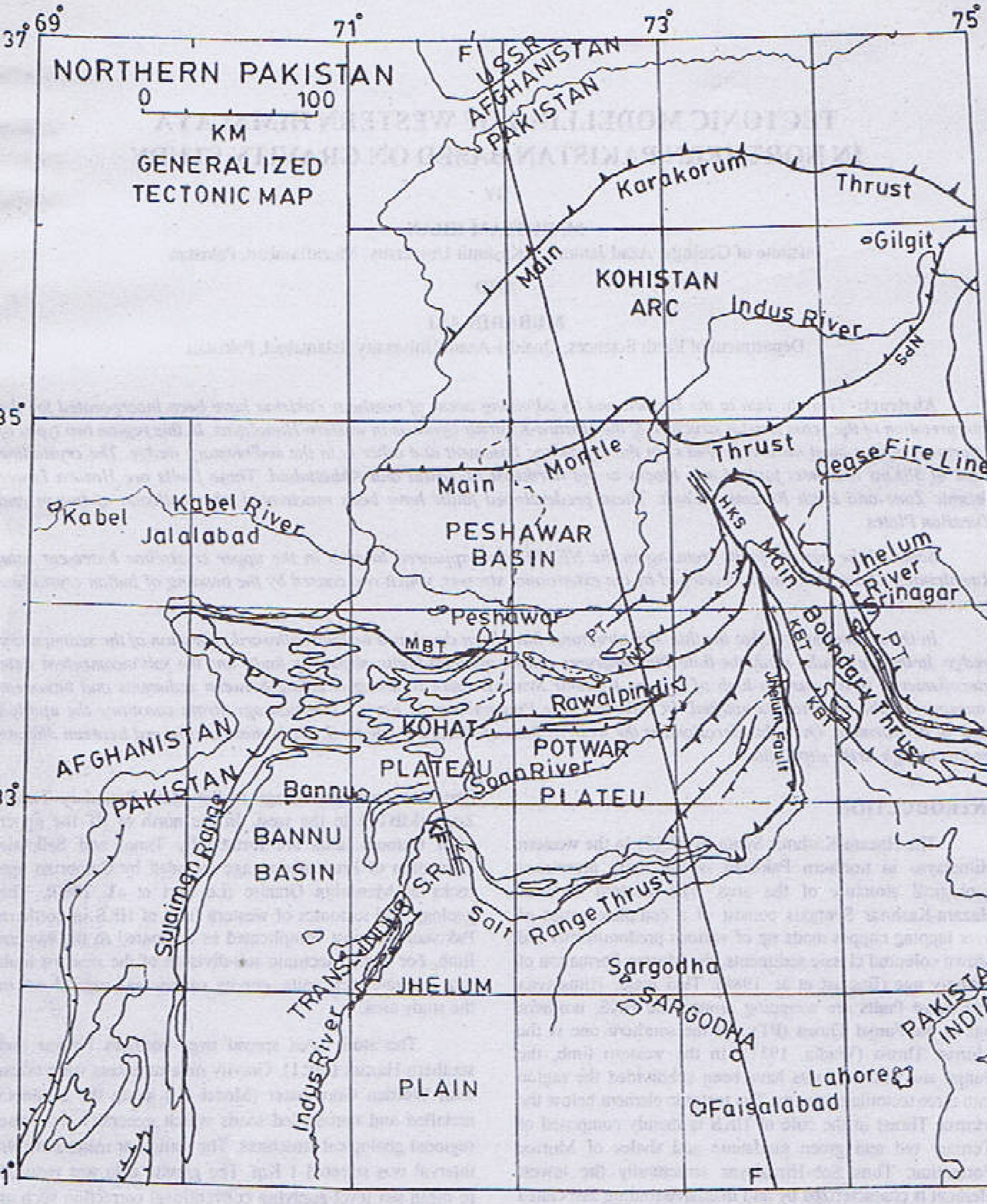


Fig. 1. Tectonic map of northern Pakistan, PT=Panjal Thrust, MBT=Main Boundary Thrust, NT=Nathiagale Thrust, KBT=Kashmir Boundary Thrust, after Kazmi and Rana (1982) and Chaudhry and Ghazanfar (1992)

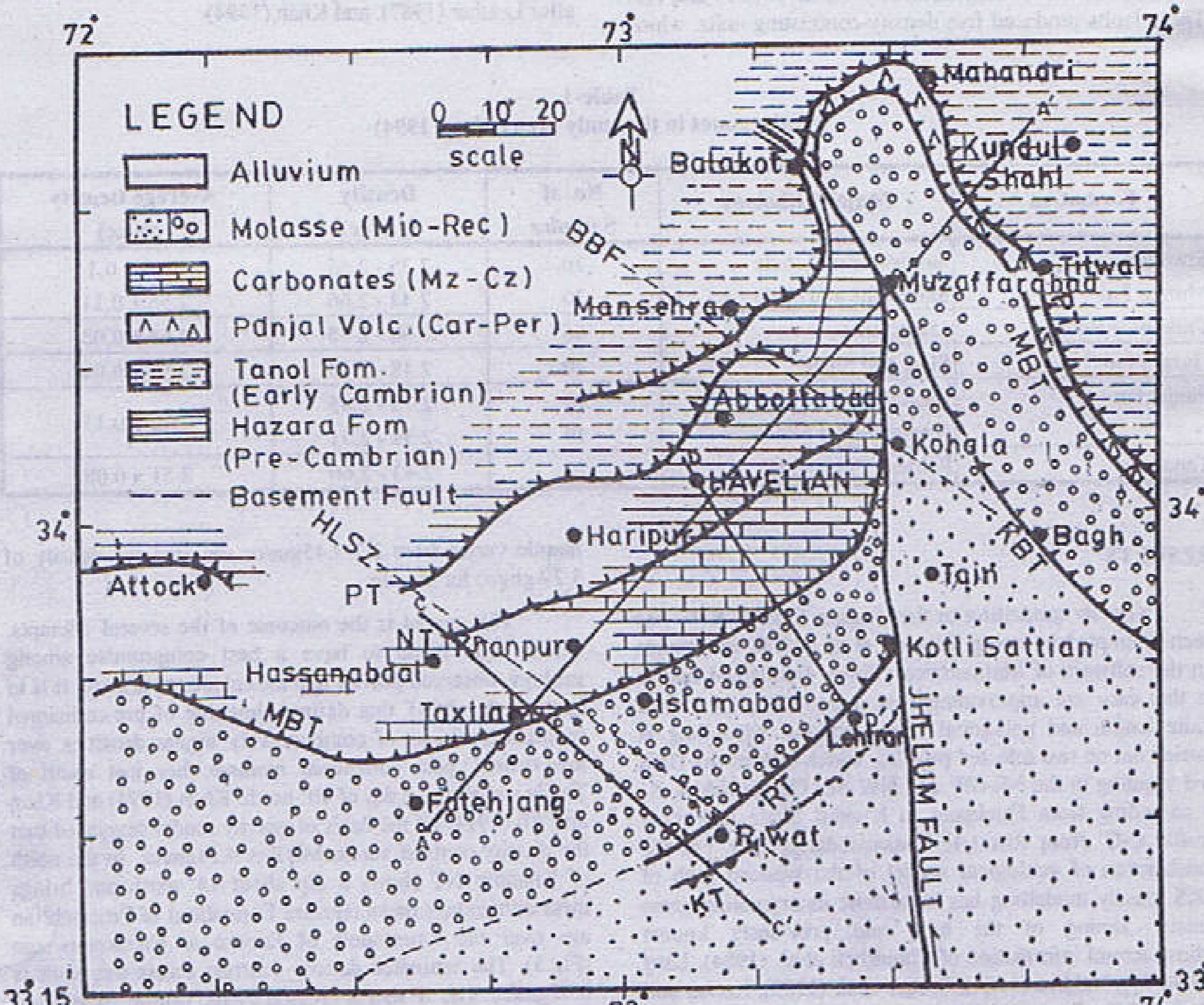


Fig. 2. Generalized tectonic map of Hazara-Kashmir Syntaxis in northern Pakistan, MT=Manshera Thrust, PT=Panjal Thrust, MBT=Main Boundary Thrust, KBT=Kashmir Boundary Thrust, RT=Riwat Thrust KT+Kahuta Thrust, HLSZ=Hazara Lower Seismic Zone, BBF=Bagh Basement Fault, compiled after Wadia (1928), Latif (1970, 1973), Calkins et al. (1975), Kazmi and Rana (1982), Baig and Lawrence (1987), Greco (1989), Chaudhry and Ghazanfar (1992), and Khan and Ali (1994). Section A-A', C-C', and D-D' are selected for gravity modelling (Khan, 1994).

**Density of Rock Units**

The lithological units crossed by the gravity sections are the Siwaliks molasses and Murree Formation (Miocene to Recent), Carbonates (Mesozoic) and Hazara Formation (Precambrian) which are separated by major faults i.e. Riwat Thrust (RT) Main Boundary Thrust (MBT) and NT. These faults produced five density-contrasting units, which are given in Table-1 and were measured by Khan (1994). In gravity modelling the density contrasts assigned to geological bodies in Table-1 and Moho density 3.29 gm/cc are relative to the average density of the crystalline basement taken as 2.95gm/cc after Verma (1991). The density used for the Salt Range Formation is 2.25gm/cc after Leather (1987), and Khan (1994).

**Table-1**
**Density zones in the study area (Khan, 1994)**

| Formation | Major Lithology | No. of Samples | Density (gm/cc) | Average Density (gm/cc) |
|---|---|---|---|---|
| Siwaliks | Sandstone and shale | 20 | 2.35 - 2.55 | 2.45 ± 0.1 |
| Murree Fm. | Sandstone and shale | 30 | 2.44 - 2.66 | 2.55 ± 0.11 |
| Carbonate Rocks | Limestones | 66 | 2.60 - 2.75 | 2.65 ± 0.08 |
| Hazara Fm. | Slate and Shale | 20 | 2.48 - 2.55 | 2.53 ± 0.04 |
| Panjal Fm. | Basic Volcanics and | 10 | 2.75 - 2.85 | 2.72 ± 0.11 |
| | Agglomeratic Slates | 10 | 2.59 - 2.71 | |
| Tanol Fm | Pelites / Psammites | 20 | 2.43 - 2.60 | 2.51 ± 0.08 |

**RESULTS**

Gravity modelling in the western limb of KHS has been attempted by using Talwani et al. (1959) techniques on the software of Malinconico (1986). Geological bodies in this case are approximated as horizontal prisms with finite length and polygonal cross sections. Modelling is carried out on two selected profiles, which crosses the HKS and trending in the NE-SW and NW-SE. One profile A-A′ is extending from Fatehjang to Kundul Shahi and other profile C-C′ from Riwat to Hassanabdal (Fig.2). For the construction of geological model of the western limb of HKS gravity modelling has been done incorporating gross density zoning of the area and previously known lithostructural information of Tahirkheli et al. (1984), Latif (1970, 73), Valdiya (1980), Seeber et al. (1980), Karner and Watts (1983), Powell and Conaghan (1973b), Greco (1989) and Khan and Ali (1994). The gravity modelling of Khan (1994) and Khan and Ali (1994) along NE-SW oriented profile A-A′ crosses obliquely the major tectonic features such as the MBT, NT, PT and the Jhelum Fault (JF) generates geological model of the area as shown in Fig.3. In the study area due to the presence of low density rocks like Salt Range Formation (2.25gm/cc), Hazara Formation (2.53gm/cc), Tanol Formation (2.51gm/cc), Murree Formation (2.55 gm/cc) and Siwaliks molasse (2.45gm/cc) decreases. The basic volcanic rocks of high density (2.83gm.cc) are very limited in the study area.

The density used for the crystallire crust is 2.95gnt/cc after Verma (1991) and Khan (1994) and the density for the Salt-Range Formation is 2.25gm/cc after Leather (1987) and Khan (1994) The actual density of mantle varies from 3.2-3.45gm/cc we used the density of 3.29 gm/cc for mentle.

This model is the outcome of the several attempts, which were made to have a best compromise among geology, observed gravity and the calculated gravity. It is to be seen that MBT that defines thrusting of pre-collisional sedimentary rocks of comparatively higher densities over low density post collisional molasse, lies just south of Taxila and shows a dip of 10° north. Khan (1994) and Khan and Ali (1994) on the basis of gravity model suggested that the density contrast across MBT is 0.14gm/cc. In the north of Khanpur NT shows a dip about 14° north and brings metasedimentary rocks (Hazara Formation) of Precambrian age over the limestone's of Eocene to Cretaceous age (Fig.3). The estimated density contrast across this fault is 0.07gm/cc. The JF that is crossed by the profile, 3km south of Muzaffarabad city has a strike slip movement and appears to dip at an angle of 80° W. The density contrast between the molasse of Murree Formation and metasediments of Hazara Formation across this fault is about 0.03gm/cc. In the eastern limb of the KHS near Titwal, MBT is a boundary between Panjal Volcanics and Murree Formation molasse. The gravity modelling (Fig.3) shows that MBT in this region is dipping at an angle of 41° NE and penetrates to a depth of 20km. The density contrast across the fault is 0.21gm/cc. PT next to MBT separates Panjal Vocanics of Carboniferous to Permian age from Tanol Formation of Cambrian age and shows a dip of 30° NE. The density contrast across this fault is roughly 0.20gm/cc.

The 2km thick Salt Range Formation (decollement) is present under the Fatehjang (Fig.3) which decreases

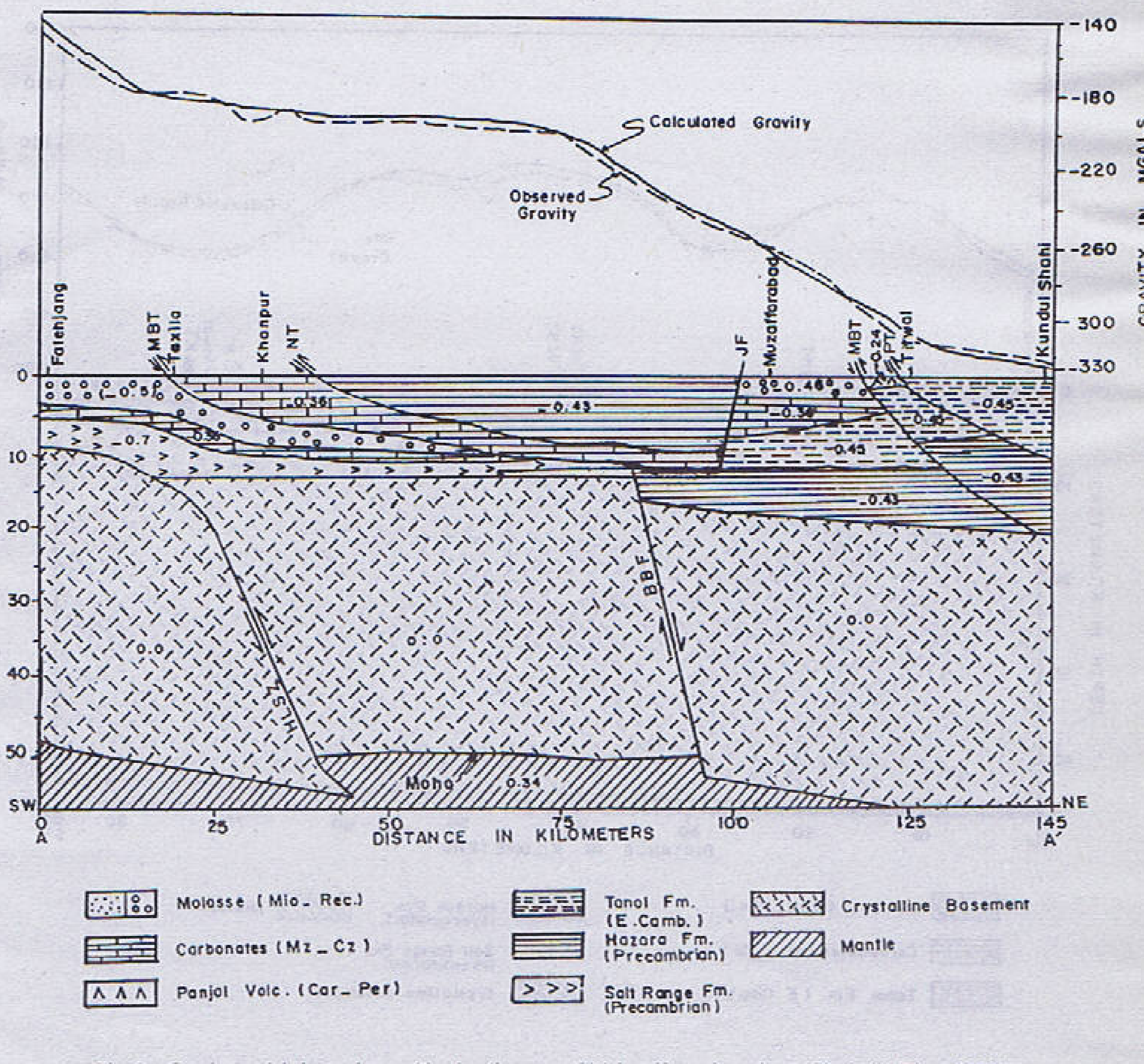


Fig. 3. Gravity model shows the combined sediments and Moho effects along the profile A-A′ (Khan, 1994).

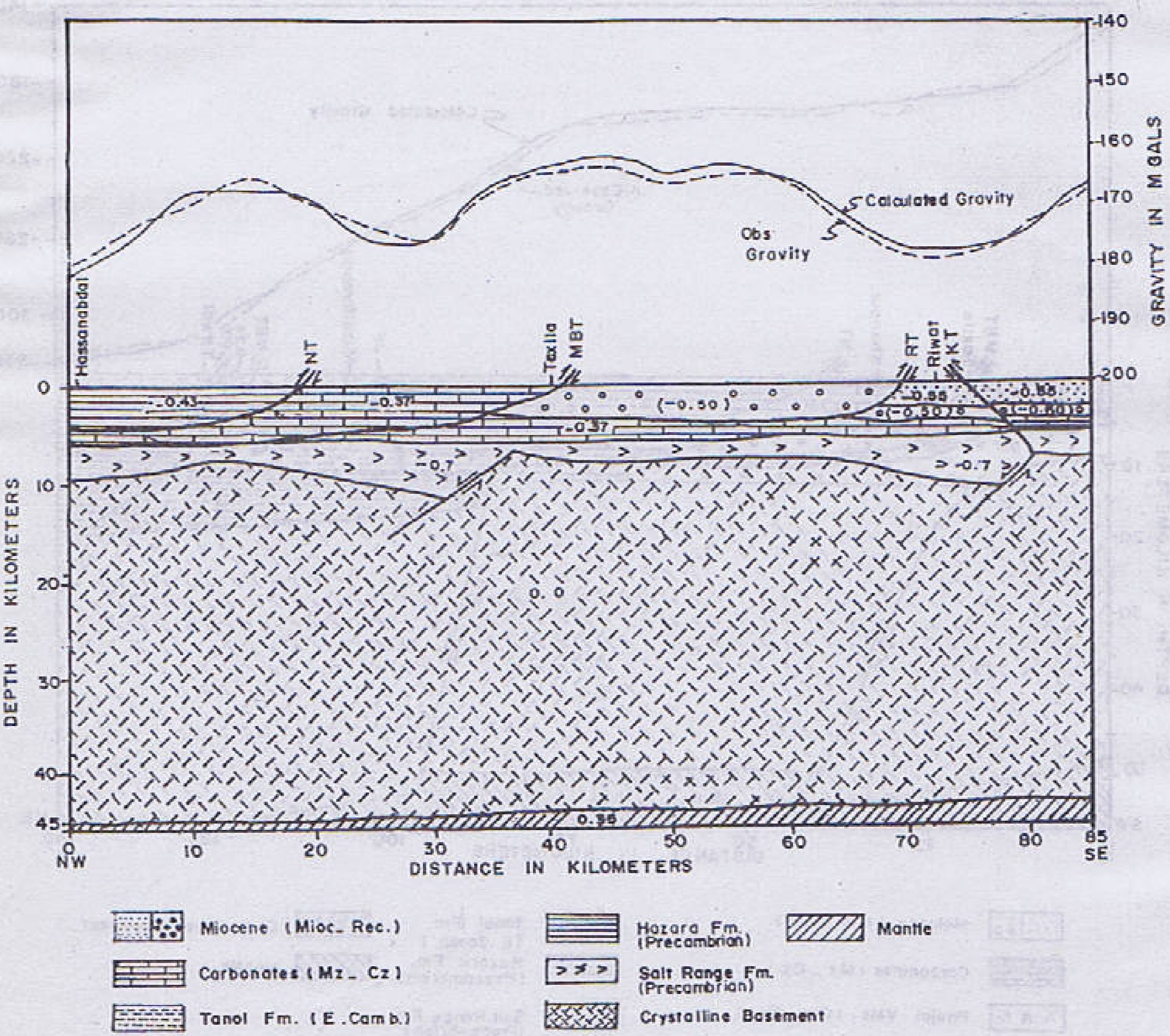


**Fig. 4.** Gravity model shows the combined effects of sediments and Moho along the profile C-C′.

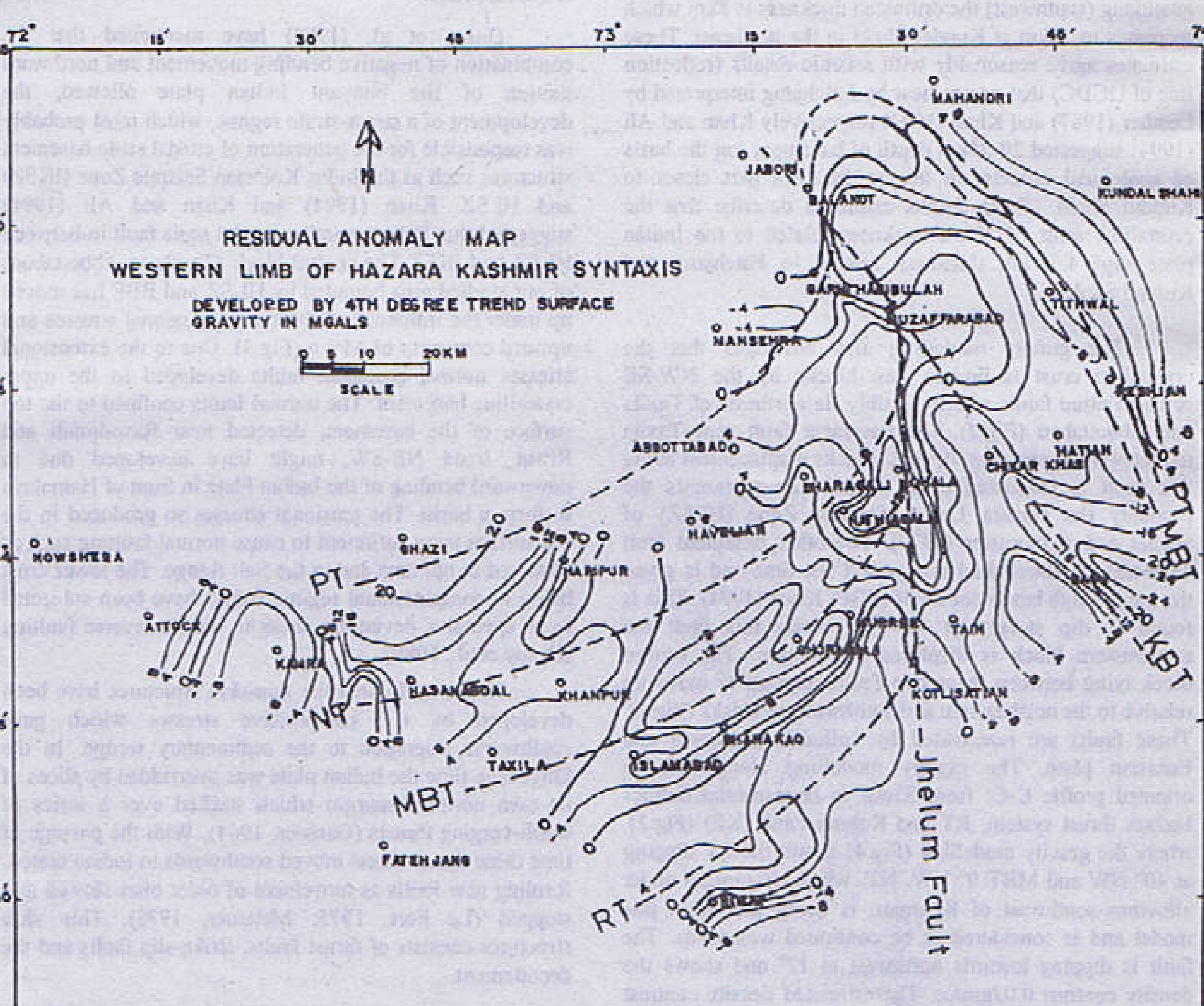


Fig. 5. Residual gravity anomaly map, PT=Panjal Thrust, NT=Nathiagali Thrust, MBT=Main Boundary Thrust, KBT=Kashmir Boundary Thrust, RT=Riwat Thrust.

towards northeast. Near JF Salt Range Formation is pinching out. It is also observed in this modelling that the sedimentary wedge is thickening towards northeast. At Fatehjang (southwest) the estimated thickness is 8km which increases to 20km at Kundal Shahi in the northeast. These estimates agree reasonably with seismic results (reflection line of OGDC) that passes near by Fatehjang interpreted by Leather (1987) and Khan (1994) respectively Khan and Ali (1994) suggested 20-25km depth of basement (on the basis of geological models) in the northeastern part closer to Kundul Shahi. These depths estimates describe that the crystalline crust of 38km thickness related to the Indian plate dips 4.73°km thickness related to Fatehjang and Kundul Shahi.

The gravity modelling also envisages that the crystalline crust is broken into blocks by the NW-SE oriented blind faults which possibly lie northeast of Taxila and Abbottabad (Fig.2). The basement fault near Taxila trends NW-SE and dips 70° NE. Blocks displacement along this fault is estimated about 6km. This represents the probably the Hazara Lower Seismic Zone (HLSZ) of Seeber and Armbruster (1979). The other basement fault northeast of Abbottabad is reported fist time and is given the name Bagh basement Fault (BBF) Khan (1994). This is found to dip steeply at 72° NE, along this fault the northeastern block is displaced about 4km. The central block lying between these two faults appears to move up relative to the northeastern and southwestern blocks (Fig.3). These faults are reactivated by collision of Indian and Eurasian plate. The gravity modelling along NW-SE oriented profile C-C' from Riwat to Hassanabdal defines Hazara thrust system, RT and Kahuta Fault (KF) (Fig.2), where the gravity modelling (Fig.4) shows the RT dipping at 40° NW and MBT 9° NW. NT, which disappears under alluvium southwest of Khanpur, is being picked in this model and is considered to be continued westwards. The fault is dipping towards northwest at 12° and shows the density contrast 0.07gm/cc. The estimated density contrast across the RT is 0.03gm/cc. In southeastern part near Riwat. KF is marked in the Siwalik molasse and appears to dip 49° SE, opposite to the dips of Hazara thrust system. This thrust shows the penetration deeper than the Rt. The modelling also includes northwest dipping faults in the upper part of the crystalline basement at 30 and 77km points near Rawalpindi (Fig 4.) It is gathered from this study that the Hazara thrust system is thin-skined feature in which each fault shows increasing dip and penetration depth towards northeast, whereas in the apex and the eastern limb the PT and MBT which trend NW-SE shows relatively deeper penetration and high angle dips in the sedimentary wedge. The fault plain appers to dip steeply near the surface and become gentle in depth. It is also envisaged, that NW-SE trending normal faults (dipping northwest) exist in the upper crystalline basement near Rawalpindi where the deeper basement faults such as HLSZ and BBF reach upto Moho trend NW-SE and dip towards northeast. The deformation (Thin-skin structure) in the sedimentary wedgy resulted due to collision of Indian and Eurasian plates.

## DISCUSSION

Duroy et al. (1989) have mentioned that the combination of negative bending movement and northward motion of the buoyant Indian plate allowed, the development of a stress-strain regime, which most probably was responsible for the generation of crustal scale basement structures such as the Indus Kohistan Seismic Zone (IKSZ) and HLSZ. Khan (1994) and Khan and Ali (1994) suggested that BBF is another crustal scale fault in-between HLSZ and IKSZ The central block (Taxila to Abbottabad) of our studied area bounded by HLSZ and BBF has moved up under the influence of these compressional stresses and upward convexity of Moho (Fig.3). Due to the extensional stresses normal basement faults developed in the upper crystalline basement. The normal faults confined to the top surface of the basement, detected near Rawalpindi and Riwat, trend NE-SW, might have developed due to downward bending of the Indian Plate in front of Hamalaya to form a basin. The tensional stresses so produced in the top surface were sufficient to cause normal faulting such as observed in our area and in the Salt Range. The lower crust being in compressional regime would have been subjected to an excessive deviatoric stress to induce reverse faulting (Duroy et al., 1989).

In the study area the thin-skin structures have been developed by the compressive stresses which gave southwards migration to the sedimentary wedge. In the Oligocene time the Indian plate was overridden by slices of its own northern margin which stacked over a series of south-verging thrusts (Gansser, 1964). With the passage of time these thrust sheets moved southwards to Indian craton, forming new faults as movement of older ones slowed and stopped (Le Fort, 1975; Mattauer, 1975). Thin skin structures consists of thrust faults, strike-slip faults and the decollement.

The thrust faults have brought incontact different stratigraphic units in the HKS. In the western limb, the NT is situated between limestones of Eocene to Cretaceous age and Precambrian metasediments of Hazara Formation. In the north of NT the presence of thick Hazara Formation might have resulted by repetition through imprecation of Hazara Formation as mentioned by Coward and Butler (1985). NT was reported as a part of the MBT (Greco, 1989; Baig and Lawrence, 1987), but it may not be true as it does not join the detachment thrust or the MBT at surface or at depth. This fault trends NE-SW and dips in NNW. The dip of the fault is found increasing towards northeast. Geologically it has been varified from Nathiagali to Hassanabdal by Latif (1984) and our study also shows its continuation in the west of Hassanabadal, and may be extending to Hissartang fault of Hylland et al. (1988), under the alluvium cover. Whereas in the northeast this fault appears to has been cut by JF about 6 Km south of Muzaffarabad City.

The MBT is the major southern most lineaments along which the pre-collisional sediments and metasediment of higher densities are being thrusted over low density post collisional molasses (Fig.3,4). Le Fort (1975) suggested that MBT was developed nearly 10 Ma ago. Like NT the dip angle of this fault also increases towards northeast and the fault plane is probably steeper in shallow depth and become gently in depth, and joins the low angle detachment fault of Seeber et al. (1986) and wrapping all around the HKS (Fig.2). Near apex in the eastern limb the gravity studies describe MBT as thin-skin fault penetrating upto the depth of upper crystalline basement in the sedimentary wedge (Fig.3).

PT in the northeast of MBT trends in the NW-SE parallel to the MBT, this fault is older than the MBT (Wadia, 1931). Gansser (1981) and Greco (1989) have drawn MCT into the PT of Kashmir near Titwal, which was not accepted by Chaudhry and Ghazanfar (1993), Baig and Lawrence (1987), Khan (1994) and Khan and Ali (1994). In the present study gravity interpretation disagree with Gansser and Greco, and suggested the presence of PT between Panjal Volcanics and Tanol Formation near Titwal and do not show the expected change of gravity over MCT upto the Kundul Shahi. This fault may be expected in the upper Neelum Valley where the thick crystalline basement of Indian Shield is exposed on the surface (Khan and Ali, 1994).

The Kashmir Boundary Thrust (KBT) of Pleistocene age has been marked by Chaudhry and Ghazanfar (1992) between Balakot and Muzaffarabad, whereas in the southeastern side it was not clearly observed. The interpretation of the residual gravity map (Fig.5) allows to extend it to Bagh. KBT is running between Murree Formation and Siwalik molasses, near Kohala Siwalik molasse was eroded (SW of KBT) and consequently Murree Formation was exposed. The KBT is cut by JF near Muzaffarabad (Fig.2). The RT and KF are extending in the NE-SW and dip in the opposite directions (Fig.4). The RT is reported as an extension of JF (strike slip) (Baig and Lawrence, 1987) and is diverging from the village Tain. Our study disagree with Baig and Lawrence and consider RT as a thrust fault because the older Murree Formation thrusts over the younger Siwaliks molasse (Fig.4). The KF (in the Siwliks molase) appears to be reverse fault and most probably is cut by JF somewhere on the south of village Kotli Satian.

The JF is the youngest sinistral fault of the area (Chaudhry and Ghazanfar, 1992) trending north south along the River Jhelum. The fault is considered to be active and is responsible for the landslide activity in the region. Chaudhry and Ghazanfar (1992) calculated about 31km southward offset of the western limb along the JF and Khan (1994) calculated 40km net slip between Balakot and Muzaffarabad. This fault is visible in residual gravity map from Tain to Muzaffarabad. City (Fig.5). The gravity modelling of Bouguer anomaly suggested that JF marks eastern boundary of salt (decollemtn) that exists under the western limb.

This study favours the view given by Lillie et al. (1987) that the thick salt layer under Hill ranges (Margalla Hills and Kala Chitta Hills) near MBT (Fig.3,4) is thinning out towards northeast. The model A-A′ (Fig.3) indicates that the Salt Range Formation (decollement) is 2 Km thick under Fatehjang, and 3.75km under Taxila near HLSZ and pinches out near JF, and is absent in the eastern limb near the apex of the HKS. The low angle faults of the western limb of HKS are the argument of southward thrusting on decollement. Whereas in the eastern limb, the absence of decollement is responsible for high topography and high angle thrust faults. The JF running along the river Jhelum joins the Salt Range Thrust Front in the south and is considered as the boundary between salt and no salt tectonics. The central block between the Kalabagh strike-slip fault (dextral) and JF (sinistral) (Fig.1) moves southward on the decollment due to south directed compressional stresses related with the collision of Indian and Eurasian Plate. At present this collision is accommodated along the Salt Range Thrust Front and MBT (Khan, 1994).

## CONCLUSIONS

The gravity modelling in the western Himalayas suggested that the HKS in northern Pakistan is underline by faults under Taxila and north east of Abbottabad. The former is the HLSZ and the later is BBF The central block between HLSZ and BBF has been uplifted. In the upper crystalline basement, NW-SE extending normal faults identified near Rawalpindi can be related to large extensional stresses created by the downbending of Indian plate.

The differential movement in the presence and absence of decollement developed the low and high angle thrust faults in the western and eastern limb respectively. JF marks the salt and no salt boundary of the area and the western limb of HKS moves southward along the Jhelum strike-slip fault.

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# MINERAL CHEMISTRY OF BASAL PERIDOTITE-MYLONITE FROM THE METAMORPHIC SOLE OF SAPLAITORGARH MASSIF, MUSLIMBAGH OPHIOLITE, PAKISTAN.

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**Abstract:-** *The basal harzburgite-mylonites from the metamorphic sole of the Saplaitorgarh massif of the Muslimbagh ophiolite contain 80-95% olivine, 5-20% clinopyroxene, 1-2% amphibole and spinel. Microprobe analyses of two samples show that the olivine porphyroclasts and neoblasts are forsterite (Fo91). The orthopyroxene porphyroclats and neoblasts are Mg-rich enstatite (En91-92) with variable Al and traces of Ca. The chrome spinel in one sample is high-Al type and in the other it is of high-Cr type. The chrome spinel grains also exhibit optical and chemical zonation. The neoblast growth and the zonation are result of reequilibration during mylonitic deformation in an early stage of the ophiolite emplacement. Under the influence of $H_2O$-rict fluids. Hydrated secondary minerals like pargasitic hornblende (replacing diopside), tremolite and talc (replacing enstatite), chlorite and magnetite (replacing spinel) formed during and after the mylonitic deformation that resulted from the emplacement-deformation of the Muslimbagh ophiolite.*

## INTRODUCTION

Ophiolites are important markers of plate boundaries (e.g., Gansser, 1964), and their age commonly indicates the time of large-scale plate reorganization. The ophiolites allow a three-dimensional study of the ocean-floor, which is not possible by the deep-sea drilling programmes. However, ophiolites undergo deformation and overprinting during their emplacement onto the continental crust and it is important to separate ocean floor and emplacement-relatred structures in order to understand the processes at the ocean floor. In this study we have focussed on the basal part of the Muslimbagh ophiolite which underwent overpinting during its emplacement.

This study presents mineral chemistry of two unaltered samples (323E and 341E, Fig.2) from the basal harzburgites. These show evidence for chemical zonation in enstatite and spinel related to the mylonitic deformation at amphibolite to granulite facies conditions, which is also characterzed by the development of pargasite.

## GEOLOGY OF THE OPHIOLITE

The Muslimbagh ophiolite is located in the upper Zhob Vally NE of Quetta, and is a part of the western ophioligte belt of Pakistan that comprises the zone of Bela-Muslimbagh-Waziristan ophiolites. This belt marks the boundary between the Indian plate and Afghan block. The Muslimbagh ophiolite is the best khnown ophiolite of the belt and has been focus of many studies (e.g., Vredenburg, 1901: Hunting Survey Corporation, 1960: Biligrami and Howie, 1960, 1964, 1968: Shams. 1964.: Van Vloten, 196 : Snelgrove and Ruotsala, 1968: Ahmed and Chaudhry. 1969: Rossman et al., Ashraf et ai., 1972: Shah, 1974 Moores et al., 1980; Munir and Ahmed, 1985; Otsuki e aL., 1989: Mahmood et al., 1995). The Muslimbagl ophiolite includes two main blocks called Jangtorgarh and Saplaitorgarh (Fig.1). The eastern Sapalitorgarh massif shows a nearly complete ophioliteic sequence as defined by the Penrose Conference (Anynymous, 1972) except the extrusive sequecne and its sedimentary cover. Ar/Ar dating by Mahmood et al. (1995) on the subophiolitic

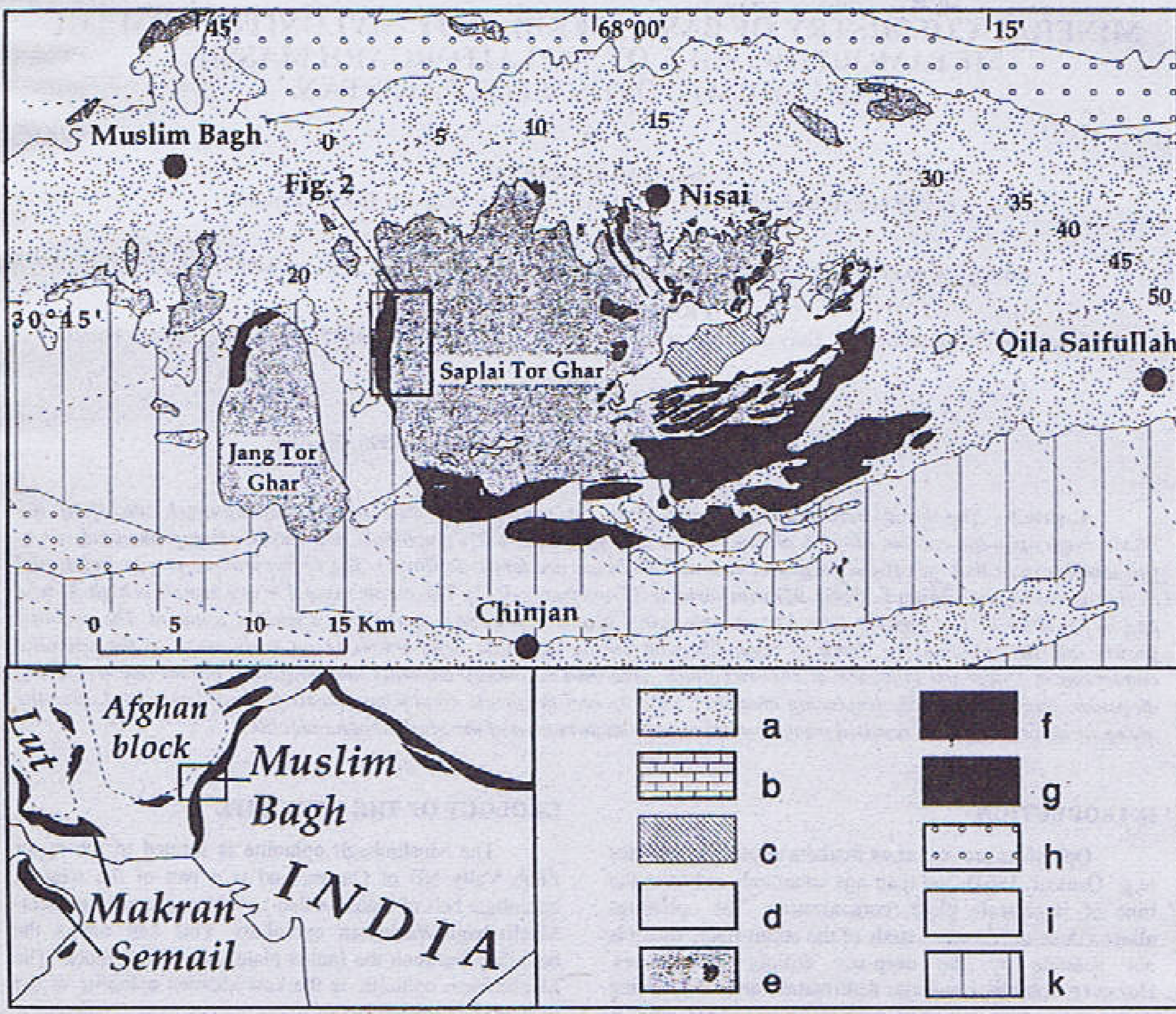


**Fig 1** Geological map of the Muslim Bagh ophiolite showing outcrops of the Saplai Torghar massif (after Hunting Survey Corporation, 1960). The gravimetry anomaly lines of the Zhob Valley in milligals are based on Farah and Zaigham (1979) This indicates an eastward thickening of the ophiolite where it is not exposed. A) Quaternary; b) Tertiary; c)sheeted dyke complex; d) gabbros; e) mantle sequence with pyroxenite/gabbro intrusions; f) flysch; k) Mesozoic carbonates.

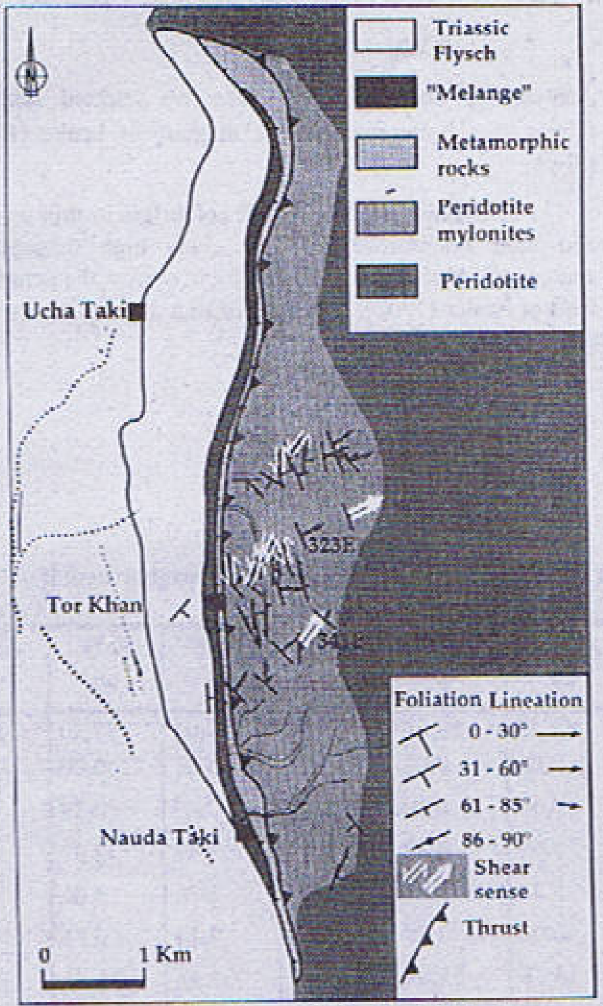


**Fig 2** Map of the basal part of the Saplai Torghar massif showing foliation/lineation in the mylonitic peridotites and location of the analyzed samples.

metamorphic rocks and metadolerites gave ages between 70.17.o and 65.1 4.1 Ma; thus dating inital ophiolitc emplacement as Masstrichtian. Final ophiolite emplacement onto the contincrtal edge probably occurred in Paleocene (Allemann, 1979). The emplacement direction was from WSW to ENE (present day orientation; Mahmood et al., 1995), but post-emplacement clockwise rotation as a result of the apline tectonics is likely.

## PETROGRAPHY

Basal peridotitic mylonites are exposed on the western side of the Saplaitorgarh massif and along the northern side of the Jantorgarh massif (Fig.1). The best outcrops are present below the Saplatorgarh massif between Ucha Taki and Nauda Taki at immediate structural contact with the subophiolitic metamorphic sole (Fig.2). Basal peridotites are distinguished by a prominent dunite/harzbugite compositional banding. The thickness of the individual bands varies from a few centimeters to a few meters. These bands are parallel to the foliation and have a mylonitic to fine-grained porphroclastic texture, In the region of Tor Khan (Fig.2) banded unit is a few meters thick and the foliation in the basal peridotites dips ENE. The contact with the underlying peridotites is sharp.

These peridotites contain on average, 80-95% olivine, 5-20% orthophyroxen, 2-5% clinopyrowxene, upto 2% amphibole and spinal. At certain levels near the contact wit metamorphic sole, the basal peridotites contain brown amphibole. Macroscopically visible lineations are marked by spinal trails and sometimes by elongated orthopyroxenes. Similar orientation of linearly streched minerals are found in the underlying metamorphic rocks. Under the microscope a few old porphyroclastic olivine grains are surrounded by small, newly crystallized olivine grains showing mosaic texture, These olivine neoblasts display weak elongation, The porphyroclasts (1.5 to 2.5) mm in size) contain subgrain boundaries and their width: length ratio is upto 1:6 Orthopyroxene alxo shows partial recystallization, and elongated pyroxene grains have width/length ratio of ca. 8. The subgrain boundaries in porphyroclasts permit determination of the shear sense. The elongated spinels are commonly transparent brown in thin section

## MINERAL CHEMISTRY

Two samples harzburgite mylonites were analyzed using an electron probe microanalyzer set up at the University of Montpellier II, France. The mineral chemical analyses are given in Tables 1 Through 5. The orthopyroxene (Table 1: Fig. 3) is enstatite (X=0.911-0.924) with $Al_2O_3$ varying from 0.82 to 2.04% in sample 341E and from 2.04 to 3.42% in sample 323E. Orthopyroxene from both the samples show very low CaO which varies from 0.13 to 0.55% $Al_2O_3$ and CaO in orthopyroxenes of peridotites index the degree of depletion (Roberts, 1992). Slightly higher values of A1 O for sample 323E may point to its lower degree of depletion. The olivine (Table 2; Fig. 3) is forsterite (X=0.911-0.914). The chrome spinel of sample 323E is rich in A1 and relatively poorer in Cr. The chrome spinel of sample 341E is rich in Cr. and low in A1 (Fig. 4A). This is also seen in the Cr# (Cr#=100 Cr/(Cr+A1) that varies from 55.66 to 71.o3 in sample 341 and 25.17 in the sample 323E.

A traverse across one grain of chromain spinel in the sample Z341 E showed a zonation of spinel with the core richer in Cr and margin richer in A1 (Fig.4b). The trend of Cr depletion and A1 enrichment towards the grain margins which has been reported from the Chilas Complex, Pakistan, by Jan et al. (1992) is regarded as result of exsolution. Chromain spinel exhibits secondary alteration. Many of the spinel in the basal peridotites show later transformation into magnetite, which is associated with the formation of cholite.

Hydrated secondary minerals formed during and after mylonitic deformation in the basal peridotites exhibit metasomatism of peridotites during the ophiolite nappe emplacement. The hydration is manifested by the growth of brown pargasitic hornblende, by the alteration of enstatite to tremolite and talc, by the alteration of chromain spinel to chlotite and magnetite, and by the formation of lizardite and chrysotele associated with fine-grained magnetite. The brown amphibole formed at the expense of diopside? Analyses of amphibole from the two selected samples (Table 4) are presented in the diagram of Leake (1978) (Fig.5).

The analyzed chlotites are colourless in thin section and their microprobe analyses show high magnesium contents (Table5). The analyses plot in or near the penninite field of Foster (1962). The composition of Talc is close To the Mg end member.

**Table - 1**

**Microprobe analyses of orthopyroxenes from the basal mylonitic peridotite of the Saplai Torghar massif**

| Sample | 341E 50 | 341E 52 | 341E 58 | 341E 60 | 341E 61 | 341E 69 | 341E 76 | 341E 77 | 323E 89 | 323E 90 | 323E 91 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 56.59 | 58.46 | 57.81 | 57.69 | 57.52 | 57.45 | 59.06 | 58.16 | 57.01 | 57.70 | 57.76 |
| $TiO_2$ | 0.01 | 0.00 | 00.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 |
| $Cr_2O_3$ | 0.43 | 0.13 | 0.49 | 0.55 | 0.59 | 0.34 | 0.00 | 0.00 | 0.47 | 0.59 | 0.00 |
| $Al_2O_3$ | 1.85 | 1.11 | 1.57 | 2.04 | 2.01 | 2.03 | 0.82 | 0.93 | 3.42 | 2.07 | 2.04 |
| FeO | 5.52 | 5.70 | 5.47 | 5.86 | 4.97 | 5.30 | 5.37 | 5.20 | 5.76 | 5.66 | 5.36 |
| MnO | 0.17 | 0.12 | 0.17 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.14 | 0.29 | 0.16 |
| MgO | 37.32 | 35.36 | 34.53 | 35.23 | 36.95 | 34.78 | 35.89 | 35.33 | 35.58 | 35.63 | 35.65 |
| CaO | 0.55 | 0.16 | 0.14 | 0.22 | 0.26 | 0.54 | 0.13 | 0.15 | 0.42 | 0.22 | 0.21 |
| $Na_2O$ | 0.00 | 0.00 | 0.02 | 0.04 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.06 | 0.01 |
| **Total** | **102.43** | **101.04** | **100.23** | **101.63** | **101.62** | **100.44** | **101.32** | **99.77** | **102.81** | **102.21** | **101.21** |
| **Norm.** | | | | | | | | | | | |
| Si | 1.908 | 1.984 | 1.978 | 1.952 | 1.941 | 1.961 | 1.994 | 1.993 | 1.911 | 1.943 | 1.956 |
| Al | 0.074 | 0.044 | 0.063 | 0.081 | 0.080 | 0.082 | 0.032 | 0.038 | 0.135 | 0.082 | 0.082 |
| Ti | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Cr | 0.011 | 0.004 | 0.013 | 0.015 | 0.016 | 0.009 | 0.000 | 0.000 | 0.012 | 0.016 | 0.000 |
| Fe++ | 0.156 | 0.162 | 0.157 | 0.166 | 0.140 | 0.151 | 0.152 | 0.149 | 0.161 | 0.159 | 0.152 |
| Mn | 0.005 | 0.004 | 0.005 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.004 | 0.008 | 0.005 |
| Mg | 1.875 | 1.788 | 1.761 | 1.77 | 1.824 | 1.770 | 1.806 | 1.804 | 1.777 | 1.789 | 1.800 |
| Ni | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Ca | 0.020 | 0.006 | 0.005 | 0.008 | 0.009 | 0.020 | 0.005 | 0.006 | 0.015 | 0.008 | 0.008 |
| Na | 0.000 | 0.000 | 0.002 | 0.003 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 | 0.004 | 0.001 |
| Xmg | 0.912 | 0.913 | 0.913 | 0.911 | 0.924 | 0.912 | 0.920 | 0.921 | 0..908 | 0.911 | 0.916 |
| | **92.092** | **91.505** | **91.576** | **91.457** | **92.872** | **92.140** | **92.190** | **92.371** | **91504** | **91.462** | **91.978** |

## Table – 2
**Microprobe analyses of olivines from the Basal peridotite mylonites of the Saplai Torghar massif**

| Sample | 341E 57 | 341E 72 | 323E 92 |
|---|---|---|---|
| $SiO_2$ | 41.76 | 41.67 | 41.92 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 |
| $Cr_2O_3$ | 0.00 | 0.00 | 0.00 |
| $Al_2O_3$ | 0.00 | 0.00 | 0.01 |
| FeO | 8.70 | 8.35 | 8.35 |
| MnO | 0.12 | 0.13 | 0.07 |
| MgO | 5.39 | 49.95 | 50.92 |
| NiO | 0.00 | 0.00 | 0.00 |
| CaO | 0.01 | 0.00 | 0.00 |
| **Total** | **100.98** | **100.09** | **100.64** |
| **Norm.** | | | |
| Si | 1.006 | 1.011 | 1.011 |
| Fe++ | 0.175 | 0.169 | 0.169 |
| Mn | 0.002 | 0.003 | 0.002 |
| Mg | 1.809 | 1.806 | 1.807 |
| Xmg | 0.910 | 0.913 | 0.914 |
| | **91.088** | **91.304** | **91.359** |

## Table – 3
**Microprobe analyses of spinels and magnetites from the basal peridotite mylonites of Saplai Torghar massif.**

| Sample | 341E 39 | 341E 40 | 341E 46 | 341E 47 | 341E 63 | 341E 64 | 341E 65 | 341E 66 | 341E 67 | 341E 68 | 323E 85 | 323E 93 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 0.41 | 0.39 | 0.25 | 0.38 | 0.27 | 0.21 | 0.19 | 0.22 | 0.21 | 0.22 | 0.22 | 0.31 |
| $TiO_2$ | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.02 | 0.04 | 0.06 | 0.04 | 0.04 | 0.00 | 0.02 |
| $Cr_2O_3$ | 0.35 | 0.00 | 44.17 | 0.21 | 46.32 | 47.96 | 53.86 | 47.01 | 52.63 | 51.31 | 22.66 | 13.79 |
| $Al_2O_3$ | 0.00 | 0.00 | 23.58 | 0.02 | 19.71 | 19.48 | 14.41 | 16.89 | 14.40 | 15.08 | 45.21 | 0.33 |
| FeO | 90.29 | 90.15 | 19.47 | 88.40 | 22.62 | 20.97 | 22.27 | 25.56 | 22.02 | 23.34 | 13.55 | 80.30 |
| MnO | 0.45 | 0.17 | 0.25 | 0.04 | 0.30 | 0.36 | 0.38 | 0.33 | 0.15 | 0.70 | 0.15 | 0.21 |
| MgO | 0.65 | 0.05 | 13.26 | 0.06 | 10.01 | 10.11 | 8.89 | 9.09 | 9.02 | 8.23 | 18.13 | 0.61 |
| CaO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | **92.16** | **90.77** | **101.00** | **89.10** | **99.24** | **99.09** | **100.04** | **99.14** | **98.46** | **98.92** | **99.91** | **95.56** |
| **Norm. to 4 O** | | | | | | | | | | | | |
| Si | 0.021 | 0.021 | 0.008 | 0.020 | 0.009 | 0.007 | 0.006 | 0.007 | 0.007 | 0.007 | 0.006 | 0.014 |
| Al | 0.000 | 0.000 | 0.850 | 0.001 | 0.747 | 0.737 | 0.557 | 0.656 | 0.564 | 0.591 | 1.463 | 0.018 |
| Ti | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 | 0.001 | 0.000 | 0.001 |
| Cr | 0.014 | 0.000 | 1.067 | 0.009 | 1.177 | 1.217 | 1.396 | 1.225 | 1.383 | 1.348 | 0.492 | 0.508 |
| Fe3+ | 1.965 | 1.979 | 0.075 | 1.970 | 0.067 | 0.039 | 0.040 | 0.110 | 0.045 | 0.053 | 0.39 | 1.459 |
| Fe2+ | 2.099 | 2.165 | 0.430 | 2.166 | 0.548 | 0.527 | 0.575 | 0.606 | 0.572 | 0.601 | 0.276 | 1.817 |
| Mn | 0.020 | 0.008 | 0.007 | 0.002 | 0.008 | 0.010 | 0.011 | 0.009 | 0.004 | 0.020 | 0.004 | 0.008 |
| Mg | 0.050 | 0.004 | 0.604 | 0.004 | 0.480 | 0.483 | 0.434 | 0.446 | 0.447 | 0.407 | 0.741 | 0.042 |
| Cr # | Mgn | Mgn | 55.660 | Mgn | 61.175 | 62.282 | 71.480 | 65.125 | 71.032 | 69.520 | 25.166 | ?? |

Table – 4

**Analyses of amphiboles from the basal harzburgite mylonites of the Saplai Torghar massif. Note the presence of a pargasitic amphibole associated with tremolites formed as alteration product from exsolutions of clinopyroxene in enststite**

| Sample | 341E 36 | 341E 38 | 341E 55 | 341E 65 | 341E 73 | 341E 74 | 341E 75 | 341E 87 | 323E 88 | 323E 96 | 323E 97 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 58.35 | 56.85 | 54.63 | 56.67 | 55.95 | 56.85 | 55.65 | 45.90 | 46.45 | 57.71 | 58.33 |
| $TiO_2$ | 0.00 | 0.03 | 0.02 | 0.02 | 0.01 | 0.01 | 0.03 | 0.11 | 0.11 | 0.01 | 0.00 |
| $Cr_2O_3$ | 0.00 | 0.37 | 0.43 | 0.46 | 0.00 | 0.48 | 0.00 | 1.73 | 2.08 | 0.00 | 0.00 |
| $Al_2O_3$ | 1.51 | 3.36 | 3.70 | 1.99 | 3.66 | 2.38 | 3.82 | 14.76 | 13.82 | 1.17 | 0.41 |
| FeO | 1.27 | 2.08 | 2.55 | 3.23 | 1.99 | 2.00 | 2.05 | 2.87 | 2.88 | 2.14 | 2.05 |
| MnO | 0.48 | 0.05 | 0.07 | 0.12 | 0.03 | 0.10 | 0.00 | 0.02 | 0.43 | 0.15 | 0.06 |
| MgO | 25.04 | 25.13 | 24.42 | 24.64 | 22.91 | 22.98 | 24.91 | 18.10 | 19.04 | 24.87 | 24.89 |
| CaO | 12.83 | 12.88 | 11.75 | 12.61 | 12.75 | 13.01 | 12.85 | 12.78 | 12.96 | 12.26 | 12.70 |
| $Na_2O$ | 0.17 | 0.39 | 0.41 | 0.30 | 0.40 | 0.24 | 0.48 | 1.89 | 1.88 | 0.79 | 0.38 |
| $K_2O$ | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 | 0.02 |
| **Total** | 99.66 | 101.15 | 97.97 | 100.03 | 97.71 | 98.03 | 99.80 | 98.16 | 99.67 | 99.13 | 98.85 |
| **Norm. to 6 O.** | | | | | | | | | | | |
| Si | 7.799 | 7.535 | 7.483 | 7.634 | 7.648 | 7.753 | 7.477 | 6.397 | 6.403 | 7.789 | 7.881 |
| Al | 0.238 | 0.525 | 0.597 | 0.315 | 0.589 | 0.382 | 0.605 | 2.426 | 2.246 | 0.186 | 0.065 |
| Ti | 0.000 | 0.003 | 0.002 | 0.002 | 0.001 | 0.001 | 0.003 | 0.011 | 0.012 | 0.001 | 0.000 |
| Cr | 0.000 | 0.039 | 0.046 | 0.049 | 0.000 | 0.052 | 0.000 | 0.190 | 0.227 | 0.000 | 0.000 |
| Fe++ | 0.142 | 0.231 | 0.292 | 0.363 | 0.227 | 0.228 | 0.230 | 0.334 | 0.332 | 0.241 | 0.232 |
| Mn | 0.055 | 0.006 | 0.008 | 0.013 | 0.004 | 0.011 | 0.000 | 0.002 | 0.050 | 0.017 | 0.006 |
| Mg | 4.988 | 4.964 | 4.985 | 4.946 | 4.667 | 4.671 | 4.989 | 3.759 | 3.912 | 5.003 | 5.012 |
| Ni | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Ca | 1.837 | 1.828 | 1.725 | 1.820 | 1.867 | 1.900 | 1.850 | 1.909 | 1.914 | 1.773 | 1.839 |
| Na | 0.045 | 0.101 | 0.110 | 0.077 | 0.105 | 0.063 | 0.125 | 0.509 | 0.501 | 0.207 | 0.100 |
| K | 0.001 | 0.002 | 0.000 | 0.000 | 0.001 | 0.000 | 0.002 | 0.002 | 0.003 | 0.008 | 0.004 |
| **XMg** | 0.962 | 0.954 | 0.943 | 0.929 | 0.953 | 0.951 | 0.956 | 0.918 | 0.911 | 0.951 | 0.955 |

Table – 5

**Analyses of talc replacing orthopyroxene in sample 341E and 323E and analyses of chlorites forming coronas around chromite/spinel grains.**

| Sample | 341E 34 | 323E 94 | 323E 95 | | Sample | 323E 79 | 323E 80 | 323E 82 | 323E 8385 |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 30.80 | 34.60 | 34.58 | | $SiO_2$ | 35.21 | 34.08 | 32.08 | 34.52 |
| $TiO_2$ | 0.00 | 0.00 | 0.00 | | $TiO_2$ | 0.00 | 0.00 | 0.00 | 0.00 |
| $Cr_2O_3$ | 1.57 | 0.00 | 0.15 | | $Cr_2O_3$ | 0.00 | 0.12 | 0.66 | 0.38 |
| $Al_2O_3$ | 19.81 | 12.95 | 13.92 | | $Al_2O_3$ | 13.93 | 14.94 | 16.60 | 13.20 |
| FeO | 3.17 | 3.59 | 4.00 | | FeO | 3.82 | 4.01 | 4.47 | 3.71 |
| MnO | 0.00 | 0.03 | 0.08 | | MnO | 0.96 | 0.09 | 0.13 | 0.00 |
| MgO | 34.89 | 36.61 | 37.17 | | MgO | 35.24 | 35.70 | 33.30 | 35.41 |
| CaO | 0.01 | 0.02 | 0.01 | | CaO | 0.03 | 0.03 | 0.00 | 0.01 |
| $Na_2O$ | 0.00 | 0.06 | 0.05 | | $Na_2O$ | 0.10 | 0.04 | 0.00 | 0.05 |
| $K_2O$ | 0.00 | 0.07 | 0.00 | | $K_2O$ | 0.35 | 0.11 | 0.00 | 0.04 |
| **Total** | **90.26** | **87.92** | **89.94** | | **Total** | **89.64** | **89.11** | **87.24** | **87.32** |
| **Norm.** | | | | | **Norm.** | | | | |
| Si | 4.424 | 5.082 | 4.979 | | Si | 3.244 | 3.150 | 3.039 | 3.248 |
| Al | 3.355 | 2.241 | 2.362 | | Al | 1.513 | 1.628 | 1.854 | 1.464 |
| Ti | 0.000 | 0.000 | 0.000 | | Ti | 0.000 | 0.000 | 0.000 | 0.000 |
| Cr | 0.179 | 0.000 | 0.017 | | Cr | 0.000 | 0.009 | 0.049 | 0.028 |
| Fe++ | 0.381 | 0.440 | 0.482 | | Fe+++ | 0.000 | 0.000 | 0.000 | 0.000 |
| Mn | 0.000 | 0.003 | 0.009 | | Fe++ | 0.294 | 0.310 | 0.354 | 0.292 |
| Mg | 7.469 | 8.012 | 7.975 | | Mn | 0.075 | 0.007 | 0.011 | 0.000 |
| Ni | 0.000 | 0.000 | 0.000 | | Mn | 4.840 | 4.917 | 4.701 | 4.965 |
| Ca | 0.001 | 0.002 | 0.001 | | Ca | 0.003 | 0.003 | 0.000 | 0.001 |
| Na | 0.000 | 0.017 | 0.014 | | Na | 0.019 | 0.007 | 0.000 | 0.009 |
| K | 0.001 | 0.013 | 0.000 | | K | 0.041 | 0.012 | 0.000 | 0.005 |
| | | | | | Si (pfu) | 6.489 | 6.299 | 6.078 | 6.496 |
| $X_{Mg}$ | 0.9514 | 0.9472 | 0.9419 | | $Fe^{++}/R^{2+}$ | 0.056 | 0.059 | 0.070 | 0.055 |

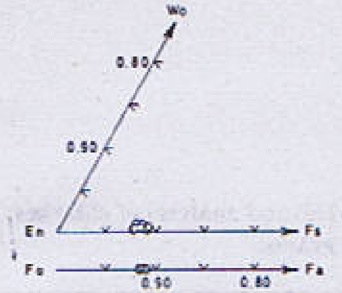


**Fig 3** Microprobe analyses of orthopyroxenes coexisting with forsterite in mylonites from the basal shear of Saplai Torghar. This diagram indicates the equilibrium conditions of orthopyroxene and olivine.

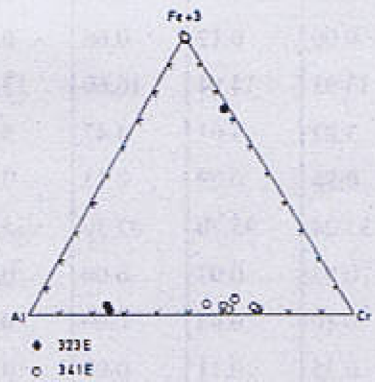


**Fig 4A** Al-Cr-$Fe^{3}$+ triangle for spinel group minerals, compositional difference of two analyzed samples.

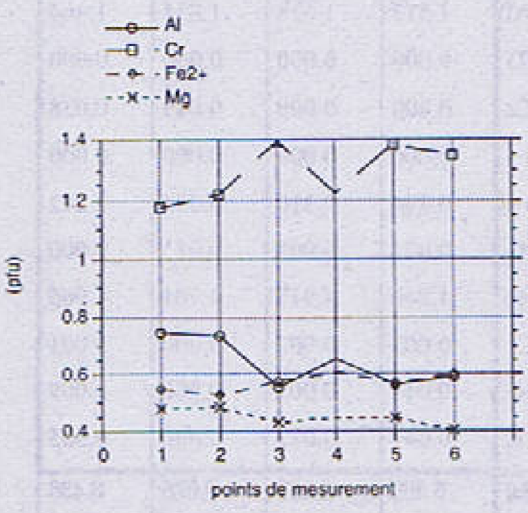


**Fig 4B** Profile showing the chemical zoning of one 0.4mm sized spinel in sample 341E.

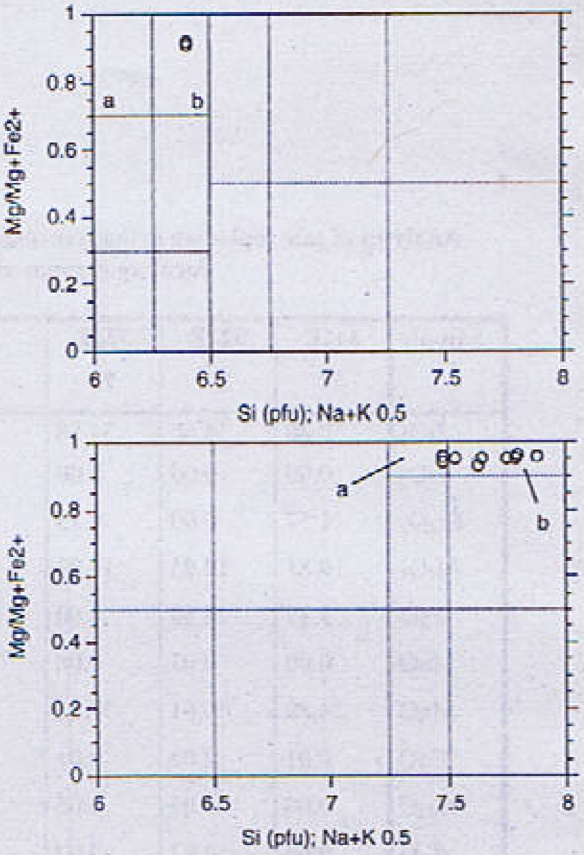


**Fig 5** Analyses of amphiboles from the metamorphic sole of Saplai Torghar. The upper figure presents the pargasitic amphiboles (a: pargasite; b: pargasitic hornblende) formed under granulite facies conditions. The lower figure displays the amphiboles formed by the alteration of enstatite (a: thuringite; b) chamosite; c) rhipidolite; d) brunsvingite; e) diabantite; sheridanite; g) clinochlore; h) penninite.

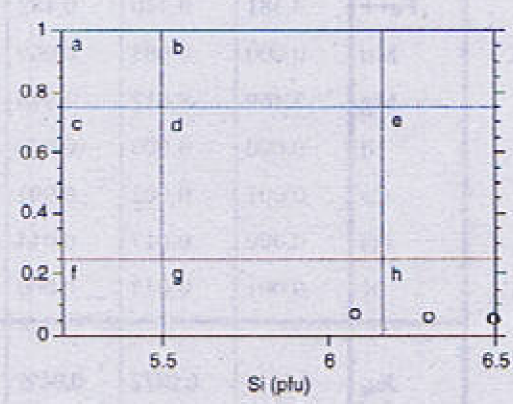


**Fig 6** Analyses of chlorites forming coronas in samples 341E and 323E around spinel/chromite grains. The fields defined by Foster (1962) are: a) thuringite; b)chamosite; c) rhipidolite; d) brunsvingite; e) diabantite; f) sheridanite; g) clinochlore; h) penninite.

## DISCUSSION

Chromain spinel composition has been widely used as an indicator of petrogentic conditions and chemical and tectonic environment of the enclosing rocks (e.g., Irvine, 1967: Thyer, 1977::Marakushey, 1979; Ahmed, 1984; Syita and Strieder, 1996). However, most previous work on the chromain spinel of the Muslimbag ophiolite (e.g., Ahmed, 1972; Bilgrami, 1963, 1968) was based on analyses of the segregated chromite only. This was mainly due to the significance of such chromite in mining in the region since 1901 (Vredenburg, 1901). The reported compositions (Bilgrami, 1968; Ahmad, 1972; Ahmad, 1986) were all of high-Cr, mostly 'metallurgical grade' chromite (Stevens, 1944). The accessory chromain spinel analyzed in the present study points to bimodal Cr-A1 reciprocal variation. This doesn't correspond to the restricted range of Cr# found in harzburgite (Arai, 1994). Cr# of chromite, widely adopted as a parameter for derivation of important genetic inferences, is considered to be an index of the degree of melting in the mantle (e.g., Dick and Bullen, 1984; Roberts 1992; Bonatti and Michael, 1989; Bridges et al., 1995). The olivine-spinel mantle array proposed by Arai 91994) consists of two variables the Cr# of spinel and Fo content of olivine. However, it relies heavily on the Cr# of spinel as a discriminant because of the very narrow range of Fo in olivine of spinel peridotites. Dick and Bullen (1984) distinguished the following types of spinels: Type-I spinels (mid-ocean ridge-derived peridotites with Cr# <60. Type-III spinels (arc-related environment); and Type-II (transitional) peridotites. The large range in Cr# shwon by the Saplaitorgarh spinels is similar to that of the Type-II ophiolites. This doesn't suggest a mid-ocean origin for the Saplaitorgarh massif, but rather a multistage melting and great variation in the degree of partial fusion and melt removal. Harzburgites and lherzolites are mantle restites; lherzolites show less depletion than the garzburgites. Harzburgite with the higher-Cr spinel may be due to greater degree of partial melting.

The microprobe analyses show that some minerals of the metamorphic sole are zoned and the basal part of te ophiolites is affected by hydration and metassomatism during its emplacement. The minerals partially reequilibrated during the ophiolite emplacement. The alkali-bearing fluids probably derived from the subophiolitic rocks which were scrapped off from the top of the subducting oceainic lithophere. The chemical composition of forsterite and enstatite did not change during this process. The chemical composition of porphyroclasts as well as neoblasts closely resembles the analyses published from other parts of the Muslim bagh ophiolite (Mahmood, 1994) which were not affected by the low-temperature deformation during the ophiolite emplacement.

## CONCLUSIONS

Prophyroclasts and neoblasts of forsterite and enstatite exhibit restricted composition range which stays around Fo91 and En 91-92, respectively. Very low A1 and Ca in enstatite may be due to the primary depleted mantle origin of the host harzburgite-mylonite. Chromain spinel exhibits different Cr# in the two samples of harzburgite.

This may possibly indicate different stages during the initial crystallization of harzburgite. Exsolution induced zonation also occurs in some chromain spinel grains. the neoblast growth and the chromain spinel zonation may have occurred by reequilibration during mylonitic defromattion in an early stage of the emplacement. Under aqueous fluids regim, hydrated secondary minerals like pargasitic hornblend, tremolite, talc and cholorite may have formed during and after the mylonitic deformation caused by the deformation during cemplacement of Muslimbagh ophiolite.

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# GEOLOGY OF GEM BEARING COMPLEX PEGMATITES FROM UPPER NEELUM VALLEY AZAD KASHMIR

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**Abstract:-** *Geology of Janawai-Folowai area in upper reaches of Neelum valley, Azad Kashmir is presented. The geology of the area is divided into two units. A migmatitic basement complex consisting of high grade pelitic gneisses, migmatites and sheet granites thrusted on to the high grade dominantly calcareous metasediments. This area is the host of a number of lithium and rare earth enriched complex pegmatites. These pegmatites have been reported to contain gem bearing cavities. This study suggests a tectonic classification of the pegmatites of this area and it is proposed that this classification has a potential in discriminating between Li, rare metal and Gem producing pegmatites from barren pegmatites.*

## INTRODUCTION

Complex pegmatites in the upper reaches of Neelum valley in Azad Jammu & Kashmir which constitutes southern to central part of Nanga Parbat Haromosh complex are known to have yielded gem bearing cavities as well as lithium micas. Geology of Nanga Parbat haramosh massif has been the subject of some recent studies (Greco 1989, Chaudhry & Ghazanfer 1989, Spencer et al., 1990). This study deals with the geology of a part of Nanga Parbat Haramosh complex in Janawai-Folowai area of Neelum valley. These areas host a number of complex pegmatites which are invariably hosted in a migmatitic gneiss. Petrography, structure and metamorphism in the area is described and an attempt is made to classify the complex pegmatites of the area which may help in prospection and exploration of gem bearing pegmatites of Nanga Parbat Haramosh massif in general.

## GEOLOGICAL SET UP

Neelum river takes an east-west course in its upper reaches about 10 KM short of Kel. Janawai and Folowai are two north-south flowing tributaries of Neelum river which provide two across the regional east-west strike cross sections of the geology of this area. The geology of the area can be divided into two major units separated by a thrust fault which run essentially along the Neelum Valley.

1. Kel formation (Non-migmatitic metamorphites).
2. Janawai-Folowai migmatitic complex.

Ghazanfar and Chaudhry (1986) have classificated all the rock units exposed north of Kel thrust as Sharda group. The units described above provide a further classification of Sharda group in this area. Detailed of Janawai-Folowai area is shown in Fig 1

### Kel Formation

The schistose rocks, marbles and garnetiferous amphibolites exposed south of the Kel thrust are proposed to be designated as "Kel Formation". It is another field mapable unit characterized by its lack of granitic aspects and pegmatites. This unit when traced wetward into adjoining Nangi Mali area joins favourably with the rock south of "Kel Thrust" and compares well with the overall lithological spectrum.

This formation is characterized by the absence of granitic compositions especially in the area investigated.

This formation contains amphibolites, marbles pelitic schists and some para gneisses.

For a comparison of the two formations, schistose rocks of the Janawai-Folowai migmatitic formation were petrographically investigated. It has been observed that garnet mica schists of Kel formation are relatively lower grade rocks which do not contain sillimanite. Pelitic rocks of this formation also contain almandine garnet.

Relatively lower metamorphic grade and lack of migmatization is considered to be a major difference

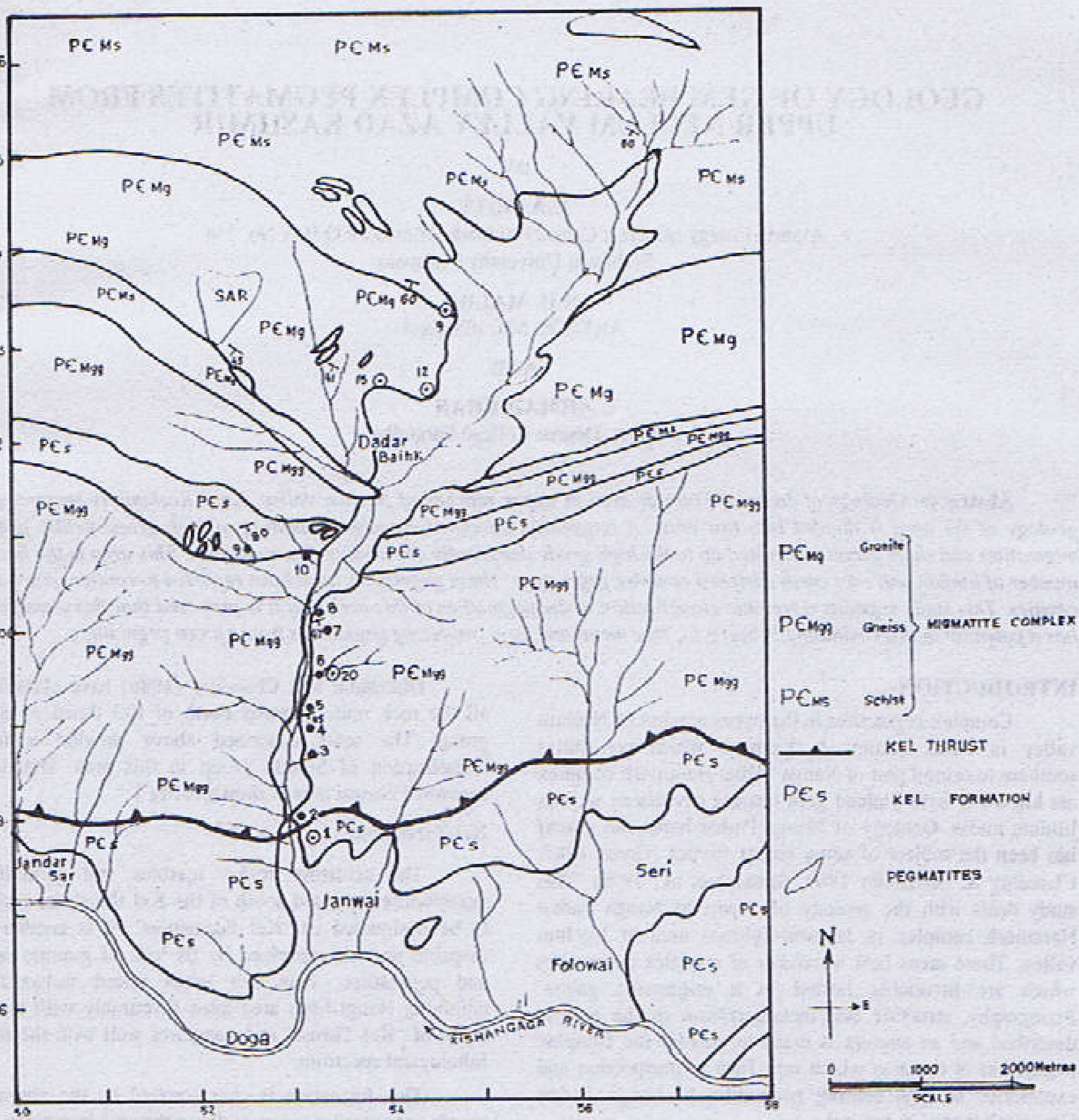


Fig. 1 Geological Map of Janwai area showing Location of Pegmatites.

between the two formations. Sheet like granites so characteristic of the janawai-Folowai migmatite formation are absent from this formation.

**Janawai-Folowai Migmatitic Formation**

Petrographic studies on rocks of Janawai-Folowai formation were conducted on samples collected from Janawai Nar section (Fig. 1). A few samples were also included from Gujar Mali area to complete the lithological spectrum. Four major lithologies have been defined:

1. Sillimanite garnet bioltite schist.
2. Silliminate granitic gneiss.
3. Sheet granites.
4. Pegmatites.

This formation appears to contain granitic rocks intimately associated with very high grade metamorphics both of a granitic composition as well as of a pelitic composition. Such formations are defined as 'Migmatite Complexes' wherein high grade metamorphic rocks are intimately associated with granitic components which has been produced due to ultra metamorphism of their hosts.

The granitic fraction that is produced during such a process is generally known to appear as sheet like granitic bodies similar to those observed in Janawai Folowai area.

***Sillimanite-Garnet-Biotite Schists :*** This rock represents the high grade metamorphism of an orinally pelitic-quartizitic formations of possible Precambrian age. These rocks are present as discontinuous layers within a gneissic to migmatitic rocks comparable to granitic aspect. These rocks show at least three cleavages.

Quartz - orthoclase - biotite - andalustic-sillimanite assemblage represents a prograde metamorphism of upper amphibolite facies which straddle on the boundary of high grade metamorphism and granite melting.

***Sillimante – Andalustie - Garnet Bearing Granitic gneiess :*** This rock type represents a gradational variety between high grade metamorphics and granitic melts. These rocks have a gneissic texture, coarse grained as compared to associated schists, but their mineralogy is comparable to those of schists. The difference between these schists and gneisses may only be due to post metamorphism cataclastic deformation changing the high grade gneisses locally into schistose rocks.

***Sheet Granites*** : Porphyritic granitic rocks are distributed within the schistose/gneissic rocks described above. Qureshi (1988) mapped a granitic body in the northern parts of the Janawai-Folowai area (Fig.1). This body also contains sillimanite andalusite and garnet in a rock which can be texturally termed as a porphyritic granite. Similarly, the gneisses mapped in the area occasionally show porphyritic granitic textures. It is, therefore, concluded that separate field mapping of granite, and granitic gneisses is rather difficult at any scale. The proposed Janawai-Folowai Migmatitic formation is mixture of porphyritic granites, granitic gneiss and schistose lithologies. The schistose rocks represents schillerens of various sizes floating in a granitic gneiss. The granitic gneiss at places, have been migmatized and cataclastically deformed. Some late tectonic granitic components which have escaped tectonism show porphyritic granitic texture. Alternatively, since the deformation of granitic rock is rarely homogeneous, such massive rocks when subjected to deformation tend to show the effects of such a deformation only at their marginal parts while the core remains undeformed. A glance at the Janawai-Folowai map (Fig. 1) shows that the granite mapped in the area is flanked on its northern as well as southern side by what has been mapped as gneiess. The granite may therefore represents the central portion of granite which has not been so penetraively deformed and its northern and southern marginal parts have been changed into a gneissic rock. Mineralogically even these relatively undeformed granitic rocks contained garnet, sillimanite and andalusite in a granitic mineralogy.

**METAMORPHISM**

From the foregoing petrographic description, it is obvious that Janawai-Folowai migmatitic formation is a mixture of schistose rocks, granite gneisses and granites. These rocks grade into one another rather imperceptibly and therefore cannot be mapped separately. This situation is typical of migmatitic complexes which represents high grade metamorphism appreciating granite melting. Fig. 2 shows the metamorphic condition prevailing in the migmatite complex. Schistose and gneissic rocks have co-existing sillimanite+ andalusite alongwith garnet which provides the limiting PT condition within the metasedeimentary pile. Same mineralogy is also prevalent in the gneisses as well as so called granitic rocks, In addition, migmatization of these gneisses is present practically everywhere in this formation. These rocks therefore, represent P-T condition ranging from upper amphibolite facies to the melting of granite.

Metamorphism of "Kel formation' as proposed in this paper is distinctly different. A few rocks examined during this study suggest that the pelitic rocks of Kel formation do not contain sillimanite. Andalusite and garnet has however been noted in pelitic lithologies. This would suggest that these rocks did not witness andalustie-sillimanite transition. The P-T condition of these rocks were, therefore, slightly lower than attained in janawai-Folowai migmatitic formation (Fig.1.). Within the P-T range of amphibolite facies the following division are proposed by Winkler (1979):

| | | |
|---|---|---|
| 1. | Cordierite + | Andalusite |
| 2. | .Almandine + | Andalusite |
| 3. | .Almandine + | Sillimanite |
| 4. | .Almandine + | Kyanite |

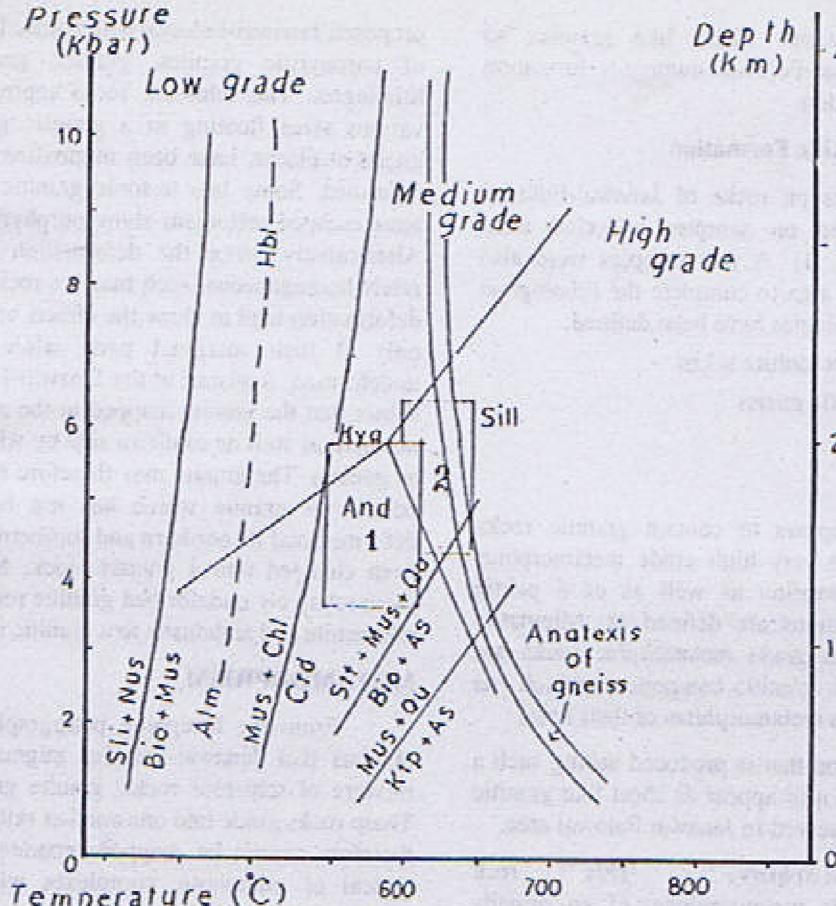


**Fig. 2** Metamorphic conditions in:
1. Kel formation.
2. Janawai-Folowai migmatitic formation.
(Mineral reactions and metamorphic grades from Winkler 1979).

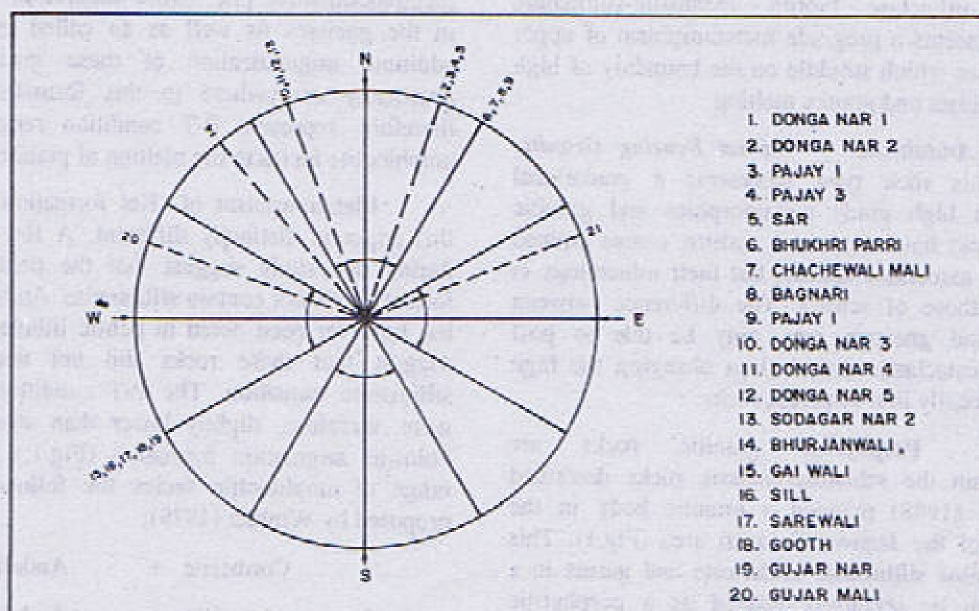


FIG. 3 STRIKE ORIENTATION OF PEGMATITES OF JANAWAI-POLOWAI AREA.

These divisions represent increasing pressure within the medium grade metamorphic rocks. Thus the almandine-andalustie assemblage in the rocks of Kel formation exposed south of the Kel Thrust represents medium grade metamorphism with slightly lower pressure and possibly temperature as compared to those attained by Janawai-Folowai migmatitic formation north of the thrust.

## PEGMATITES

### Field Occurrences

Field relations of the most of these pegmatites have been summarized in a number of reports i.e. Qureshi (1988), Hashmi et'al, (1990).

Qureshi (1988) made the first attempt to generalize the field occurrence of various pegmatites on the basis of:

1. Schist hosted pegmatites.
2. Granite hosted pegmatites.

Each of the above categories was further sub-divided on the basis of their concordant or discordant relation with the host country rocks:

1. Sill type
2. Dike type.

Internally zoned structure of various pegmatites has been abundantly documented and it has been demonstrated that most pegmatites are zoned. Some of these zones may not be present in certain occurrences.

Detailed geologic maps produced by the workers referred above show that some pegmatites are folded whereas others are not. It is important to examine these classifications with respect to their applicability in exploration.

The classification of pegmatites on the basis of host rock lithology has been proposed. A solitary example of the productive Donga nar pegmatite hosted in schistose unit does not provide sufficient data to conclude that all schists hosted pegmatites are likely to be productive.

Moreover, the mineralogical difference between the schists and gneiesses are not significant enough to expect a substantial difference in the schists and gneiss hosted pegmatites.

Zoned and unzoned nature of pegmatites may be valid, but it is also a function of the level exposure of a particular pegmatite. This classification may therefore not help much in discriminating productive pegmatite from the rest.

The following tectonic classification of pegmatites may hold some potential for discrimination between gem bearing and a gem barren pegamtites.

### Tectonic classification of Pegmatites

Detailed geologic maps of Hashmi et al. (1990) show that some pegmatites are folded whereas others are not. This data provides an important basis for the classification of pegmatites into: Pretectonic, Late tectonic, and post tectonic pegmatites.

*Pretectonic Pegmatites*: These pegmatites shows ductile deformation and are folded in a fashion suggesting plastic deformation characteristic of migmatitic terrains. These are mostly small bodies of the migmatite complex.

*Late Tectonic Pegmatite*: These pegmatites are folded. Folding is simple isoclinal but not irregular as in pretectonic pegmatites. These include Gai Wali, Sill, Sarwali, Goot, Gujar Nar (Folowai), Gujar Mali, Sodagar nar 1. Most of these pegmatites have an orientation of conjugate fractures correlatable to an east-west P[max] (Fig.3). This is an older tectonic event (Butt, 1988). Pegmatites associated with this event have invariably been considered unfavourable for gem prospecting (Qureshi, 1988).

*Post Tectonic Pegamatites*: These pegmatites do not show any folding. These pegmatites appear to have been intruded along a set of conjugated fractures, that could have resulted from an approximately north-south P-max, thereby providing fractures at N30 W orientation. Most productive Donga Nar pegmatite is a post tectonic pegmatite. From the foregoing, it is logical to conclude that the post tectonic pegmatites hold the best chances for the discovery of miarolitic pegmatites with gem bearing cavities.

## REGIONAL CONSIDERATIONS

The south Asian pegmatite belt of Rossovski (1981) comprises deposits and occurrences of rare metal gemstone gem bearing pegmatites, extending from Hinduush through the Himalayas to Northern Burma. While the position of this belt suggests that the pegamtites might all be related in some way to the India-Asia collision, in detail the belt consists of a number of sub-provinces of distinct ages and geologic setting.

Gem bearing pegmatites described by Kazmi et al., (1985) form Shingus and Dassu are an example of such a situation. While the pegmatites in Shingus are a part of Nanga Parbat Haramosh massif, those in Dassu occur on Asian plate. Gem pegmatite deposits of Nepal and Bhutan, like the NP-H massif lie on the foreland thrust belt of India.

In Nepal the pegmatites, with tourmaline, aquamarine, and reportedly sapphire, are restricted to the central gnesisses near the base of the higher Himalayan succession above the Main Central Thrust. The pegmatites clearly cut the gneisses and are generally considered to be related to post collision movement on the thrust during the Himalayan orogeny. In this respect the pegmatites of Janawai-Folowai area occur in a comparable geological setting.

Kazmi et al., (1985) have described a number of similar pegmatites from Shingus and Dassu region. Shingus area represents northern part of Nanga Parbat-Haramosh migmatite complex. Lepidolite, tourmaline, aquamarine, and topaz bearing pegmatites are hosted in a biotite gneiss, which is petrographically identical to the garnet mica schist horizons of the Janawai-Folowai area. Whether the granite hosted pegmatites of Shingus area are also similar would be of some interest from exploration point of view. Kazmi et al. (1985) offer little information in this regard.

It may be pointed out that according to Mariano (1991) Shingus group of pegmatites have no lepidolite or spodumene. Mineralogically, Donga Nar pegmatite and pegmatite at Stak Nala Beluchi and Dassu area have also been reported to contain and lepidolite.Kazmi et al., (1985) also reported spodumene from Beluchi. There is an absolute mineralogical structural, host rock and possible chronological identity between the pegmatites of the two areas.

Mariano (1991) stated that Azad Kashmir pegmatites are a part of the vast pegmatite belt within the Pamir, Hindu-Kush,Karakoram and Western Himalaya.

Azad Kashmir pegmatite are hosted in a remobilized located in the Pamir block. According to Jankovic (1984), basement (Butt, 1983) of the Indian plate, while pegmatites of Hindu-Kush (Rossovski 1981 and London 1986) are Indus Suture Zone (or MMT) marks the southern boundary of this block. Kazmi et al. (1985) deals with two occurrences, i.e. Shingus and Dassu, the former from NP-H massif south of MMT and the latter from Dassu region north of MKT. An important difference being that Dassu pegmatite lacks lithium minerals.

Azad Kashmir pegmatites differ from Afghan pegmatites in that most of the latter are spodumene-pegmatites which contain elbaites whereas lepidolite bearing Azad Kashmir pegmatites are comparable to Himalayan pegmatite, with lepidolite-lithium muscovite replacement.

Another important difference between Azad Kashmir and Afghan pegmatites is the grade of metamorphism of the host rocks. Afghan pegmatite are hosted in lower grade metamorphics, whereas Azad Kashmir pegmatites are hosted in very high grade migmatitic terrain.

The unusual relationship of Azad Kashmir pegmatites intruding high grade metamorphic rocks and still hosting high level pegmatite is not so surprising since this is an area which has in the past, and probably still is rising at a tremendous rate (Zietler et al., 1982).

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# INDUSTRIAL APPLICATIONS OF THE FULLER'S EARTH DEPOSIT D.G. KHAN PAKISTAN

BY

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**Abstract:** *Twenty samples of the fuller's earth were collected from the Sirki Shale Member of Eocene Kirthar Formation in the Sulaiman Range (Dalana area, D.G.Khan Pakistan) to evaluate its usefulness for different industrial applications.*

*Mineralogical determination show that fullers earth of Dalana area is mainly composed of mixed layer illite - smectite clays with minor impurites of kaolinite ,quartz, gypsum and hematite. X-ray fluorescence spectromety results ($Al_2O_3$ = 16.33 to17.15%, $Fe_2O_3$ = 7.35 to 11.01%, MgO = 2.86 to 3.44 % , $K_2O$ = 2.81 to 3.36 % , CaO < 1 % ) were also in conformity with the mineralogical conclusions that the illite -montmorillonite mixed layers clay is the major species.*

*The cation exchange capacity of the collected samples were measured to assess the industrial suitability of the fuller's earth. The cation exchange capacity values ( 25.04 to 31.92 mequvi / 100 gram measured by methylene blue method , while 26.13 to 36.18 mequiv / 100 gram measured by Soil Survey U.K. Labortory method ) happened to be those of the illite. Swelling index values 1.5 ml to 2.6 ml , plastic limit 33-35 , liquid limit values 68 -75 and plasticity index values 35-41 showed that this material is highly illitic and poor in montmorillonite. The surface area of the raw material 21.04 to 33.35 $m^2/g$ is low relative to bentonite that is 48-97 $m^2/g$. However, the values 66.84 $m^2/g$ to 125.04 $m^2/g$ obtained after activation are much higher.*

*In conclusion, the fuller's earth of the Dalana area lacks good quality for industrial use. However, as there is an increase in the surface area on acid activation, further work to asses its suitability for oil decolorization and purification is recommended.*

## INTRODUCTION

The present study involves different techniques for a detailed investigation of the fuller's earth to evaluate its industrial uses from the Sirki Shale Member of the Eocene Kirthar Formation. The area under investigation is located in the Sulaiman Range , southern Pakistan and is covered by the Survey of Pakistan,s topo sheet NO 38 J/ 8.( Fig 1)

Samples were collected by channel sampling method for laboratory studies. Trenches ranging from 4.5 to 11 meters were dug and a channel was made through these trenches. At every meter, chip sampling was run. During field investigation, twenty representative samples were collected from A, B, C and D zones of the Sirki Shale Member from the trenches marked on geological map (Fig.1 & Table 1).

Bulk mineralogy, clay mineralogy and morphology of the clay minerals was determined by X.R.D and S.E.M.Whole rock chemistry which gave a rough estimate of clay and other accessory minerals present in the rock were known by X-ray fluorescence spectrometry. Liquid limits and plastic limits were determined to see the behaviour of clay when immersed in water. Cation exchange capacity was measured to determine the presence of replaceable cation. Surface area was measured to calculate the external surface area which show the quality of clay. Swelling index was measured to check the expension property of clay. Acid activation technique was used for its suitability for bleaching vegetable oil.

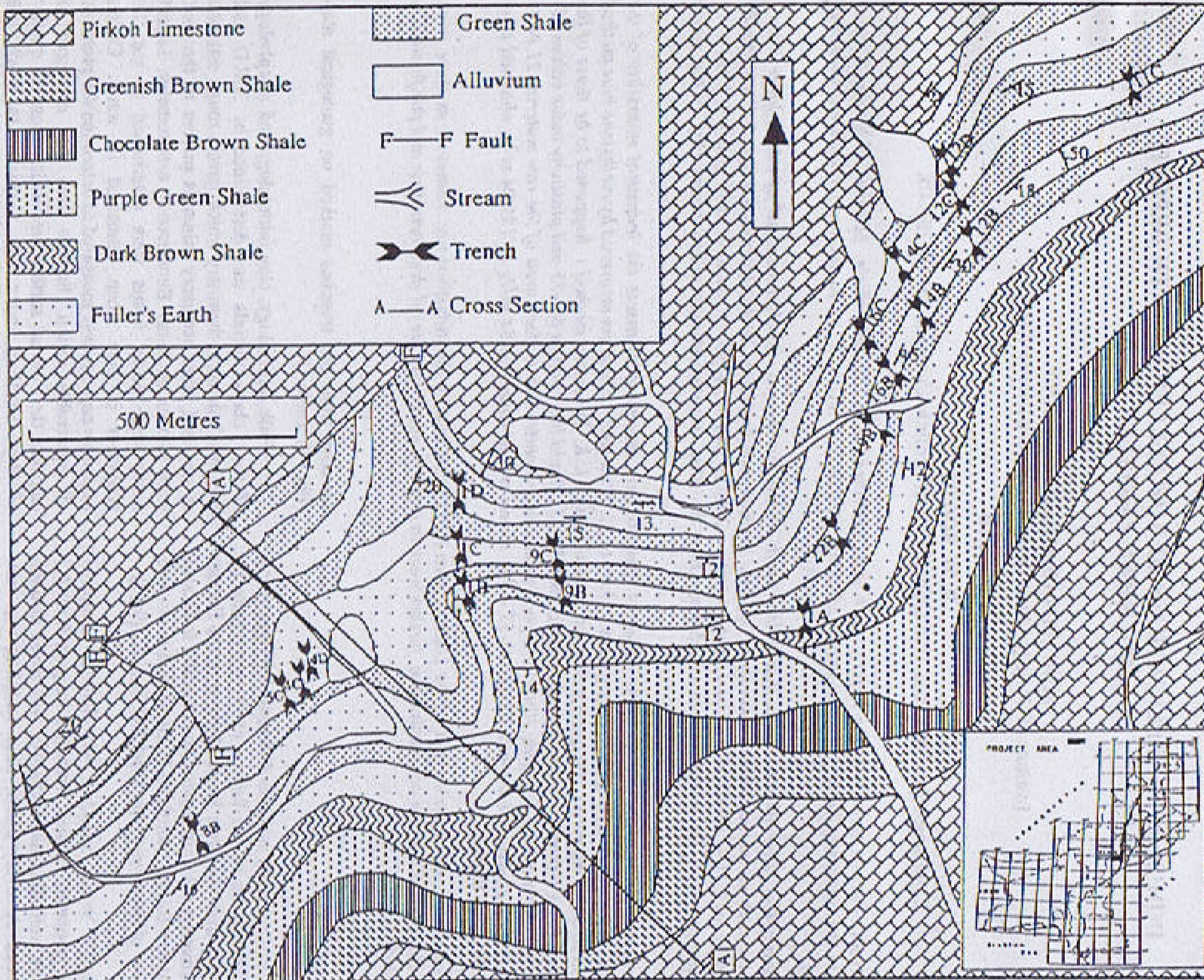


Fig.1 Geological Map of the Dalana Area (D. G. Khan), Pakistan

## GEOLOGICAL SETTING

The area under investigation is located in the K- he Suleman Range which lies in the southern part of he Punjab province, ( Pakistan ). It is covered by the Surve of Pakistan topo sheet No 38 J/8 and lies at a distance of about 36 Km from the Dera Ghazi Khan Town.

Sizeable and well exposed beds about 1 meter to 15 meters in thickness of fuller's earth in the form of layres and interbeds is widely distributed in the Sirki Shale Member of Kirthar Formation extending from Sakhi Sarwar through Dalana, Zindapir, Moh Zein in Rodo in D.G. Khan mountaineous belt running more or less north south. The stratigraphic postion of Kirthar Formation is Indicated as follows (Eames, 1952; Tanish et al., 1959; & Hemphill and Kidwai, 1973).

Nari Formation
(Oligocene)

---------------------------Unconformity---------------------------

Kirthar Formation Drazinda Shale Member
( Eocene )

Pir Koh Limestone and Marl Member

**Sirki Shale Member**

Habib Rahi Limestone Member

Ghazij Formation
( Eocene )

The fuller's earth beds present in the Sirki Shale Member show alternating pinkish red and greyish colourations with well - spread surficial yellow powder and less common orange brown coating . The beds exhibt compact to thinly laminated character and with gypsum films along foliation planes which locally extend at angles across the bed.Fuller's earth deposit of Dalana area are easily discernible and named as A,B,C,D and E zones in their order of superpositions.Fuller's earth is lying exposed without overburden or smaller overburden of the ratio of 1:1 or less. The thickness of zone A is about 12-16 meters, zone B = 11-15 meters, zone C = 12.1 meters, zone D = 3-4 meters and zone E is 2 - 3.4 meters.The colours of the fuller's earth is light grey, grenish grey and brownish grey. Weathering to off-white, orange and rusty brown colours.

The upper part of zone A contains numerous calcareous bands while shally interclations occur in the middle part.Main part of the zone B contain thin shaly interclations while upper part contains interclations of indigo blue stained fuller's earth and shale. Gypsum is present in the form of needles. Zone C contains dark grey to dull green indigo blue stained fuller's earth band which are dark grey to dull green. Fibrous gypsum along microjoints are also present. Fuller's earth of zone D is thinly to moderately laminated. Fibrous gypsum along microjoints is present. Zone E contains splintery light grey and grenish grey fuller's earth.

## EXPERIMENTAL PROCEDURE

X-ray diffraction (XRD.) was performed on powders and orientated samples on a Philips PW 1729 diffractometer to idntyfy the clay and non clay material.Several treatment on orientated samples were used (1) saturation with ethylene glycol to test the expandability of the inter- stratified minerals (2) heating to $550^0$ C for 1 hour and 45 minutes.The dehydration temperature of the structural water of clay was measured by Differential Thermal Analysis (DTA.) on the - 63 um fraction.The morphology of the clay minerals was determined by Scanning Electron Microscope (SEM). The samples were mounted on aluminium stubs and coated with gold. Specimens were studied at magnifications ranging from X 2.00K to X 5.00 K.

**Table 1.**

**Length and location of trenches.**

| Trench No. | Length in meters | Grid Ref. |
|---|---|---|
| 1--A | 4.6 | 510142 |
| 1-B | 10.0 | 504142 |
| 8-B | 10.0 | 498137 |
| 9-B | 8.0 | 506142 |
| 12-B | 6.50 | 514148 |
| 14-B | 4.25 | 512147 |
| 16-B | 5.75 | 511147 |
| 19-B | 7.60 | 512145 |
| 22-B | 7.90 | 510144 |
| 1-C | 11.0 | 504143 |
| 4-C | 5.0 | 499140 |
| 5-C | 5.0 | 500141 |
| 9-C | 10.0 | 507142 |
| 11-C | 9.25 | 516152 |
| 12-C | 2.75 | 514149 |
| 14-C | 4.0 | 512148 |
| 16-C | 6.0 | 512147 |
| 1-D | 3.0 | 505144 |
| 4-D | 5.0 | 500141 |
| 12-D | 2.0 | 512151 |

To determine the chemistry of the material analyses were performed by X-ray fluoresence (XRF) method.For this purpose Philips PW 1400 with 3Kv chroma anode X-ray tube was used.Loss-on-ignition (LOI) was calculated from weight loss after heating 4 gram of sample at $990^0$ C for one and half hours in a muffle furnace. To determine the purity of the material the cation exchange capacity was measured by the methylene blue method. For crosscheck cation exchange capacity (CEC) was measured by British Soil Survey Laboratory Method.Liquid limit and plastic limit (Atterberg Limits) were determined by BS 1377 : 1975 Methods of test for soils for civil engineering purposes.The whole sample was used to determine liquid limit and plastic limit.Surface area was determined by Brunauer, Emmett and Teller ( BET ) method.To calculate the swelling index of clays, the swelling test was carried out.

## MINERALOGY

To determine the mineralogy of the fuller's earth XRD, DTA /TG and SEM techniques were used. XRD diffraction pattern of unorientated samples show that illite-smectite and kaolinite are the dominent clay constituents, with accessory concentrations of quartz and minour amount of gypsum is also present. Traces of orientated samples of < 2um show illite-smectite as major phase and kaolinite as minor constituent. Glycolation confirmed the presence of montmorillonite as mixed layer of illite-smectite The shifting of peaks shows the presence of mixed layered illite - smectite (Moore and Reynolds, 1989)Traces of heated samples at $550^0$C show only illite as the smectite component of I-S collapsed 10Å Kaolinite also disappear at this temperature.

D.T.A shows that second endothermic peak between $128^0$C-$140^0$C which is due to adsorbed water by the montmorillonite . Third endothermic peak of hydroxyl water occurs at $505^0$C-$550^0$C, the last endothermic peak due to the structural changes is shown between $895^0$–$940^0$C. TG show dehydroxylation steps in the $500^0$-$600^0$C range and small steps are just visible in the $700^0$-$800^0$C range. Similar behaviour is shown by the mixed layer clays. (Mackenzie,1970).

SEM study indicates that the clay is fine grained from cryptocrystalline to microcrysalline (0.91 to 4.54um). It is laminated and show honeycomb texture similar to pore-filling illite-smectite types clays honeycomb texture (Burley, 1989). Illite-montmorillonite constitute main mass of the rock.Quartz occurs as tiny subangular to subrounded grain, ranges in size from 0.45 to 2.18um. Pyrite is present as accessory mineral ranges in size from 1.45 to 3.67um.

The XRD, DTA and SEM studies of the Dera Ghazi Khan Deposit (Dalana Area) indicate that it is mainly composed of mixed layer illite - smectite clays with minor impurities of Kaolinite, quartz, gypsum and hematite (Siddiqui ,1997).

## CHEMISTRY

The chemical analyses of Dera Ghazi Khan clays (Dalana area) show that silica content varies between 53.39% to 57.56%, while alumina content ranges from16.33% to 17.15% (Table 2). Iron content ($Fe_2O_3$) is between 7.35% to 11.01%. This amount of iron oxide exists both in illite as well as in hematite. Peaks of hematite were detected on X-ray diffraction. MgO content ranges

**Table- 2**

**Chemical Analysis of Fuller's Earth**

| | 1-A | 1-B | 1-B | 8-B | 12-B | 16-B | 1-C | 12-C | 16-C | 1-D | 12-D |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 55.80 | 57.56 | 57.19 | 57.55 | 54.24 | 53.95 | 55.18 | 54.10 | 53.39 | 55.79 | 55.30 |
| $Al_2O_3$ | 17.15 | 16.77 | 16.73 | 16.93 | 16.96 | 16.52 | 16.94 | 16.83 | 16.79 | 16.61 | 16.33 |
| $TiO_2$ | 0.96 | 0.87 | 0.87 | 0.88 | 0.97 | 0.91 | 0.96 | 0.91 | 0.94 | 0.85 | 0.89 |
| $Fe_2O_3$ | 9.41 | 7.62 | 7.66 | 7.35 | 10.32 | 11.01 | 9.38 | 10.93 | 10.97 | 10.35 | 10.82 |
| MnO | 0.07 | 0.06 | 0.07 | 0.06 | 0.07 | 0.08 | 0.07 | 0.06 | 0.08 | 0.07 | 0.09 |
| MgO | 3.07 | 2.89 | 2.86 | 3.02 | 3.10 | 3.13 | 3.01 | 3.33 | 3.44 | 2.81 | 3.17 |
| CaO | 0.12 | <lod | <lod | <lod | <lod | <lod | 0.12 | 0.09 | 0.21 | <lod | <lod |
| $Na_2O$ | 0.74 | 0.85 | 0.97 | 0.98 | 0.78 | 0.67 | 0.72 | 0.76 | 0.75 | 0.64 | 0.81 |
| $K_2O$ | 3.15 | 2.90 | 2.81 | 2.83 | 3.19 | 3.36 | 3.17 | 3.10 | 3.36 | 3.1 | 2.97 |
| $P_2O_5$ | 0.11 | 0.10 | 0.09 | 0.09 | 0.13 | 0.13 | 0.11 | 0.13 | 0.08 | 0.13 | 0.13 |
| L.O.I | 7.70 | 9.48 | 9.48 | 8.80 | 8.57 | 8.33 | 8.24 | 8.00 | 8.07 | 8.17 | 7.95 |
| **Total** | **98.28** | **99.10** | **98.60** | **98.50** | **98.33** | **98.09** | **97.91** | **98.25** | **98.08** | **98.52** | **98.47** |

between 2.86 to 3.44 and is probably contained in the montmorillonite lattices (Table 2). These clays have very low amount of CaO (0.09-0.21wt%) and $Na_2O$ (0.64-0.98wt%) and a higher concentration of $K_2O$ (2.81-3.36wt%). Potassium oxide is expected to be mostly in the clay lattice as a part of illite. X-ray diffraction analysis show the presence of minor amount of gypsum, so this small amount, CaO may in part be due to gypsum.

**Table 3**
**Cation exchange capacity**

| Sr.No. | Sample No. | Methylene blue method CEC mequiv/100g | British Soil Survey Laboratory method Average CEC mequiv/100g |
|---|---|---|---|
| 1 | 1-A | 27.29 | - |
| 2 | 1-B | 27.28 | 29.48 |
| 3 | 8-B | 27.82 | - |
| 4 | 9-B | 27.48 | - |
| 5 | 12-B | 25.73 | - |
| 6 | 14-B | 27.68 | - |
| 7 | 16-B | 26.21 | - |
| 8 | 19-B | 31.92 | - |
| 9 | 22-B | 29.54 | - |
| 10 | 1-C | 26.73 | - |
| 11 | 4-C | 27.80 | - |
| 12 | 5-C | 25.68 | - |
| 13 | 9-C | 27.90 | 26.63 |
| 14 | 11-C | 27.93 | - |
| 15 | 12-C | 26.79 | - |
| 16 | 14-C | 25.49 | - |
| 17 | 16-C | 25.54 | - |
| 18 | 1-D | 27.91 | 36.18 |
| 19 | 4-D | 26.95 | - |
| 20 | 12-D | 26.87 | - |
| 21 | British fuller's earth | | 68.89 |

- Not determined

The calculated cation exchange values of the Dera Ghazi Khan clays ranges between 25.04 to 31.92 mequvi/100 gram (Table 3) measured by methylne blue method, while 26.13 to 36.18 mequiv/100 gram based upon the procedure adopted by the British Soil Survey Laboratory Method.These values are below the standard values (80-150) of montmorillonite (Grim, 1968) and calculated cation exchange capacity value of British fuller's earth is 68.89. Cation exchange values of Dera Ghazi Khan clays fall in the range of standard values (10-40) of illite (Grim, 1968). It is assumed that in the mixed layer clays the amount of illite is higher than montmorillonite.

## PHYSICAL PROPERTIES

### Surface Area

The surface area of the raw material calculated from 10 samples (Table 4) from different horizons of the deposit varies between 21.04 to 33.35 m2/g. The mean value 26.90 m2/g is relatively low when compared with the published value of bentonite. Olphen and Fripiat (1979) quotes the values of montmorillonite between 48 to 97 m2/g. These low values may be due to relatively low proportion of smectite in the illite-smectite mixed layer clays.

**Table 4**
**Showing the surface area**

| Sr.No. | Sample No. | Surface Area $m^2/g$ |
|---|---|---|
| 1 | 1-A | 21.04 |
| 2 | 8-B | 21.98 |
| 3 | 12-B | 28.03 |
| 4 | 16-B | 27.83 |
| 5 | 22-B | 32.16 |
| 6 | 4-C | 30.43 |
| 7 | 11-C | 20.39 |
| 8 | 14-C | 25.97 |
| 9 | 16-C | 27.78 |
| 10 | 1-D | 33.35 |

### Liquid Limits, Plastic Limits and Plasticity Index

Dera Ghazi Khan clays (Dalana area) give plastic limit in the range of 33-35, liquid limit 68-75 and plasticity index 35-41.The results of plastic limit, liquid limit and plasticity index are shown in Table 5.

Generally Ca, Mg-bentonite gives LL in the range of 100-200 (Morgan, 1990). Typical plasticity index values of Ca-montmorillonite (fuller's earth) lie between 50 and 100 (Bain, 1971). A typical illite clay, and in particular a clay fraction prepared from an illite soil with the removal of coarse micaceous constituents, would have plastic limit and plasticity index values both of the order of 40-50 (Bain, 1971).

On the basis of the results and comparing the data with published clay identification chart (Bain, 1971), Dera Ghazi Khan clays are highly rich in illite and poor in montmorillonite.

**Table 5**
**Plastic limit / Liquid limit**

| Sr.No. | Sample No. | LL | PL | PI |
|---|---|---|---|---|
| 1. | 12-B | 68.7 | 33.17 | 35.53 |
| 2. | 4-C | 75.5 | 33.94 | 41.56 |
| 3. | 1-D | 74.5 | 35.38 | 39.12 |

**Swelling Index**

The swelling index of the Dera Ghazi Khan clays is between 14 ml to 16 ml for every 10 gram sample. Addition of 1% $Na_2CO_3$ causes expension between 15 ml to 21 ml while with 2% $Na_2CO_3$ the swelling ranges between 16 ml to 24 ml and for 3% $Na_2CO_3$ it ranges from 21 ml to 26ml.

By increasing $Na_2CO_3$ beyond 3% no visible swelling is noted but the values start decreasing as shown in the Table 6. The maximum swelling which is 21 ml to 26 ml is achieved by mixing 3% $Na_2CO_3$.

A moderately swelling bentonite produces 15 to 20 ml gel (Morgan, 1990), while the results of Dera Ghazi Khan clays are far below that, ranging from 1.5 ml to 2.6 ml.

**Table 6**
**Showing the swelling of raw and Na activated fuller's earth (ml per 10 gram of clay)**

| Sr.NO. | Sample No. | Raw | 1% $Na_2CO_3$ | 2% $Na_2CO_3$ | 3% $Na_2CO_3$ | 4% $Na_2CO_3$ | 5% $Na_2CO_3$ |
|---|---|---|---|---|---|---|---|
| 1 | 1-A | 16ml | 20ml | 20ml | 24ml | 20ml | 16ml |
| 2 | 8-B | 16 | 21 | 21 | 24 | 21 | 16 |
| 3 | 9-B | 16 | 21 | 21 | 21 | 16 | 16 |
| 4 | 12-B | 16 | 20 | 21 | 24 | 16 | 16 |
| 5 | 16-B | 15 | 16 | 21 | 24 | 16 | 16 |
| 6 | 4-C | 16 | 21 | 24 | 26 | 20 | 21 |
| 7 | 11-C | 16 | 21 | 23 | 24 | 21 | 21 |
| 8 | 16-C | 14 | 15 | 16 | 20 | 16 | 15 |
| 9 | 1-D | 15 | 21 | 24 | 26 | 26 | 26 |
| 10 | 12-D | 14 | 16 | 24 | 25 | 24 | 21 |

## TECHNICAL PROPERTIES

**Acid Activation**

Two representative samples 12-B and 4-C of Dera Ghazi Khan clays were selected for acid activation (Hydrochloric acid). The surface area of the both samples (about 0.5% gram weight) were calculated before activation, which was 28.03 and 30.43 m2/g for 12-B and 4-C respectively. After acid activation (about 0.25 gram weight) the surface area of the samples were increased as shown in Table 7.

At a normality of 6 and treating time of six hours the surface area increases to 125.04 m2/g for sample 12-B and 120.48 m2/g for sample 4-C. The increase in surface area after activation is therefore just more than four fold. Hydrochloric acid treatment is suitable but perhaps with some-what higher acid concentration than 6N and longer. Treatmnt time up to 6 hours or above 6 hours.

**Table 7**
**Surface area after acid activation**

| Sr.No. | Acid normality/time | Surface area m²/g of 12-B | Surface area m²/g of 4-C |
|---|---|---|---|
| 1 | 1N-1H | 70.29. | 66.84 |
| 2 | 3N-1H | 85.43 | 83.78 |
| 3 | 6N-1H | 84.58 | 90.64 |
| 4 | 1N-3H | 70.20 | 68.03 |
| 5 | 3N-3h | 120.0 | 86.53 |
| 6 | 6N-3H | 122.34 | 88.69 |
| 7 | 1N-6H | 76.48 | 82.49 |
| 8 | 3N-6H | 112.73 | 106.29 |
| 9 | 6N-6H | 125.04 | 120.48 |

## DISCUSSION

The X-ray diffraction patterns of raw -63 micron, glycolated and heat treated sample at 550° C indicate that the deposit is mainly composed of illite-smectite mixed layer clays with minor impurities of kaolinite , quartz, gypsum and hematite. Concentration of smectite was too low to be estimated from the XRD traces. Though the traces of glycolated samples show a peak shift which is an indication for the presence of smectite. The results of the D.T.A also support the finding from the XRD . The morphology of the clays as observed by S.E.M studies, is similar to that of typical illite- smectite mixed layer clays . S.E.M studies also revealed the presence of quartz and pyrite in the samples.

The chemical analyses of the samples show that they have very low amount of CaO ( 0.09 - 0.21 Wt % ) and $Na_2O$ (0.64-0.98 Wt %) and a higher concentration of $K_2O$ (2.81-3.36Wt%). These chemical characteristics suggest a high abundance of K-bearing clays ( e.g., Illite ) and a low or total lack of CaO and $Na_2O$ bearing spiecies (e.g,Montmorillonite). These chemical signatures are in conformity with the XRD traces which indicate that these samples are mainly composed of illite- smectite mixed layers.The cation exchange values (25-36 mequvi/100gram) of D.G.Khan clays fall within the range of standard values (10-40 mequvi/100gram, Grim, 1968) for illite. Low cation exchange capacity values are due to paucity of exchangeable cations in the interlayer.

The surface area determination of these clays show low values (21.04 to 33.35$m^2$/g) which do not match with the published values (82 $m^2$/g) of bentonite. Liquid limit (69-70) plastic limit (33.2 to 35.8) and plasticity index (41.6) values of D.G.Khan clays are not matching with those of pure bentonites (82- 97plastic limt , 118-700 liquid limit Grim,1950). These values (40-50, both for PLs and Pl) of illite material (Bain, 1971) indicate the presence of major illitic content in this deposit. The swelling index values of D.G.Khan clays ranging from 1.5 ml to 2.6 ml are thus less than those (15 to 20ml gel) of even the moderately swelling bentonite. The low values of these clays are probably due to the absence of Na type montmorillonite. However the addition of 3% of sodium carbonate made it passible to swell up to 1.5 of the original volume. The surface area of the raw material varies between 21.04 and 33.35 $m^2$/g. After treatment with HCl of 1N, 3N and 6N the surface area was found to increase . With HCl of 6N after heating at temperature of $70^0$ C for 6 hours the surface area was increased up to maximum value of 125 $m^2$/g , which is 4 times greater than the surface area of the raw material. The both factors, higher strengh and greater time play an important role in increasing the surface area and consequently reactivity.

The results of different tests carried out for industrial evaluation of D.G.Khan illite-smectite deposit indicate that this material is not suitable for various end uses of bentonite, however the acid activation results show a promising use of this clay for blaeching of edible oil. It is suggested that bleaching tests should be carried out to know its bleaching capacites with activated clay at different combinations of normalities and heating time.

## INDUSTRIAL APPLICATION OF THE FULLER'S EARTH OF THE DALANA AREA

1 - Low cation exchange capacity values (25-36) are due to paucity of exchangeable cations in the inter layers. Due to very low contents of Ca and Na as exchangeable cations Dera Ghazi Khan clays are not suitable for the oil-well drilling muds., foundries, refining and bleaching of glyceride oil, clarification and purification of sugar solutions, syrups and wine. It may also not be used in pharmaceutics and absorbents (Bain, 1971).

2- Due to low plasticity index values (35 to 41) the material does not have good bonding properties, which are utilised in a wide range of applications, including pelletising animal feeds or plants seeds, binding togather foundry sand and pelletising iron ore.

3- The swelling index values are less than those of even moderately swelling bentonite. The bounding properties depends on high swelling volumes as these clays have poor swelling values so these may not be used in foundry.

The surface area after acid activation increased but no firm conclusion can be reached on the utility of the deposit in the absence of bleaching test.

## CONCLUSIONS

The following main conclusions are drawn regarding the mineralogical and industrial suitability of fuller's earth of Sirki Shale Member Dalana area Dera Ghazi Khan, Pakistan.

X-ray diffracton and differential thermal analysis studies show that the deposit is not a pure Ca-montmorillonite (fuller's earth) but is composed of illite-montmorillonite mixed layer clays with minor impurities of quartz, kaolinite, gypsum and hematite.

The chemical analyses show higher concentraton of $K_2O$ rather than CaO. This also furthēr support the above conclusion. The small amount of CaO in the analyses seem to have been accommodated in gypsum as is also shown by the XRD traces.

The results obtained by physical tests i,e; shown as surface area, swelling index, plastic limit and liquid limit determination are consistent with those of mineralogical studies and chemical analyses of the samples conclude that it consist of illite-montmorillonite mixed layer clays with higher concentration of illite. Therefore, its industrial use become limited. However, after an activation, the deposit may be useful for bleaching vegetable oil which is a gk./ood market in Pakistan

## ACKNOWLEDGEMENTS

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# REGRESSION ANALYSIS OF LIQUID LIMIT AND CLAY CONTENT OF FLUVIAL SOILS AND THEIR RELATIONSHIP

BY

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**Abstract :-** *The soil samples collected from overbank facies of Nullah Bhimber were tested for their index properties. Clay % and liquid limit have been plotted against each other on equal area graph corresponding points cluster around a best fit line known as regression line of liquid limit upon clay %. This regression gives the relation* C=1.167 (LL. - 15).

*The clay % determined by hydrometer and calculated by above relation varies in a range of ± 2% which is quite a good approximation. With the help of this relation (-) # 200 mesh material can safely be differentiated into silt and clay without using lengthy hydrometer analysis. Secondly when soil is texturally differentiated, it further provides an opportunity of economical use of compaction machinery for earth work and to properly evaluate the soil for earth work and foundation after assessing the activity i.e. the potential volume changes.*

## INTRODUCTION

The pioneer work on the consistency limits was carried out by Atterberg (1911) who suggested three stages of moisture at which soil transit from one state to the other i.e. solid, plastic and liquid. The corresponding moistures at which these stages begin to appear are termed as shrinkage, plastic and liquid limit. The numerical difference between liquid and plastic limit is termed as P.I. (Plasticity Index).

Russell (1928b) suggested that PI is a linear function of clay fraction (0.005 mm size). He also developed a linear relationship between PI and clay content in a soil mass which is

$$PI = 0.6\,C - 12$$

Where C denotes clay fraction in soil mass.

Casagrande (1932) related plasticity Index and liquid limit by following equation:-

$$PI = 0.73\,(LL. - 20)$$

Which is just an approximation and do not fully applicable in Pakistan.

As a first approximation in the identification of soils, retain/passing %age of 0.065 mm sieve i.e. ASTM # 200 mesh are determined. Liquid and Plastic limit of passing materials ASTM # 40 sieve are used to get plasticity index. Under AASHTO and Unified soil classification procedures # 200 sieve gives the boundary between sand and silt/clay fraction. The various % of soil fraction can only be taken if grains size distribution down to colloidal fraction is made by hydrometer or pipette method. This testing involves a lengthy process for the assessment of soil components specially in the field. To over come this problem and to have a general approximation of silt and clay fraction, a mathematical relationship has been tried to develop between liquid limit and clay fraction which is discussed in the following :

## METHODOLOGY

To develop the relationship between liquid limit and clay fraction, following scheme of sampling and testing has been adopted.

### Sampling

The area is composed of fluviatile deposits which have developed under high flow regime (flash floods) of Nullah Bhimber. The overbank facies are generally cohesive in nature. The cohesiveness is the reflection of variable % of clay fraction. Sampling of the study area was carried out systematically at 1 Km. interval grid. The upper 3 - 4 inches of soil was removed so that a uniform and less contaminated soil with organic material be obtained.

### Preparation of test specimens

The soil samples were air dried under shade and then pulverized. The soil material for liquid limit was sieved through # 40 ASTM Sieve and pass was retained in polythene bags. For Hydrometer analysis 100 gm of pulverized soil was taken which was treated with 6% hydrogen per oxide until gas bubbles are no longer given off. This removes organic material.

**Test performance**

***i) Liquid Limit*** Liquid and plastic limits are two of the five limits proposed by Atterberg (1911). These limits are widely used for the identification and classifications of soils. Liquid limit be arbitrarily defined as that water content at which a pat of soil placed in a brass cup, cut with a standard groove and dropped from a height of 1 cm will undergo a groove closure of 12.7mm when dropped 25 times.

Research of Casagrande (1932) and Bowels (1984) have shown that ordinary air drying of many soils lowers the liquid limit as much as 2 to 6%. To void this problem, the air dried samples be either mixed with field moisture content or mixed with water and allowed to cure for 24 to 48 hours. So that the soil should regain its original limits.

So the samples prepared as explained above were mixed with different % of moisture and were kept under polythene sheet for 24 hours, so that the moisture be uniformly mixed with soil. The liquid limit was determined by following ASTM D 4318-84 and AASHTO T-89-93. The maximum size of soil particle in this study was medium grained sand. The liquid limit of the soil obtained by this method for various soils varies from 15-45%.

***ii)Hydrometer Analysis*** To differentiate between granular (+) 200 ASTM sieve and fine material passing (-) 200 ASTM sieve, Hydrometer analysis is employed as per recommended practice of ASTM D 422-63 and AASHTO T-88-93. This analysis is based on the velocity of fall of spheres in a fluid, the diameter of the sphere, specific weight of the sphere and fluid, and viscosity of the fluid.

Soil samples of 50 grams each were taken from the pretreated material as explained above. The same were placed in a beaker having a solution of $NaPo_3$ (Sodium metaphosphate). The same were mixed by employing stirring apparatus. This solution was thus shifted to 1000 ml jar. The hydrometer (152-H) was used which is calibrated to read grams of soils of value Gs = 2.65 in 1000 ml suspension. After doing all necessary calculations for determination of D (Dai of particle), the data was plotted on the semi-logarithmic paper from where percentage of clay was determined.

## REGRESSION ANALYSIS

The data of fluvial soil obtained from previously described tests have been plotted against each other on equal area graph paper in which clay fraction (0.002 mm size) is plotted along x-axis as independent variable and liquid limit along Y-axis as dependent variables. Researchers are well familiar with general analysis when two variables are changing together. The plotting and calculation involved in straight line laws provide example of this. Since the corresponding points scatter along a line which is known as scatter diagram. This line is the line of best fit and is known as the line of regression of Y upon X which represent the relationship between these two variables. The mathematics for the slope of this line is as under:

$$\frac{Y - Y1}{Y2 - Y1} = \frac{X - X1}{X2 - X1} \quad (1)$$

When X1 = 0, Y1 = 15, X2 = 35 and Y2 = 45
The above equation transforms as under:

$$Y = \frac{6}{7} X + 15 \quad (2)$$

Which is the equation of line of regressious of Y upon X.

$$Y = Ax + B$$

Where

Y = Liquid limit of the soil = LL.

X = % Clay fraction in soil = C

6/7 is A, = Constants for slop of line and 15 is B intercept of liquid limit of sand fraction (medium to fine grained) in the soil.

By re-arranging the above regression equation (2). The relationship becomes as under:

$$C = 1.167 (LL. - 15) \quad (3)$$

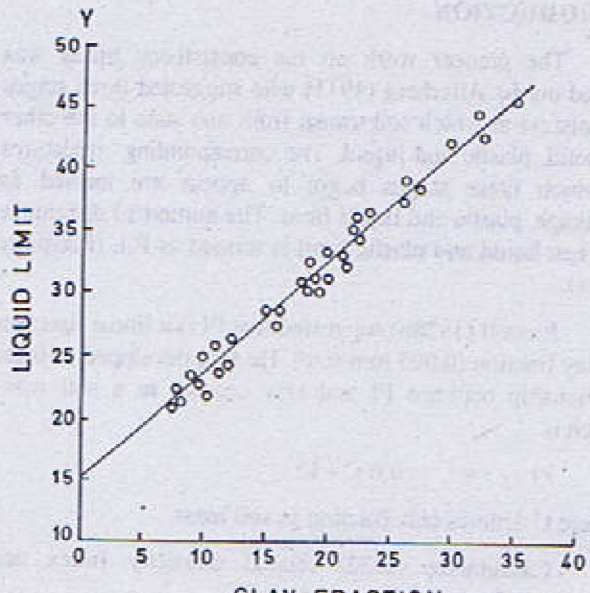


**Fig. 1** Equation of Regression Line of Y upon X
Y = AX + B

## DISCUSSION

Sand and silt upto 0.005mm size are considered to be skeletal material in soil mass. Clay and humus are active ingredient of soil because of their high specific area due to mineralogical and chemical compositions. Sandy soils are not physio-chemically active because of large quantity of skeletal material where as clays on the other hand are plastic and sticky, shrink on drying and swell on wetting.

Table 1.

**Comparison between clay % determined by hydrometer and calculated by relationship**
**C = 1.167 (LL - 15)**

| Sample No. | Liquid Limit by Casagrande apparatus | Clay % Hydrometer analysis | Clay % calculated by relationship |
|---|---|---|---|
| 1 | 34.15 | 22.5 | 22.35 |
| 2 | 36 | 22.5 | 24.5 |
| 3 | 24.2 | 11.5 | 10.74 |
| 4 | 45 | 35 | 35.01 |
| 5 | 28.5 | 15 | 15.75 |
| 6 | 36 | 26 | 24.5 |
| 7 | 24.5 | 12 | 11.09 |
| 8 | 28 | 15 | 15.17 |
| 9 | 31 | 19 | 18.67 |
| 10 | 25.5 | 11 | 12.25 |
| 11 | 33 | 20 | 21 |
| 12 | 30 | 18.5 | 17.5 |
| 13 | 33 | 20 | 21 |
| 14 | 23.75 | 9 | 10.21 |
| 15 | 44 | 32 | 33.83 |
| 16 | 42 | 30 | 31.5 |
| 17 | 30.5 | 18 | 18.09 |
| 18 | 38 | 27.5 | 26.83 |
| 19 | 33.5 | 21.5 | 21.59 |
| 20 | 25 | 10 | 11.67 |
| 21 | 26 | 11 | 12.83 |
| 22 | 21.5 | 8.5 | 7.58 |
| 23 | 32.5 | 18.5 | 20.42 |
| 24 | 31 | 20 | 18.67 |
| 25 | 21 | 8 | 7 |
| 26 | 30 | 19.5 | 17.5 |
| 27 | 25 | 10 | 11.66 |
| 28 | 22.5 | 8 | 8.75 |
| 29 | 28.3 | 16 | 15.52 |
| 30 | 26.12 | 12.5 | 12.97 |
| 31 | 32 | 21.5 | 19.83 |
| 32 | 42 | 32.5 | 31.5 |
| 33 | 36 | 23 | 24.5 |
| 34 | 22 | 10.5 | 8.17 |
| 35 | 35 | 22 | 23.34 |
| 36 | 34.6 | 22.5 | 22.17 |
| 37 | 24.5 | 11.5 | 11.09 |
| 38 | 26.5 | 12.5 | 13.14 |
| 39 | 31 | 20 | 19.83 |
| 40 | 24.52 | 12 | 10.11 |
| 41 | 23 | 10 | 9.33 |
| 42 | 24 | 12 | 10.5 |
| 43 | 33 | 21 | 21.006 |
| 44 | 38.5 | 26 | 27.42 |
| 45 | 27.5 | 16 | 14.58 |

Since plasticity is a function of fine fraction, in soil. The increase in clay % increases the liquid limit and plastic limit so as to increase the PI value. Russell (1928b) has reported that PI is a linear function of clay contents. The grain size, shape and grading also effects the soil index properties. Dumbleton and West (1966) has pointed out that the coarse fraction imparts a resistance to deformation and will tend to increase the liquid limit. In this study this fact has accordingly been considered and intercept value of 15 (Fig-I) is taken as the liquid limit of medium to fine grained soil of sandy silty composition when clay percentage is zero.

Numerous experimental findings have shown that physio-chemical properties of soils are dependent upon the surface activity of clay fraction. Davidson and Sheller (1952) have pointed out that inorganic clays are primary seats of cation exchange capacity. They have plotted the values of cation exchange capacity versus index properties which shows a curvilinear relationship but the relationship with clay % (fraction) was found to be linear. They have also shown that exchange capacity increases with distance from the main channel as clay quantity increases in distal areas.

The fluvial soils in general possess poly modal grain size distribution from sandy soils in levees, channel bars, silty soils in the flood plains to clayey soil in the back swamps and distal areas. The reworking of the soil by wind and sheet flow on the micro-relief and collection of fines in topographic depressions also impart pronounced variation in soil composition and texture which in turn is reflected by variable behaviour of index properties. The regressive analysis of the data presented at Figure-I and in table I is in full agreement with the above discussion.

## CONCLUSION

The clay fraction determined by hydrometer is compared with that of calculated with relationship i.e.

$$C = 1.167\,(LL. - 15)$$

This comparison shows that the relationship gives a good approximations of clay % in fluvial soils with $\pm$ 2% variance. This relationship can safely be used in assessing the textural distribution of soil particles which in term help in deciding about the compaction efforts and use of appropriate compaction plants. It will also help in knowing about the potential volume changes of the soil i.e.

$$\text{Activity} = \frac{\text{Plasticity Index}}{\text{Percent Clay}}$$

Activity of the soil in term of volume change is a principal concern in evaluating the soil for use in earth works and foundations. Further studies of index properties in relation to variable clay contents for other areas is recommended with the proposition that the variance of $\pm$ 2% may become less.

## ACKNOWLEDGMENTS

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# RECONNAISSANCE MICROFACIES ANALYSIS OF THE UPPER JURASSIC SAMANA SUK FORMATION, NORTHERN HAZARA, PAKISTAN

By

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**Abstract:-** *The Samana Suk Formation of the Upper Jurassic age from the Sanger-gali Maira Rehmat Khan area of northern Hazara has been studied for microfacies and diagenetic fabrics. The upward shoaling lithofacies are differentiated on the basis of the presence of oolites, bioclasts, pellets, cements and terrigenous content. A total number of eleven microfacies have been recognised. Microfacies from bottom upwards are carbonate mudstone (biomicrite), wackestone (biomicrite), packstone (oomicrite), dolostone, packstone (biomicrite), grainstone (biosparite), mud to wackestone (biomicrite), packstone (spar biomicrite), mudstone (biomicrite), wackestone (pelmicrite) and mudstone (micrite). The study of texture, structure and diagenetic fabrics shows that the Samana Suk Formation was deposited in marine shallow water open circulation shelf environment. The rock units represent a complex diagenetic history. Cementation of grains with coarse crystalline calcite represents an early cement and equigranular calcite cement representing a later phase. Textures of intraclasts, cements and ooides have been replaced by dolomitization. The phenomenon of dedolomitization has also been observed.*

## INTRODUCTION

Microfacies and diagenesis of the Samana Suk Formation from northern Hazara is presented in this article. The Samana Suk Formation was chosen for the study because it shows many facies. Microfacies analysis is based on the classification of Wilson (1975), Folk (1974), Dunham (1962) and Flugel (1982).

In Baragali area of Hazara, Masood (1989) worked on the microfacies and diagenetic history of Samana Suk Formation. He identified seven microfacies of Samana Suk Formation, incontrast during this study eleven microfacies have been identified.

Samana Suk Formation is well exposed near Sangergali-Maira Rehmat Khan area, northern Hazara lat. 34° 14´ 30" long 73° 20´55", Malsa lat. 34° 09´15" long 73° 22´ 45" Bagh Seri lat. 34° 06´15" long 73° 18´00" and Bagnohtar Late 34° 06´30" Long 73° 21´30" (Fig 1). Its thickness varies at different localities. Thickness at Sangargali Maira Rehmat Khan, Malsa Baghseri and Bagnotar is 211 meters, 240 meters, 230 meters and 269 meters respectively.

## METHOD OF STUDY

57 oriented samples of Samana Suk Formation were collected from bottom to top. Thin sections were prepared for the petrographic and microfacies study. The thin sections were stained with aliziarine red S and potassium ferricyanide in a very weak acid solution (Friedman, 1959). The staining process helps to identify calcite from dolomite and also helps to distinguish between ferroan calcite from iron free calcite and ferroan dolomite from iron free dolomite (Evamy, 1963).

## STRATIGRAPHY

In the investigated area, rock units from Precambrian to Upper Jurassic are present. These units are the Hazara,.

| AGE | FORMATIO N | DESCRIPTION |
|---|---|---|
| Upper Jurassic | Chichali Formation | Blackish splintery shales and sandstone beds. |
| Disconfomity | | |
| Upper Jurassic | Samana Suk Formation | Thinly to thickly bedded oolitic, ferrogenous and quartzose dolomitic limestones. |
| Middle Jurassic | Shinawari Formation | Limestone, marl, calcareous and non calcareous shales, ferrogenous quartzose and calcareous sandstone. |
| Lower Jurassic | Datta Formation | Variegated sandstone, quartzite and varicoloured shales. |
| Disconformity | | |
| Cambrian | Sangergali sandstone | Cross and gradded bedded purple and very hard sandstone. |
| Cambrian | Tannaki boulder bed | Boulder conglomerate |
| Disconformity | | |
| Precambrian | Hazara Formation | Slates, phyllites and shales. |

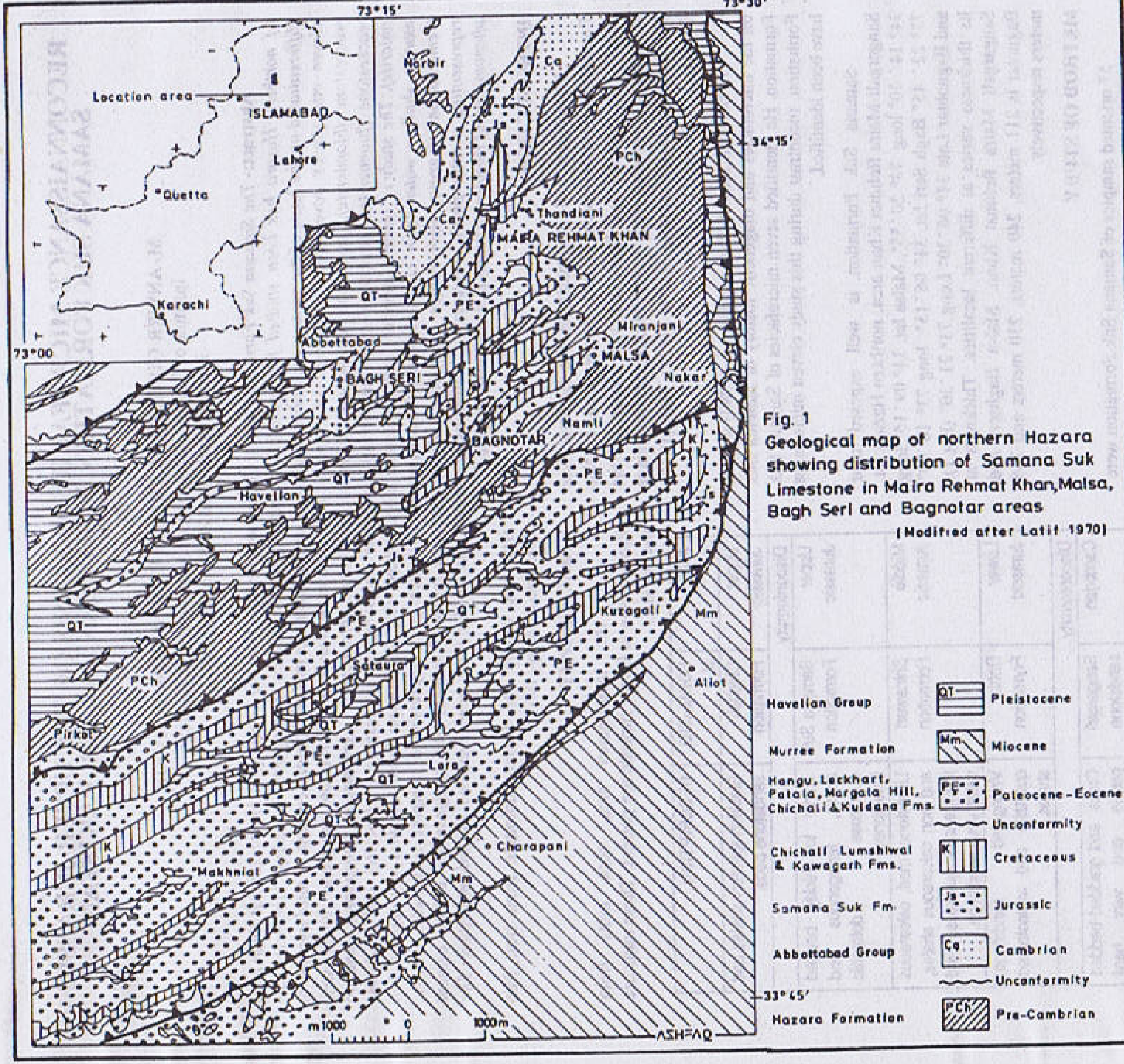


**Fig. 1**
**Geological map of northern Hazara showing distribution of Samana Suk Limestone in Maira Rehmat Khan, Malsa, Bagh Seri and Bagnotar areas**
**(Modified after Latif 1970)**

Datta, Samana . and Chichali Formations. Three unconformities have been recorded one at the base of Tannaki boulder bed second at the base of Datta Formation and the third at the base of Chichali Formation. Brief lithology of the area is described in the table as under

## MICROFACIES

During petrographic studies eleven microfacies have been identified in an upward shoaling lithologic sequence. For this purpose the work of Wilson (1975) and Flugel (1982) is adopted for microfacies identification. Classsificaton of Dunham (1962) and Folk (1974) have been used in nomenclature. The fossils of crinoides, gastropods, algae and genus *Reofax* are present at different horizons.Dominantly, the facies fall into two categories.

1. Open circulation shelf facies.
2. Shoaling facies in agitated water.

MF1 (SMF 8). Whole fossils wackestone. This is defined by sessile organisms rooted in micrite which contains only a few scattered bioclasts. The sediment is formed in quiet water below normal wave base (Fig 3).

MF 2 (SMF 10). Coated and worn bioclasts in micrite, packstone-wackestone. This sediment show textural inversion and formed in shoals in proximity to shoals. Dominant particles are of high energy environments and have moved down local slopes to be deposited in quiet water (Fig. 4).

MF3 (SMF 11). Shoal environments in agitated water, coated bioclasts in sparite grains. Bioclasts are micritized and are formed in areas of constant wave action where lime mud is removed (Fig. 10).

MF4 (SMF 12). Coquina bioclastic grainstone or mudstone shell hash sediment formed in an environment of constant wave or current action with mud removed by winnowing (Fig. 6).

MF5 (SMF 14). Lag deposits: These are coated and worn particles in places mixed with ooides and peloids which are blackened and iron stained with phosphate. These lags are characteristically thin deposits representing slow accumulation (Fig. 7).

MF6 (SMF 15). Oolite, ooide grainstone. well coated ooids ranging in size from 0.5 to 1.5 mm in diameter originated through water movement on oolite shoals and tidal bars. The best formed oolites are typically produced on tidal bars (Fig. 5 & Fig. 8).

MF 7 (SMF 16). Pelsparite or pelloidal grainstone: This consists of hardened fecal pellets in places admixed with concentrated ostracod tests or foraminifera. The pelloids are derived from organic pelleting of mud and may represent only slight water movement (Fig. 12).

MF 8 (SMF 17). Grapestone pelsparite or grainstone: This is a mixed facies of isolated peloids, agglutinated peloids and some coated particles are lumps which are in part small intraclasts (Fig. 10).

MF 9 (SMF 19). Laminated to bioturbated pelleted lime mudstone-wackestone grading occasionally into pelsparite with fenestral fabric (Fig. 9 & Fig. 11).

MF 10 (SMF 23) Unlaminated, homogenous and unfossiliferous pure micrite (Fig. 2).

MF 11 (SMF 24). Coarse lithoclastic rudstone or floatstone: The clasts are generally unfossiliferous micrite with variable spars matrix. These may be termed interformational limestone pebbly conglomerate (Fig. 4 & Fig. 13).

## DIAGENESIS

The pore filling cement crystals in a limestone can yield information about the environment of cementation. Two types of cements have been recognised; first one is the blocky sparry calcite cement and the second type of cement is the result of pore solutions (Fig. 14). In some of the rock slides it has been observed that ferroan cement is intermixed with iron free cement (Fig. 15). Some other cements are micrite cement, drusy mosaic, microstalactic and compromise boundaries (Fig.16). The phenomenon of dolomitizaton is common in ooides (Fig.17). Sometimes ooides internal lamellae have been replaced by dolomite rhombs (Fig.17).

The two types of cement suggest two types of diagenetic processes (Purser, 1969). One type is found as crystals replacing the whole rock and the second type is seen in the allochems replacing their internal lamellea. Dolomitization is also present. Sometimes dolomitization cut across all the allochems and other features and some are wholly dolomitized both with nonferroan and ferroan dolomite (Fig. 17).

Chemical compaction has been reported in oolite leading to various categories of pressure solutioning (Purser 1969). Stylolites have been observed in some of the units which shows pressure solutioning after deposition and lithification (Fig. 19). Stylolites can be recognised due to their irregular boundaries which are highlighted due to the iron staining or presence of the organic matter in the sutures. Ooides show eroded boundaries and part leaching of the grains. Some of the oolites show their edges corroded away due to the pressure solutions (Fig. 19). The phenomenon of bioturbation (Dravis, 1979) is evident in some of the rock units. Some of the calcite veins are primary whereas others are late diagenetic which cut across all the allochem and other features (Fig. 17).

## DISCUSSION

The Samana Suk Formation is an example of shoal type environment. Mostly the microfacies fall in the category of open shelf environment with shoaling waves and currents and this is confirmed by the presence of local sandy beds hard ground surfaces and Oyster beds. Towards the top of the rock unit the presence of clastic content

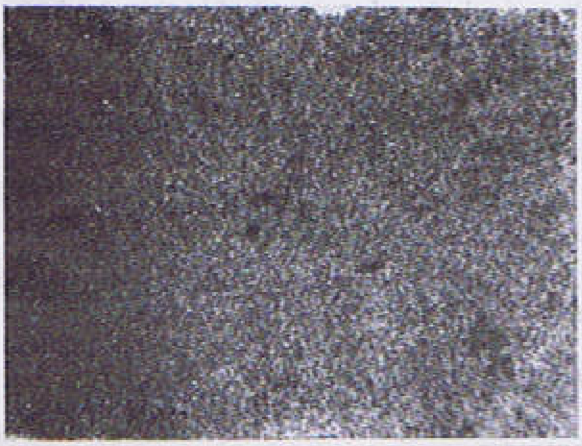

Fig. 2 Micrite-mudsotne (PPL; 4x; FV. 1.74 mm).

Fig. 3. Bioclastic micrite-wackestone (PPL; 4x; FV. 1.74 mm).

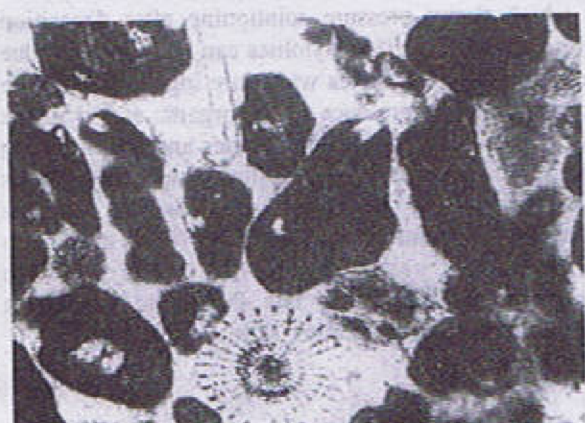

Fig. 4. Coated and worn bioclasts in micrite wackestone-packstone (PPL;4x;FV.1.74 mm).

Fig. 5. Coated bioclasts in sparite-grains-pelletal oosparite (PPL; 4x; FV. 1.74 mm).

Fig. 6. Coquina-bioclastic grainstone or bioclastic Pelsparite (PPL; 4x; FV. 1.74 mm).

Fig. 7. Coated and worn particles in sparite-lag deposits-pelsparite (PPL; 4x; FV. 1.74 mm).

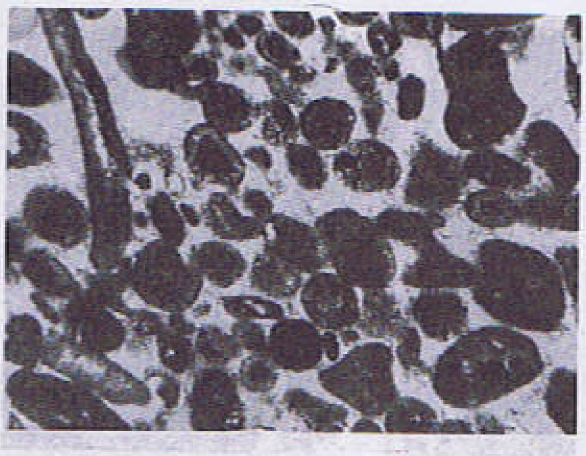

**Fig. 8.** Oolitic and ooidal grainstone-oosparite (PPL; 4x; FV. 1.74 mm).

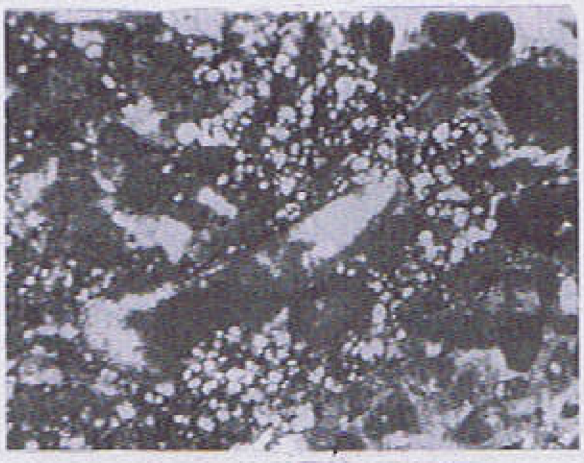

**Fig. 9.** Pelloidal grainstone-dolomitic pelsparite (PPL; 4x; FV. 1.74 mm).

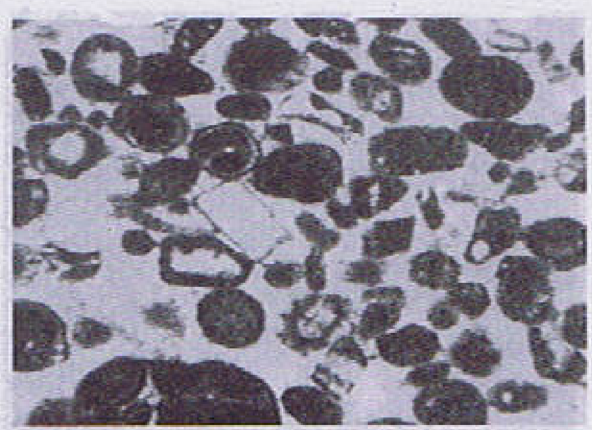

**Fig.10** Bioclastic ooidal and pelletal grainstone-pelsparite (PPL; 4x; FV. 1.74 mm).

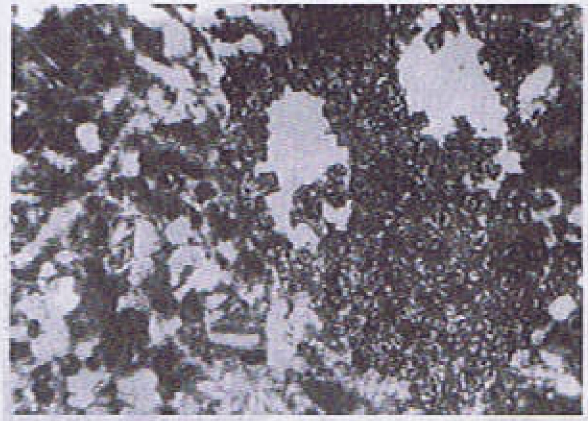

**Fig.11** Dolomitic and bioturbated pelletel lime-mudstone (PPL; 4x; FV. 1.74 mm).

**Fig.12** Homogenous unfossiliferous mudstone (PPL; 4x; FV. 1.74 mm).

**Fig.13** Coarse lithoclastic rudstone-oolitic pelsparite (PPL; 4x; F.V. 1.74 mm).

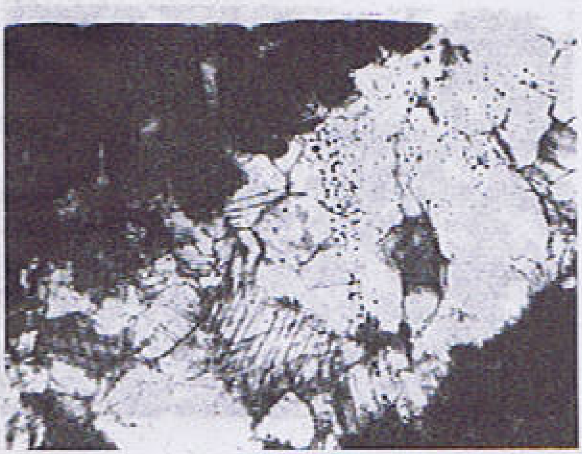

**Fig.14** Blocky sparry calcite (PPL; 4x; FV. 1.74 mm).

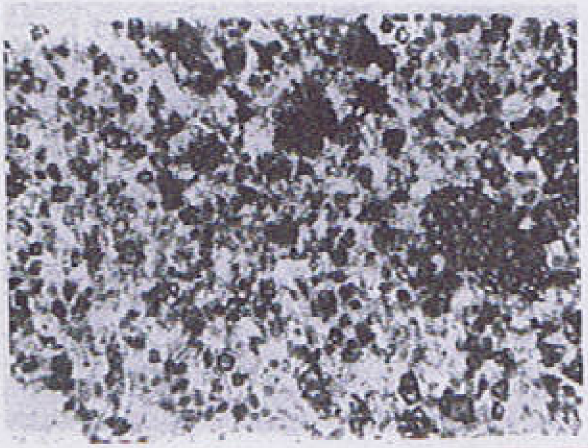

**Fig.15** Ferroan cement intermixed with iron free cement (PPL; 4x; FV. 1.74 mm).

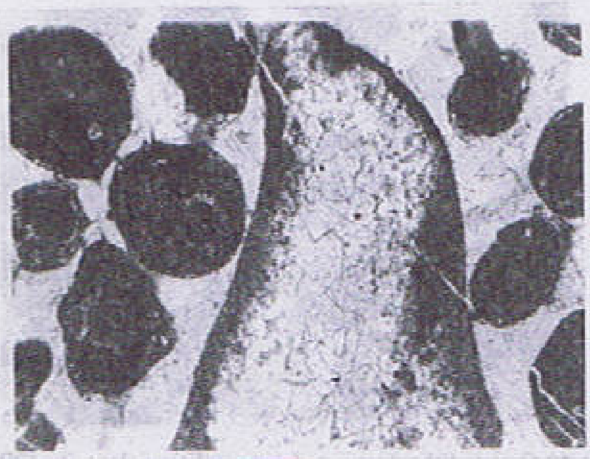

**Fig.16** Cementing material showing drusy mosaic (PPL; 4x; F.V. 1.74 mm).

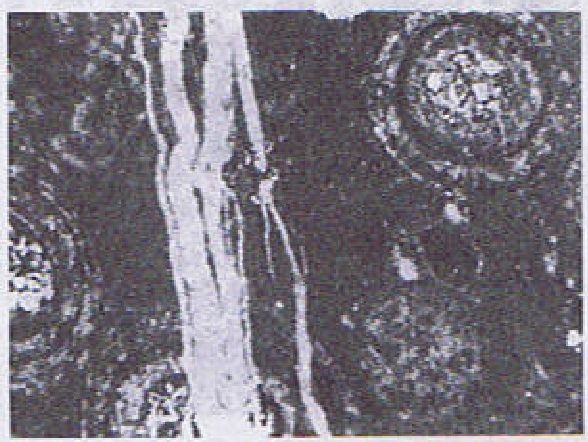

**Fig.17** Ooid grainstone-secondary or late diagenetic calcite vein (PPL;4x;FV. 1.74 mm).

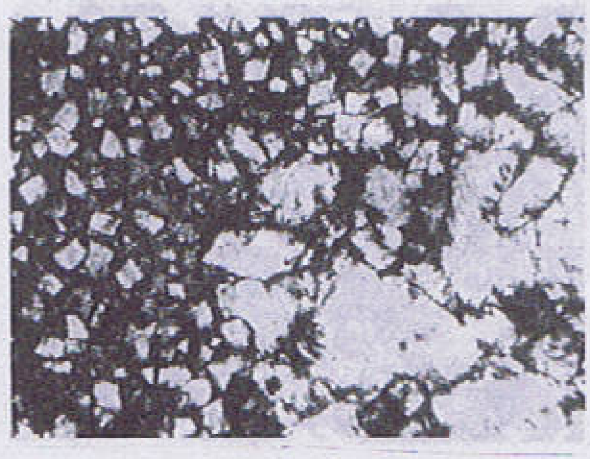

**Fig.18** Dolomitization (PPL; 4x; FV. 1.74 mm).

**Fig.19** Stylolite-pressure solutioning (PPL; 4x; FV. 1.74 mm).

indicates the shallowing of the basin conditions. The presence of hard grounds after some bed intervals indicates that the deposition was slow at times causing the sea floor to harden prior to the deposition of the next bed (Bromlyey 1968).

The diagenetic changes including precipitation of sparite, filling of interpartical spaces, dolomite replacement, dolomitization, pressure solutioning, deformation of ooides and other allochem structures indicate that the Samana Suk Formation is a shelf facies with open circulation and shoaling waves and currents. Water depth is not more than hundred meter having sufficient quantity of oxygen supply, salinity and water circulation (Folk 1974).

## CONCLUSIONS

Study of the standard microfacies suggests that the Samana Suk Formation is an example of the shoal type of environments. Most of thin sections indicate that the constituents grains were winnowed away in the basin before they were deposited. Most microfacies represent the open shelf environments with shoaling waves and currents. There are however differences in the wave energy, water depth and water temperature.

Dolomite replacement, pressure solutioning and the precipitation of sparite that fills the interparticle spaces are the diagenetic changes in the Samana Suk Formation. The precipitation of sparite in vugs caused the porosity to decrease. The pressure solution has deformed the ooides and also at places the internal structure of the oolite has been obliterated. Basically, it is an example of the shelf facies with open circulation and shoaling waves and currents and water depth of few tens to hundred of meters.

## ACKNOWLEDGEMENTS

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# LOWER TERTIARY LITHO-BIOSTRATIGRAPHY OF THE BAGLA-KOHALA-BALA AREA, HARIPUR HAZARA (NWFP), PAKISTAN

By

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**Abstract :-** *The Lower Tertiary shallow water marine sequence of Bagla-Kohala-Bala area overlies unconformably on the Late Cretaceous deep water marine Kawagarh Formation. The Lower Tertiary shaly, marly and limestone sequence of Lockhart Limestone, Patala Formation, Margala Hill Limestone, Chorgali Formation and Kuldana Formation yields rich foraminiferal assemblages. The study of four stratigraphic sections yield 19 age diagnostic benthonic larger foraminiferal species. These foraminiferal species include Lockhartia tipperi, Lockhartia conditi, Assilina granulosa, Assilina subspinosa, Assilina laminosa, Daviesina khatiyahi, Miscellanea miscella, Miscellanea stampi, Nummulites atacicus, Nummulites boninesis, Nummulites globulus, Nummulites sp., Operculina canalifera, Operculina complanta, Operculina salsa, Operculina subsalsa, Daviesina langhami, Ranikothalia nuttalli and Bigenerina sp. The analysis of these benthic foraminifers suggests that the deposition of the Lower Tertiary sequence occurred in an open sea upper slope to outer shelf shallow marine environment.*

## INTRODUCTION

The Bagla-Kohala-Bala area lies in the southern Hazara fold-and-thrust belt of Pakistan. The southern Hazara fold-and-thrust belt occurs to the north of Potwar basin and to the south of the Mansehra metamorphic zone (Baig and Lawrence, 1987). In this study 760 square kilometers area is mapped on the Survey of Pakistan topographic sheet No. 43 G/1 at a scale of 1:50,000. The mapped area includes villages of Kohala-Bala, Barkot Hili, Bagla, Sumbal, Malot and Bandi and lies between Latitude 73° .02' to 73°.11' and Longitude 33°.50' to 33°.55' (Figure 1). The rocks of Mesozoic to Cenozoic age are imbricated and folded during the Himalayan orogeny. The Early Jurassic to Early Middle Eocene rocks received much attention by various workers in different parts of Pakistan . The Lower Tertiary sequence is mostly well developed in the areas of Hazara, Islamabad, Upper Indus basin and Azad Kashmir (Latif 1970 1970b and 1976 Ashraf et al. 1983; Wells and Gingerich, 1987; Afzal and Daniels, 1991; Sameeni and Butt 1992). This study presents the litho-biostratigraphy of the Bagla-Kohala-Bala area. These areas belong to the eastern Tethyian region and are classic for the tropical to sub-tropical marine sedimentary deposition. The Lower Tertiary sedimentary units of Bagla-Kohala-Bala area are characterized by the development of foraminiferal assemblages. The foraminifera have an important role in biostratigraphic studies. In comparison to most other organisms the amount and distribution of foraminifera data in the study area are vast and the environment of deposition varies from upper slope to outer shelf.

***Previous Work:*** The Hazara area is one of the most accessible mountain terrain in the Lesser Himalaya of Pakistan. Pioneer work on the litho-biostratigraphy was carried out by Latif (1970 1970a and 1976) in Hazara. In this study, we present the Lower Tertiary litho-biostratigraphy of the Bagla-Kohala-Bala area of southern Hazara.

## LITHOSTRATIGRAPHY OF LOWER TERTIARY SEQUENCE

The Jurassic, Cretaceous and Lower Tertiary sequence in Bagla-Kohala-Bala area is folded into northwest vergent open to overturned anticlines and synclines (Fig.1). The anticlines and synclines are imbricated along southeast-directed backsteepen reverse faults. The Middle Jurassic Samana Suk Formation Late Jurassic to Early Cretaceous Chichali and Lumshiwal Formations and the Late Cretaceous Kawagarh Formation occur in the core of anticlines and/or at places thrust over the Lower Tertiary Formations. The Lower Tertiary sequence consists of Hangu Formation, Lockhart Limestone, Patala Formation, Margala Hill Limestone, Chorgali Formation and Kuldana Formation. The contact between the Lower Tertiary sequence and the Cretaceous is marked by an unconformity. The Lower Tertiary sequence lies in the core of synclines and/or along the limbs of anticlines (Figure 1). The detail lithostratigraphy of the area is presented as follows:

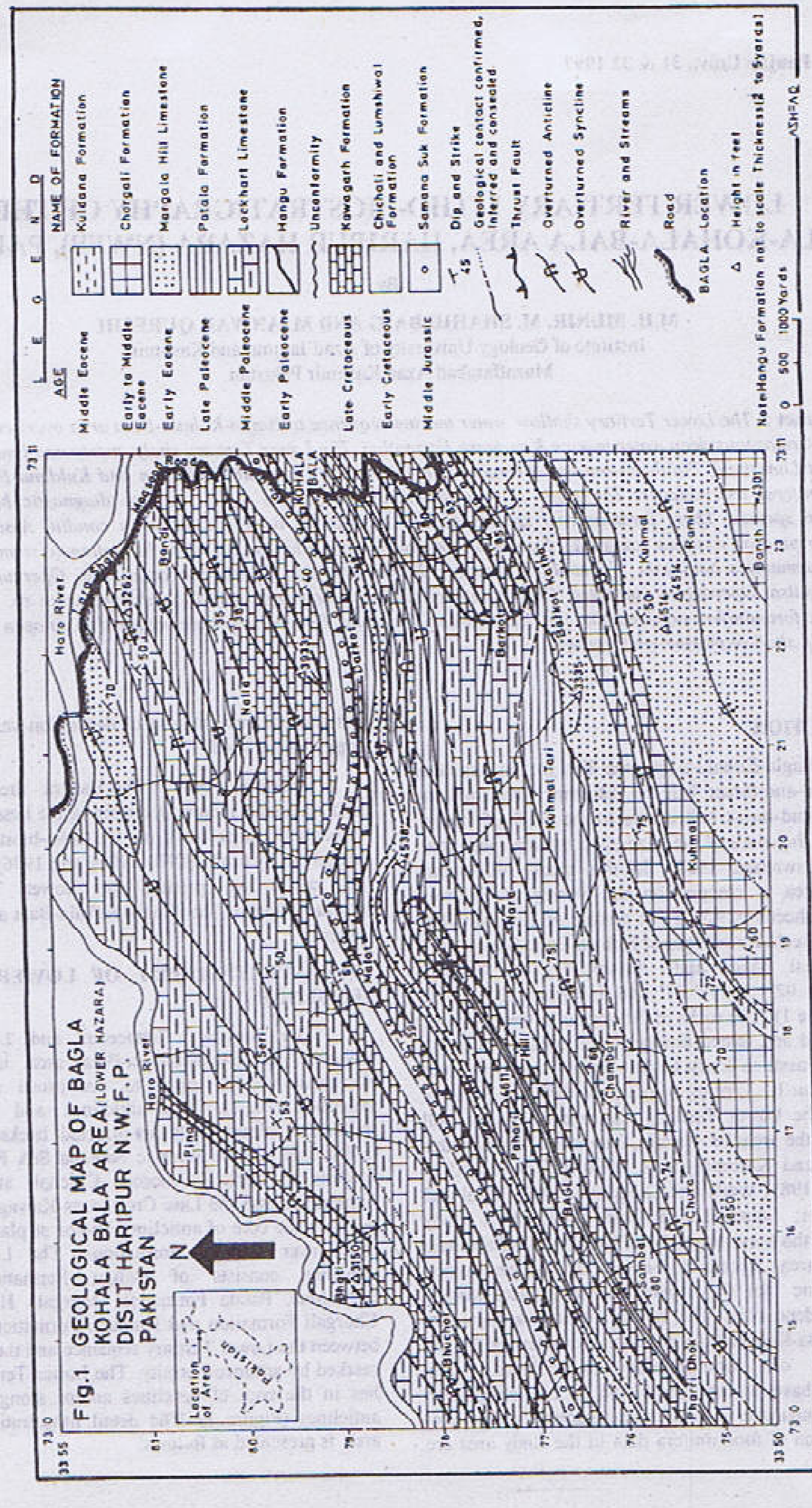
Fig.1 GEOLOGICAL MAP OF BAGLA KOHALA BALA AREA (LOWER HAZARA) DISTT HARIPUR N.W.F.P. PAKISTAN
N
Location of Area
PAKISTAN
L E G E N D
AGE
NAME OF FORMATION
Middle Eocene
Kuldana Formation
Early to Middle Eocene
Chorgali Formation
Early Eocene
Margala Hill Limestone
Late Paleocene
Patala Formation
Middle Paleocene
Lockhart Limestone
Early Paleocene
Hangu Formation
Unconformity
Late Cretaceous
Kawagarh Formation
Early Cretaceous
Chichali and Lumshiwal Formation
Middle Jurassic
Samana Suk Formation
Dip and Strike
Geological contact confirmed, inferred and concealed
Thrust Fault
Overturned Anticline
Overturned Syncline
River and Streams
Road
BAGLA Location
Height in Feet
Note: Hangu Formation not to scale Thickness (2 to 4 yards)
0 500 1000 Yards
ASHFAQ
Haro River
KOHALA BALA

| GROUP | FORMATION | AGE |
|---|---|---|
| | Murree Formation | Miocene |
| | Kuldana Formation | Early to Lower Middle Eocene |
| | Chorgali Formation | Early Eocene |
| Galis | Margala Hill Limestone | Early Eocene |
| | Patala Formation | Late Paleocene |
| | Lockhart Limestone | Middle Paleocene |
| | Hangu Formation | Early Paleocene |
| | ------------ Unconformity ------------ | |
| | Kawaghar Formation | Late Cretaceous |

**Hangu Formation**

The lithology of the Hangu Formation includes light grey to brownish grey sandstone, grey to brownish grey siltstone and brown to dark brown bauxite. The brown to dark brown colour of the Formation is due to the presence of iron. The bauxite is pisolitic in nature. The pisolits are bounded together by ferogenous cement. Pisolits range in diameter from 2mm to 5mm. The Hangu Formation unconformably overlies the Kawagarh Formation and has a sharp confirmable contact with the overlying Lockhart Limestone. The Hangu Formation marks a distinct mappable horizon. It occurs generally as a band of 1-8 meters. However, in Barkot, Sohab and Kohala-Bala areas the thickness reduces to few centimeters The Formation is unfossiliferous in nature. The age is Early Paleocene marked by underlying and overlying Late Cretaceous Kawagarh Formation and Middle Paleocene Lockhart Limestone respectively.

**Lockhart Limestone**

The Lockhart Limestone is mainly nodular limestone in the lower part with interclations of shales in the upper part. The limestones and shales are fossiliferous and size of fossil varies from 0.5mm to 2mm in diameter. The limestone is dark grey to black on fresh surface and grey to dirty grey on weathered surface. It is fine to medium grained, thin to medium bedded, nodular, fossiliferous and very hard limestone. The secondary calcite veins are common in the limestone. Nodularity is more pronounced in lower beds. The limestone forms steep slopes and sometimes unapproachable cliffs. Shales are greyish to khaki and splintery in nature. Its main exposures are at Bandik Kohala Bala Seri Barkot and Hili areas (Fig. 1). The thickness of the Lockhart Limestone varies from 89 to 178 meters. The lower contact with the Hangu Formation is unconformable and the upper contact with the Patala Formation is gradational. The Lockhart Limestone is richly fossiliferous with species of foraminifera and mollusca. The larger foraminifera can be seen with the naked eyes. Middle Paleocene age is assigned to the Lockhart Limestone.

**Patala Formation**

The Patala Formation consists of shales with some interbedded limestone and marl. On the weathered surface shale is generally khaki to grey brown and greenish grey however on the fresh surface it has more or less the darker shades of these colours. The interbedded limestone is nodular, highly fossiliferous, fine grained and dark grey in colour. The size of fossil varies from 0.5mm to 2.5mm in diameter. The main exposed outcrops are at Bandi, Kohala, Darkot, Barkot, Bagla, Sumbal and Kuhmal areas (Fig. 1). The thickness of the Patala Formation varies from 40 to 150 meters. The lower and upper conformable contacts are with the Lockhart Limestone and the Margala Hill Limestone respectively. The formation is richly fossiliferous and contains abundant foraminifera, mollusca and ostracodes. On the basis of faunal assemblage the age of the formation is Late Paleocene.

**Margala Hill Limestone**

The Margala Hill Limestone consists of grey limestone with some interclations of khaki shales and marls. The limestone occurs in the form of well exposed thick outcrops. It is generally nodular limestone. The nodule size ranges from 15 cm to 35 cm in diameters. The limestone, shale and marl are highly fossiliferous. The size of fossil varies from 1 mm to 3 mm in diameter. The limestone is medium grained. The secondary dirty white calcite veins are common in the limestone. The Margala Hill Limestone is well exposed in Ramial, Kuhmal, Barkot and Bhuchar areas (Fig. 1). The limestone forms cliffs in the area. The thickness of the unit varies from 100 to 189 meters. The lower and upper conformable contacts are with the Patala Formation and the Chorgali Formation respectively. The Margala Hill Limestone is assigned Early Eocene age on the basis of foraminifera assemblage.

**Chorgali Formation**

The Chorgali Formation consists of mainly thin bedded limestone with interclations of limemud, siltstone, marl and shale. The limestone is flaggy and micritic in nature. The limestone weathers into creamy, light yellow and light grey colours whereas the fresh surface is light grey. At places the limestone weathers to chalky appearance. The limemud is generally medium hard and light to medium grey in colour. Siltstones, marls and shales show light shades of khaki and grey colours. Because of the competent and incompetent nature of lithologies the limestone beds are stretched and strained. The formation is fossiliferous. The size of fossil varies from 3 mm to 6 mm in diameter. The formation is well exposed at Kuhmal and Sangreri areas. It forms gentle slopes and thick soil cover in the area. The thickness of the unit varies from 90 to 166 meters. It conformably overlies and underlies Margala Hill Limestone and Kuldana Formation respectively. The Early Eocene age is assigned to the formation on the basis of foraminiferal assemblage.

**Kuldana Formation**

The Kuldana Formation consists of varied coloured shales clays and marls. The occasional beds and lenses of chalky grey gypsum and pale grey marly limestone also

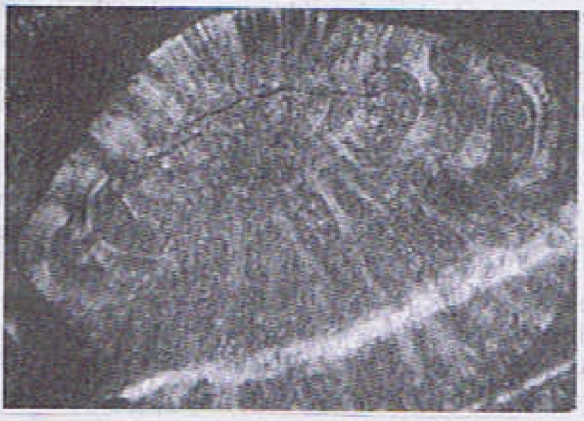

Fig. 2 *Lockhartia Tipperi* (Davies) axial section Chorgali Formation (CN 4x FV. 1.74 mm).

Fig. 3 *Lockhartia conditi* (Nuttall) axial section Chorgali Formation. (CN 4x FV. 1.74 mm).

Fig.4 *Assilina granulosa* (D. Archiac) axial section Kuldana Formation (CN 4x FV. 1.74 mm).

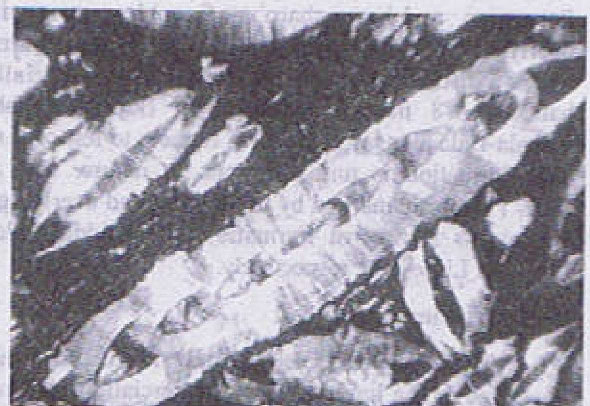

Fig.5 *Assilina subspinosa* (Davies and Pinfold) Margala Hill Limestone (CN 4x FV. 1.74 mm).

Fig.6 *Assilina laminosa* (Gill) axial section Margala Hill Limestone (CN 4x FV. 1.74 mm).

Fig.7 *Daviesina khatiyahi* (Smout) thin section Lockhart Limestone (CN 4x FV. 1.74 mm).

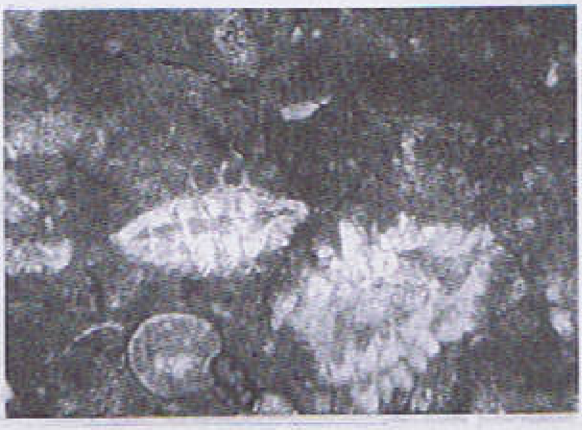

**Fig.8** *Miscellanea miscella* (D. Archiac and Haime) axial section Patala Formation (CN 4x FV. 1.74 mm).

**Fig.9** *Miscellanea stampi* (Davies) transverse section Lockhart Limestone (CN 4x FV. 1.74 mm).

**Fig.10** *Nummulites atacicus* (Leymerie) transverse section Margala Hill Limestone (CN 4x FV. 1.74 mm).

**Fig.11** *Nummulites boninesis* (Hanzawa) axial section Kuldana Formation (CN 4x FV. 1.74 mm).

**Fig.12** *Nummulites globulus* (Leymerie) transverse section Margala Hill Limestone (CN 4x FV. 1.74 mm).

**Fig.13** *Nummulites sp.* axial section Chorgali Formation (CN 4x FV. 1.74 mm).

**Fig.14** *Operculina canalifera* (D. Archiac) planer section Lockhart Limestone (CN 4x FV. 1.74 mm).

**Fig.15** *Operculina complanta* (Defrance) planer section Patala Formation (CN 4x; FV. 1.74 mm).

**Fig.16** *Operculina salsa* (Davies) equatorial section Patala Formation (CN 4x FV. 1.74 mm).

**Fig.17** *Operculina subsalsa* (Davies) equatorial section Lockhart Limestone (CN 4x FV. 1.74 mm).

**Fig.18** *Daviesina langhami* (Smout) axial section Lockhart Limestone (CN 4x FV. 1.74 mm).

**Fig.19** *Ranikothalia nuttalli* (Davies) axial section Lockhart Limestone (CN 4x FV. 1.74 mm).

Fig.20 *Bigenerina sp.* thin section Lockhart Limestone (CN 4x FV. 1.74 mm).

occur. The red colour of Kuldana Formation is due to the presence of iron oxides. The Kuldana Formation is present near Kumal gali at Ziarat. It is about 50 to 60 meters in thickness. This outcrop band extends from Kumal to Pir Sohawa out of mapped area. The underlying contact with the Chorgali Formation is conformable. The age of the formation is Early to Lower Middle Eocene.

## BIOSTRATIGRAPHY OF LOWER TERTIARY SEQUENCE

The Lower Tertiary sequence of Bagla-Kohala-Bala area is investigated for the larger foraminifera. 40 samples are collected from the Seri, Khumal, Hili and Barkot sections. 40 samples include 3 from Hangu Formation, 8 each from Lockhart Limestone, Patala Formation, Margala Hill Limestone and Chorgali Formation and 5 from Kuldana Formation. Fossils are collected from the bottom to top of formations. Samples are from limestones and shales. The fossils are more recoverable from limestones than shales. The foraminifera species are good index fossils for age determination of the rock units because these are restricted in stratigraphic ranges. These species are quite common in the equivalent geological deposits of the world and are the good criteria for the regional and inter-regional correlation of the strata.

### Hangu Formation

The samples from the Hangu Formation yield none of the Lower Tertiary foraminifera.

### Lockhart Limestone

The Lockhart Limestone yields foraminifera species of *Daviesina khatiyahi* (Fig.7), *Miscellanea stampi* (Fig.9), *Operculina canalifera* (Fig.14), *Operculina subsalsa* (Fig.17), *Daviesina langhami* (Fig.18), *Ranikothalia Nuttalli* (Fig.19) and *Bigenerina sp.* (Fig.20). The Lockhart Limestone is assigned Middle Paleocene age on the basis of above mentioned species.

### Patala Formation

The *Operculina complanta* (Fig. 15) and *Operculina salsa* (Fig. 16) species are found from the Patala Formation. These species assign Late Paleocene age to the Patala Formation.

### Margala Hill Limestone

The foraminifera species include *Assilina subspinosa* (Fig.5), *Assilina Laminosa* (Fig.6), *Nummulites atacicus* (Fig.10) and *Nummulites Globulus* (Fig.12). On the basis of these foraminifera species the age of the Margala Hill Limestone is Early Eocene.

### Chorgali Formation

The *Lockhartia tippri* (Fig.2), *Lockhartia conditi* (Fig.3) and *Nummulites sp.* (Fig.13) are present in the Chorgali Formation. The Chorgali Formation is assigned Early Eocene on the basis of above mentioned foraminiferal species.

### Kuldana Formation

The fossils of *Assilina granulosa* (Fig.4) *and Nummilites boninesis* (Fig.11) have been found from the samples of Kuldana Formation. The age of Early to lower Middle Eocene is assigned to the Kuldana Formation.

## DISCUSSION

The rock units from Jurassic to Eocene are deposited in the Tethyian ocean and mark the opening and closing of the ocean. These environments vary from shallow water marine to deep water marine. The Middle Jurassic Samana Suk Formation, Late Jurassic to Early Cretaceous Chichali Formation and Early Cretaceous Lumshiwal show shallow water marine platform to shelf environments. The Late Cretaceous Himalayan collision between the Indian plate and the Kohistan island arc caused the downing of the Tethyian shelf in the subduction zone and initiated the deposition of the Kawagrah Formation in deep water shelf environments (Baig 1990). The presence of planktonic foraminifera such as *Globotrancana elevata calcarata Globotrancana lapparenti coronata Globotrancana concavata carinata Globotrancana fornicata-caliciformis Globotrancana fornicata Globotrancana lapparenti lapparenti Heterohelix reussi Heterohelix globocarinata and Heterohelix globulosa* shows the deep water shelf environment for the Kawagrah Formation. There is abrupt change in deep water marine to shallow water marine environment of deposition across the Late Cretaceous to Early Paleocene boundary. This change is the result of initial Late Cretaceous to Early Paleocene (70-64 Ma) Himalayan collision between the Indian plate and the Kohistan island arc (Baig, 1990; Baig, 1991). The Late Cretaceous to Early Paleocene regression of the Tethyian ocean caused the terrestrial deposition of the Hangu

Formation (Baig, 1990). The absence of Early Paleocene foraminifera in the Hangu Formation confirms that the Early Paleocene was the main time of Tethyian regression in this area. The Lower Tertiary sequence of Middle Paleocene Lockhart Limestone, Late Paleocene Patala Formation, Early Eocene Margala Hill Limestone, Early Eocene Chorgali Formation and Early to Lower Middle Kuldana Formation marks a complete cycle of transgression and regression of Tethyian ocean. The presence of Middle Paleocene to Early Eocene shallow water marine foraminiferal assemblages (*Lockhartia tipperi, Lockhartia conditi, Assilina granulosa, Assilina subspinosa, Assilina laminosa, Daviesina khatiyahi, Miscellanea miscella* (Fig.8), *Miscellanea stampi, Nummulites atacicus, Nummulites boninesis, Nummulites globulus* (Fig.12), *Nummulites sp.* (Fig.13), *Operculina canalifera, Operculina complanta, Operculina salsa, Operculina subsalsa, Daviesina langhami, Ranikothalia nuttalli* and *Bigenerina sp.*) in the limestones, shales and marls of the Lower Tertiary sequence shows that the deposition occurred in tropical to sub-tropical open sea upper slope to outer shelf shallow marine environments. The presence of marine limestones, continental variegated clays and shales, and evaporitic gypsiferous bands in the Early Middle Eocene Kuldana Formation shows transitional environment of deposition. The Kuldana Formation marks the end of transgressive cycle and initiation of regression of the Tethyian ocean. In other parts of Hazara, the Kuldana Formation is overlain by the Himalayan molasse deposits of the Murree Formation. Thus the Kuldana Formation shows the closing of Tethyian ocean and the initiation of Himalayan molasse deposition in the Early Middle Eocene (Baig 1990).

## ACKNOWLEDGMENTS

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# PRELIMINARY ANALYSIS OF THE VERTEBRATE FAUNA FROM THE SIWALIKS OF CHAKWAL DISTRICT; KALLAR-KAHAR-DHOK TAHLIAN AREA, POTWAR PLATEAU, PAKISTAN

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**Abstract:** *About 440 mammalian fossils were collected from 20 different sites in Kallar Kahar-Dhok Tahlian area. Small collection of interesting carnivores consisting of* ***Herpestes*** *SP. and gen. et. sp. Indet. Of Mustelidae family are simultaneously of 130 Mya and 16.0 Mya. Gen. et. sp. Indet. Of Mustelidae is the first fossil record in the Siwaliks of Pakistan, which seems to have closer affinities with African fauna. Similarly canine of a* ***Sivapithecus indicus*** *also reveals the first appearance of a Hominoid in this area*

## INTRODUCTION

The potwar Plateau of the Punjab Province, Pakistan is an elevated area of some 20,000 Km2 bounded to the north by the Kala Chitta and Margala Hills, south by the Salt Range, east by the Jhelum river and west by the Indus river, (Fig. 1). Neogene molasse was deposited in subsiding basins on the southern flanks of the rising Himalayas. During and after deposition, the area was subject to folding and faulting. A good deal of the plateau is covered by the late Pleistocene alluvium, but substantial amount of Neogene rock is exposed as badlands.

The Kallar Kahar-Dhok Tahlian area (Distt. Chakwal) exposes the most complete Siwalik Group sequence in the southern Potwar Plateau (Fig. 2). In a cumulative stratigraphic thickness of 2.0-2.5 km and comprising all the five component formations (e.g. Kamlial, Chinji, Nagri, Dhok Pathan and Soan) of the Siwalik Group, the Kallar Kahar-Dhok Tahlian area contains an almost continuous geological record spanning from (approx.) 18.5 My. B.P. to 405 My B.P. (Johnson etal, 1982). Thus a long terms project for the study of stratigraphyical and palaeontological aspects of the Siwalik group in this area has been initiated. The main objective of the research in this area is to develop a comprehensive lithostratigraphic, faunal and biostratigraphic framework, which in conjunction with adjacent better studied areas would later become a principal reference region for the continental Miocene in Pakistan.

The Kallar Khar-Dhok Tahlian area does not seem to be as fossiliferous as those of the adjoining Kanatti-Chinji-Nargri area. However, the eastern part (i.e. the Dhok Tahlian area) has yielded more fossils than the western Khokher Zer area, it is plausible that high dips and structural complications as witnessed in the western part may also have increased the paucity of fossil localities. After a brief faunal search in the Dhok Pathan, Nagri, and Chinji Formations, we concentrated our efforts to the Chinji Formation. A total of twenty fossil localities at different stratigraphic levels have been discovered from which almost 440 vertebrate fossils are collected. Four of these localities have been intensively sampled for small mammal analyses in the laboratory.

The macro-vertebrate assemblage consists of fragmentary dentary and other skeletal elements of Denotherium *Pentapotamiae, Giraffokeryx punjabiensis, Dorcatherium sp.* aff *Helicopprtax traqelaphoides,* crocodiles and ophidians. The locality 8608 micro-vertebrate assemblage consists of isolated teeth and fragmentary skeletal elements. In addition to broken small mammal limb elements and a few of reptilian affinity, the assemblage includes many fish spines and varanid

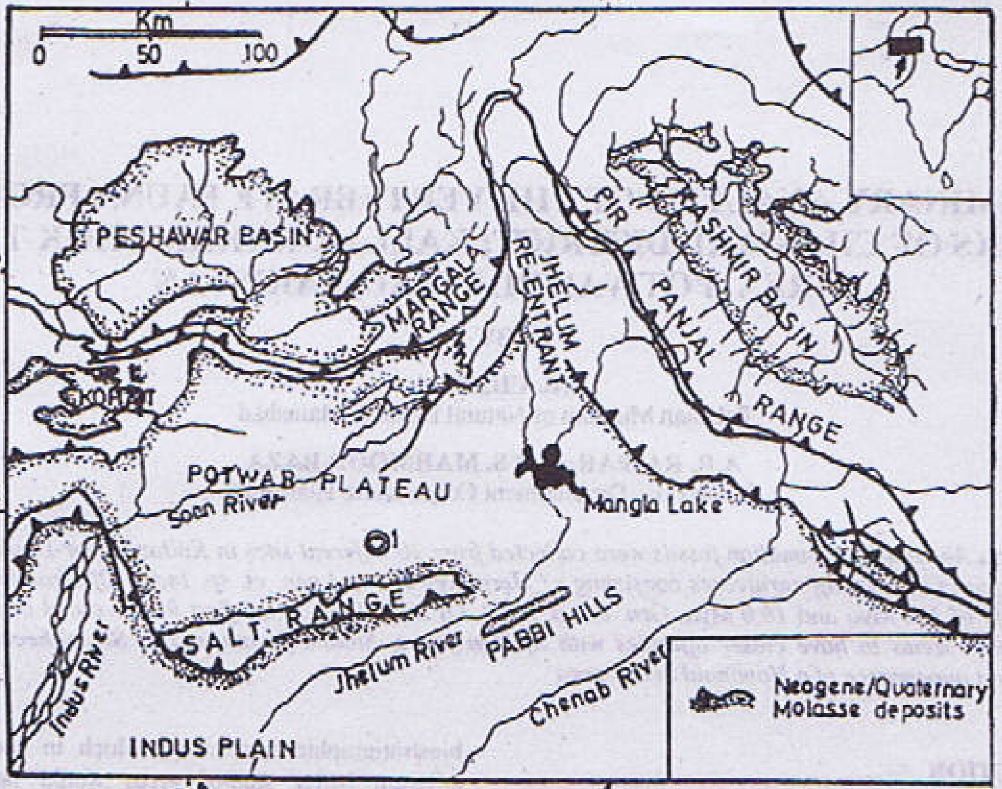


**Fig.1.** Generalised geological map of northern Pakistan showing the extent of Neogene Quaternary mollase deposits. Kallar Kahar Tahlian Fossil Localities.

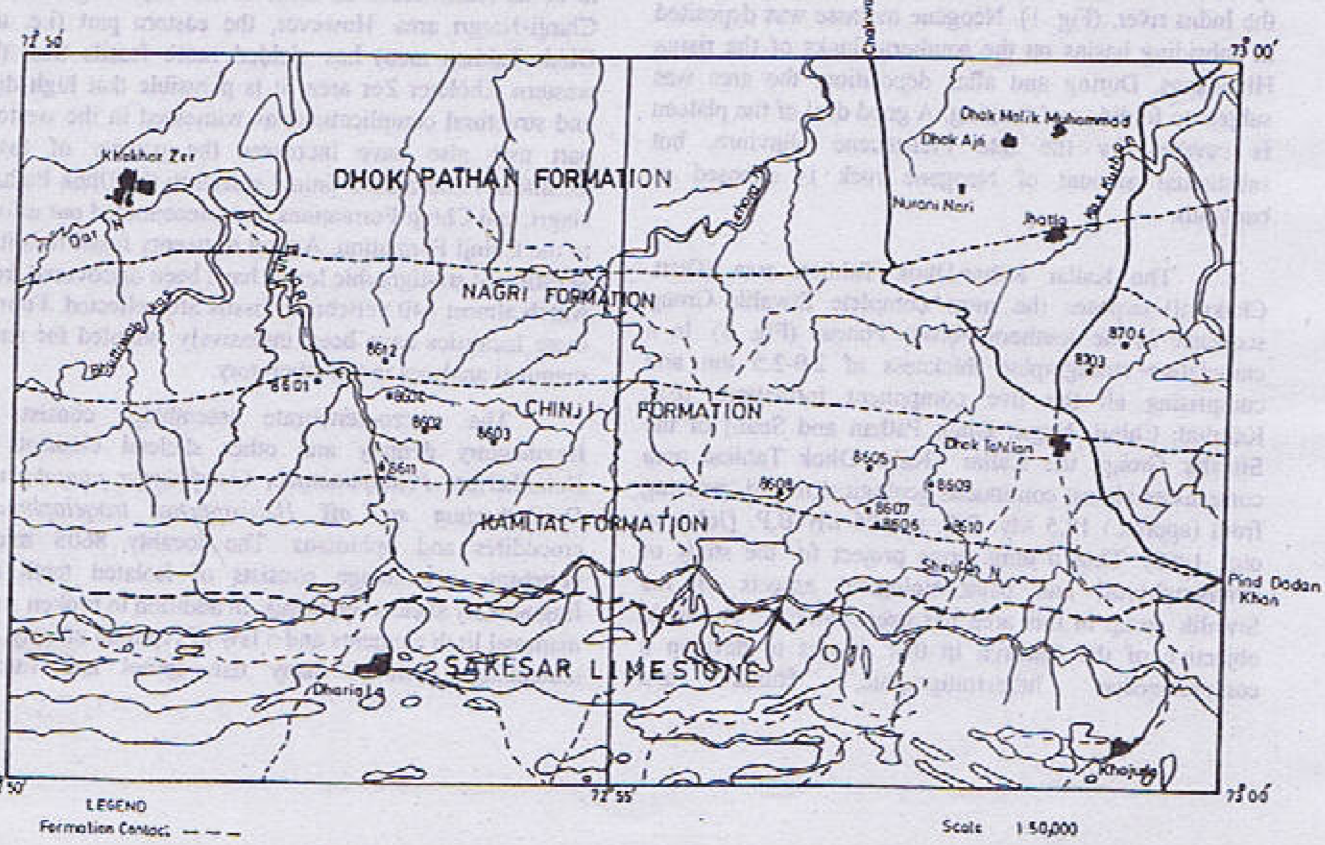


**Fig.2.** Geological map of Kallar Kahar-Dhok Tahlian area.

mandibular fragments. The taxonomy described here however is based entirely on isolated teeth of relatively high quality preservation. The small mammals represented are rodents, insectivores and a chiropteran.

## PALEONTOLOGY

Seventy percent of the fossil specimens collected in the field are identifiable to family and lower taxonomic levels. The following frequencies of various vertebrate groups are given as below: -

| Group | No. of Specimens | Frequency (%) |
|---|---|---|
| Mammalia | 419 | 95.22 |
| Reptilia | 10 | 2.27 |
| Pisces | 6 | 1.36 |
| Aves | 2 | 0.45 |
| "Coprolites" | 3 | 0.68 |

In Reptilia and Pisces, a fossil specimen counted above is not the real representation. It is mainly due to the fact that one big size carapace or scute piece can be fragmented into several small bits and thus can show the statistics, substantially, Therefore, only representative and bigger sized fragments have been collected. Same is true for fish specimens which are mostly represented by vertebrate or spine fragments. Care has been taken to piece together broken fragments to avoid the over representation of some skeletal unit. Reptillian teeth and skeletal and dental fragments of fishes make up more than 50% of the total micro-vertebrate assemblage analyzed in the laboratory.

The preliminary identifications of the Chinji fauna from the Kallar Kahar-Dhok Tahlian area are given in Table 1.

### Mammals

Mammal remains dominate all faunal assemblages and constitute 95% of all fossils identified in the area. The Chinji mammal fauna of the Dhok Tahlian-Khokher Zer area includes at least eleven families of medium and large size mammals. Table 2 provides the family distribution of the mammalian assemblage on the basis of fauna collected.

### Carnivore

The total carnivore fossils recovered number to 6 only but each of them is from six different localities. These localities have given relatively more fauna and thus it can be postulated that occurrence of carnivore specimens. Two specimens, a P2 (PMNH-EV3298) and a calcanium (PMNH-EV3312) belong to family Hyaenidae. The P2 is of *Percrocuta carnifex* whereas the calcanium has also been tentatively ascribed to this species.

Two small molars of two different carnivores were collected and identified respectively from PMNH 8604 and PMNH 8606 localities. The RM1 from the locality PMNH 8604 has been identified as *Herpestes* sp. PMNH-EV 3348 (Fig. 3 and Fig. 4). This will be the first record of *Herpestes* from such an old stratigraphic level, tentatively dated as about 13 My B.P. Barry (1982) has earlier described first occurrence of *Herpestes* from 10My B.P. beds Khaur area. The *Herpestes* sp. lower molar from Khokher Zer area thus extends the first appearance datum to at least 13 My B.P. and may suggest that the migration from Africa which has introduced many new genera at 13 My B.P. datum also brought the first mongoose in South Asia.

Similarly the M2 of a gen. et. sp. indet. From locality 8606 which comes from the basal part of the Chinji Formation belongs to family Mustilidae, PMNH-EV 3354 (Fig. 5 and Fig. 6). This also seems to be the first record of genus and species indeterminate from the Potwar Plateau, Pakistan (Barry pers communication) as compared to earlier Mustilidae reported from Zone 2, 3, 5, 6, and 10 (Pilbeam et al, 1979). Age of Zone 2, 3, 5, 6, and 10 was calculated as 11, 10, 9.5, 8.6 and 8.2 My B.P. respectively.

An upper canine PMNH-EV 3192 is a complete specimen with some wear on the inside of the tooth. The canines are difficult to identify to family level.

## HOMINIDAE

Only two molars of the Order Primates are complete right upper canines (PMNH-EV 3247) from the locality PMNH 8609 and (PMNH-EV 3248) from the locality PMNH 8702 identified as *Sivapithecus indicus*. They are long-rooted and short crowned specimens whose tip has been fairly worn-out. Yhey are identical with those of other Chinji *Sivapithecus indicus* canines but smaller in size than the GSP 15000, cranium from the late Miocene Siwalik rocks of the Khaur area (Pilbeam et al., 1980). This is the first record of hominoids from this area.

### Proboscidea

*Gomphotherium brownie* is the common species among the Proboscidea. An almost complete tusk of *Choerolophodon corruqatus* from the locality PMNH-8611, located in the basal most sandstone unit of the Chinji Formation is he first record of such a complete specimen at this stratigraphic level. Only one specimen, a half lower molar of *Denotherium Pentapotamiae* represents the Deinotheriidae.

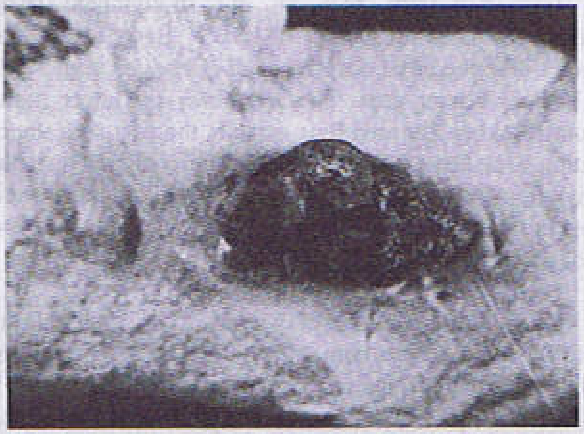

**Fig.3.** Herpestes species, RM1, dorsal view.

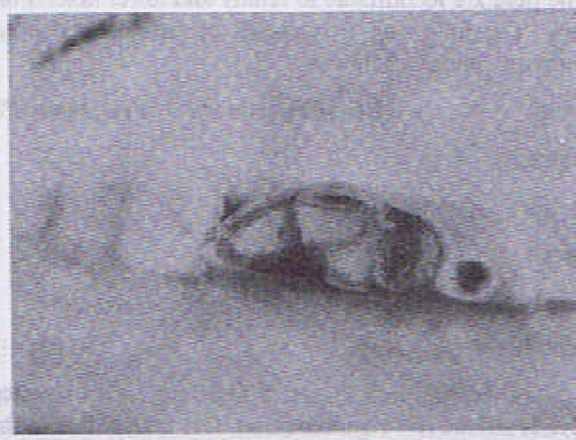

**Fig.5.** Mustelidae, genus and species M2, dorsal view.

**Fig.4.** Herpestes species,RM1, Lateral view.

**Fig.6.** Mustelidae, gen. and sp. indet. M2, lateral view.

**Perissodactyla**

With the exception of one phalanx of *Chalicotherium*, rest of the twenty three specimens belongs to rhinocerotids. Fourteen specimens consist of isolated (and mostly) fragmentary molar (and also one incisor and a P3) whereas nine specimens are have podial and limb bones. Preliminary identifications indicate common presence of *Barchypotherium oerimense*. Other Chinji species reported from elsewhere in potwar plateau such as *Gaindatherium browni* and *Chalicotherium intermedium* may also be present in the Kallar Khar-Dhok Tahlian area.

**Artiodactyla**

The artiodactyles are a well represented diverse group ranging in size from small tragulids *(dorcatherium minor) and a very small bovid (Elachistoceras sp.) to the okapi-size Giraffokeryx punjabiensis.*

*Listriodon pentapotamiae* and *Conohyus sindiense* are the two most common suids in the Chinjis of the Kallar Kahar-Dhok Tahlian area. This is also true for the Chinji Formation in other areas of the Potwar Plateau. Tragulids are represented by *Dorcatherium minus* and a few *Dorcatherium majus*. The post-cranials can be attributed to the two species but it appears that most of them are also of *D. minus*. Giraffidae are the second most common group and are mostly represented by podials, isolated teeth, and few limb elements. On the basis of teeth and an ossicone they have been identified as *Giraffokeryx punjabiensis*

**NON-MAMMAL GROUPS**

The lower vertebrates (fishes and reptiles) of the Chinji Formation in the Type Chinji and Khaur areas have remained largely unstudied mainly because of being too fragmentary. Same is true for the Kallar Kahar-Dhok Tahlian area includes Bovidae, Giraffidae, Rhinocerotidae, Tragulidae, Suidae, Proboscidea, Carnivora, Anthracotheriidae, Chalicotheriidae and Hominidae. Table 2 shows the number of relative frequency of identified elements for each of taxa found in the area.

Chinji Formation is the earliest lithostratigraphic unit of the Muree-Siwalik complex to record an abundance and species diversity of bovids. Although the first appearance of bovidae is recorded from the middle Kamlial Formation in the Chinji-Kanatti area, the lower third of the Chinji Formation document sudden diversity of bovid genera/species as well as become the dominant group in the assemblage. Same trend is witnessed in the Chinji assemblage of Kallar Kahar-Dhok Tahlian area where bovid remains contribute 26% of the total mammalian fauna. For taxonomic identifications of bovids, horn-cores are the most diagnostic to be followed by complete mandible and maxillary part. Post-cranials can also be categorized by size and certain elements (e.g. femur, humerus, radius, innominates) are useful for understanding the locomotion and thus of knowing the habitat preferences.*Protraqocerus qlutens. Elachistocerus* aff. *E.khauristanensis* and *Sivoreas eremita* have identified on the basis of horn cores, representing PMNH-EV 3152, EV 3227 and EV 3233, respectively.

Bovid is the most common group and is followed by Giraffidae, Suidae, Rhincerotidae, Tragulidae, *Hipparion*, Carnivora, Proboscidea, Reptilia, Pisces, Aves, Hominidae, Anthracotheriidae and Chalicotheriidae.

The high percentage (16.36%) of taxonomically undentifiable elements is indicative of the fragmentary nature of many of the bones collected from the area.

**Table 1.**

**Preliminary faunal list of the Chinji Formation from the Kallar Kahar-Dhok Tahlian area.**

**MAMMALIA**
PRIMATES
HOMINIDAE
*Sivapithecus indicus*
CARNIVORA
VIVERRIDAE
*Herpestes sp.*
MUSTELIDAE
Gen. et sp. indet.
HYAENIDAE
*Percrocuta carnifex*
PROBOSCIDEA
DEINOTHERIIDAE
*Deinotherium pentapotamiae*
GOMPHOTHERIIDAE?
*"Gomphotherium" browni*
*Choerolophodon corruqatus*
PERISSODACTYLA
CHALICOTHERIIDAE
*Chalicotherium sp.*
RHINOCEROTIDAE
*Brachypotherium perimense*
*Gaindatherium browni*
ARTIODACTYLA
SUIDAE
*Listriodon pentapotamiae*
*Conohyus sindiense*
ANTHRACOTHERIIDAE
Gen. et sp. indet.
TRAGULIDAE
*Dorcatherium majus*
*D. minus*

*D. sp.*
GIRAFFIDAE
*Giraffokeryx punjabiensis*
BOVIDAE
*Protraqocerus qlutens*
*Sivoreas eremita*
*Elachistoceras khauristanesis*
Gen. et sp. indet.
**REPTILIA**
CHELONIA
*Trionyx sp.*
CROCODILIA
*Crocodylus sp.*
*Gavialis sp.*
OPHIDIA
Gen. et sp. indet.

**Aves**
Gen. et sp. indet.

**Pisces**
SILURIFORMES
Gen. et sp. indet

**Table 2.**

**Total number of specimens and frequency of various large mammal taxa from the Chinji Formation of Kallatr Khar-Dhok Tahlian.**

| Taxon | No. Specimens | Frequency(%) |
|---|---|---|
| Bovidae | 102 | 23.18 |
| Giraffidae | 71 | 16.13 |
| Suidae | 44 | 10.00 |
| Rhinocerotidae | 30 | 6.81 |
| Tragulidae | 28 | 6.36 |
| *Hipparion* | 28 | 6.36 |
| Carnivora | 25 | 5.68 |
| Proboscidea | 15 | 3.40 |
| Reptilia | 10 | 2.27 |
| Pisces | 6 | 1.36 |
| Aves | 2 | 0.45 |
| Hominidae | 2 | 0.45 |
| Anthracotheriidae | 1 | 0.22 |
| Chalicotheriidae | 1 | 0.22 |
| Mammal indeterminate | 72 | 16.36 |

**Taphonomy of Faunal Assemblages**

The fauna listed in Table 1 and discussed above is based on the surface collection of vertebrate bones from twelve localities. These assemblages are composed of disarticulated and fragmented bones, which have been transported to variable extent before burial. These fossil localities occur in all the three lithofacies type of the Chinji Formation with some prefence to coarser lithofacies (i.e. sandstone). This tendency is suggestive of the fluvial agencies being the main agent of bone concentration in forming all fossil localities. However, the lithological make up of the richest locality, PMNH 8609, indicate in addition to the main channel the river banks and adjoining flood plain may also be contributing bone materials by bank cannibalization and flood erosion of the plains.

The relative abundance of different skeletal elements in fossil assemblages is a reflection on the mode of bone construction at a locality and helps in assessing the proportion of in situ (or with short transportation) bone in put from those transported from a farther area. These parameters become important when reconstruction of fossil communities and/or paleoecologic interpretation are to be attempted. The skeletalelements frequency data from four localities (PMNH 8602, 8606, 8609 and 8612) is collected in terms of six skeletal groups, which represent different disticulation and dispersal units. These groups are teeth (isolated), vertebrae, forelimb, hindlimb, podials and phalanges. Fig. 2 shows that all localities in general have a similar pattern. Teeth and podials are the most common elements in all the assemblages. While teeth are the most resistant element, podials preponderance can be due to their shape enhancing easy fluvial transportation and also that they remain covered with skin and ligaments for much longer time than any other body part in a carcass. The locality PMNH 8609 having a good sample size is a true reflection of a typical bone accumulation in a fossil locality. The high percentage of podials, phalanges and limb elements as compared to their relative proportions in single mammalian skeletons suggest that they have undergone some fluvial transportation and sorting. It is also likely that fore and hind limbs may have been added by bank collapses during flood seasons Teeth with high density usually are the least transportable elements. Since most of the locality PMNH 8609 teeth are of medium to small size mammals, they could also have been added from nearby areas, during high flow regimes.

The similar faunal composition of each locality with variable proportions of skeletal elements suggest that though intensity of fluvial sorting of the death assemblages influenced the formation of a locality but the assemblages are fair reflection of the then existing wildlife populations. Thus, the absence of a particular mammalian group in a locality and its presence in another may be a pure coincidence. On the other hand, if other taphonomic parameters suggest that fossil assemblage portrary the autochthonous death assemblage (s), then appearance of any faunal group may indicate their first appearance datum. For example, a single mandibular fragment of *Herpestes sp.* (PMNH-EV 3348) in the locality PMNH 8604 and *genus et species indeterminate* (PMNH-EV 3354) in the locality 8606 assemblages may be the real earliest record of family Viverridae and Mustelidae respectively in the Potwar Plateau and also in south Asia.

| Species | Zone/Loc. | Age(Mya) | |
|---|---|---|---|
| *Enhydriodon sp.* | Z 11 | 4.7 | Pilbeam et al., 1979. |
| *Sivaonyx bathygnothus* | 6 | 6.5 | Pilbeam et al., 1979 |
| *Of. Ischyricties* | 6 | 6.5 | Pilbeam et al., 1979 |
| *Eomellivora sp.* | 6 | 6.5 | Barry, 1983, |
| *Herpestes, large sp.* | Y 19 | 7.0 | Pilbeam et al., 1979. |
| *Plesiogula crossa* | Z 10 | 7.8 | Barry, 1983. |
| *Herpestes, medium sp.* | Y 327, 310 | 8.0 | Barry, 1983. |
| *? Herpestes, small sp.* | Y 259 | 9.5 | Pilbeam et al., 1979. |
| *Eomellivora sp.* | Z 3 | 10.6 | Pilbeam et al., 1979. |
| *Vishnuonyx chinjiensis* | Z 3 | 10.6 | Pilbeam et al., 1979. |
| *Eomellivora sp.* | Z 2 | 11.5 | Pilbeam et al., 1979. |
| *Martes lydekkeri* | Z 2 | 11.5 | |
| *Herpestes sp. Mustelidae,* | PMNH 8604 | 13.0 | |
| *Gen. Et sp. Indet PMNH 8606* | PMNH 8606 | 16.0 | |

**Table 3.**

**Dental measurements (mm) of carnivora referred to *Herpestes* species and mustilidae, gen. Et sp. Indet.**

| Taxon | Catalogue No. | Length | Width |
|---|---|---|---|
| *Herpestes* species | PMNH-EV 3348 | 3.0 | |
| Mustilidae, gen et sp. indet | PMNH-EV 3354 | 1.9 | |

PMNH: Pakistan Museum of Natural History.

EV: Earth Sciences Division, Vertebrate.

## CONCLUSIONS

The geological studies of the Siwalik Group rocks of Kallar Kahar-Dhok Tahlian area have been done togather information from an area whose nearby western and eastern regions are well studied. The motivation has been to extend studies eastwards in subsequent years so as to obtain a physical lithostratigraphic framework established for the whole area, extending from Dhok Tahlian to Mirpur Bhimber areas.

The Siwalik group formations in the Kallar Kahar-Dhok Tahlian area are not as thick as in the adjoining Chinji-Kanatti area. For instance, Chinji Formation is estimated to be between 510 to 550m as thick in this area whereas it is 600-650m thick in its stratotype Chinji-Kanatti area.

Preliminary stratigraphic analyses indicate a general increase in mudstone proportions relative to sandstone thickness in the Chinji, Nagri and Dhok Pathan formations of the Kallar Kaher-Dhok Tahlian area. For example, the mudstone to sandstone ratio in the Chinji Formations ranges between 4:1 and 3:1.

Inspite of adequate exposures, fossils are not easily found in the area. It is partly because of steeper dips and some structural complication, thus reducing the area of exposure per bed, and also increase in mudstone indicates existence of flood plains, which relatively have lesser potentials for fossilization.

The Chinji Formation proved to be the most fossiliferous unit from which 440 specimens from 20 localities have been identified. This is exclusive of rich microvertebrate fauna recovered in the laboratory by

A single left canine of *Sivapithecus indicus* from the analyzing nearly 1000kg. Sediments from four localities.locality PMNH 8609 are the first record of hominid from this area.

A lower molar (partially complete) PMNH-EV 3348 from the locality PMNH 8604 is identified as *Herpestes sp.* This is the earliest record of mongoose from south Asia and perhaps documents the immigration datum from Africa, which also include aardvark and hominoids in other areas of the Potwar Plateau. This migratory event took place some time around 12 (+o.5) My B.P.

Gen. et sp. Indet. Belongs to family Mustelidae (PMNH-EV 3354) comes from locality 8606, which is situated at the basal part of the Chinji Formation. Age of the locality is estimated as 16.0 Mya. This is the first record from the Siwaliks, which seems to have closer affinities with African fauna.

A single horn core has recorded the smallest bovid of the Siwalik Group rocks, named Elachistoceros. This discovery extends the range of this bovid, which hitherto has been described, from the upper Nagri Formation of Khaur area (northern Potwar Plateau).

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# PETROGENESIS OF THE ALKALINE IGNEOUS PROVINCE OF PAKISTAN

By

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**Abstract:-** *The Alkaline Igneous Province of Northwest Pakistan (AIPNP) extends from Loe-Shilman in the West to Tarbela in the East for a distance of about 150 Km.*

*There are at least two distinct periods of magmatic / volcanic activity in the alkaline province. One is Permo-Carboniferous in age and is related to the break up of Gondwana land through Intra continental rifting.*

*The second activity is Tertiary in age. This is related to bending of Indian Plate during subduction. This bending caused tension and rifting.*

*Tectonically the alkaline province falls in the following Himalayan subdivisions.*

*(a) Tarbela, Koga, Utla, Babaji, Ambela and Loe Shilman falls in the Lesser Himalaya South of the Main Central Thrust.*

*(b) Sillai Patti and Jambil fall in the Higher Himalaya North of the MCT.*

*It may therefore be concluded that alkaline province is not restricted to the Lesser Himalaya alone.*

## INTRODUCTION

Geochemical, field and petrographic studies show that there are at least three major rock associations within the Koga-Ambela alkaline complex. These three series form separate complexes but they overlap at places.

The alkaline igneous rock complexes occur as scattered bodies in a semi circle around northern and western parts of Peshawar plain. The complexes so distributed are comprised of Loe Shilman carbonatites, Shewa alkali porphyries, Babaji soda granites, syenites, Koga nepheline syenite and associated carbonatites (Ashraf and Chaudhry, 1977), along with basic intrusions. These rocks are emplaced along E - W trending fault zones in the Early Palaeozoic older metasediments forming a long belt which extends from Afghanistan through Khyber, Mohmand Agency, Malakand Agency, Malakand Lower Swat and Tarbela area. The distribution of alkaline and carbonatite complexes is given in Fig. 1.

The Koga nepheline syenite is not an isolated and independent local derivative, but it is a part of the alkaline province starting from Loe Shilman and ending at Tarbela.

## REGIONAL SETTING

The geology of NW Himalaya can be described under three main geological domains as follows;

a) Indo-Pakistan plate
b) Kohistan magmatic island arc sequence and
c) Eurasian plate (Tahirkheli, 1979).

Two major suture zones separating these domains are the Main Mantle Thrust (MMT) and the Main Karakoram Thrust (MKT). The MMT marks the boundary along which the Indo-Pakistan plate has been subducted under the Kohistan island arc. The MKT marks the boundary along which Gawachi Back Arc basin was closed and Kohistan Arc was brought against Asian mass (there is a melange zone in between, which varies from 500 to 10 Km in width). The collision of the Indo-Pakistan plate with the Eurasian mass and subsequent under thrusting has developed deep imprints of stresses in Peshawar basin. It is likely that the tensional forces in the basin behind the zone of compression might be responsible for producing the Tertiary rifting, a few carbonatitic bodies like those at Loe Shilman are associated with this rifting.

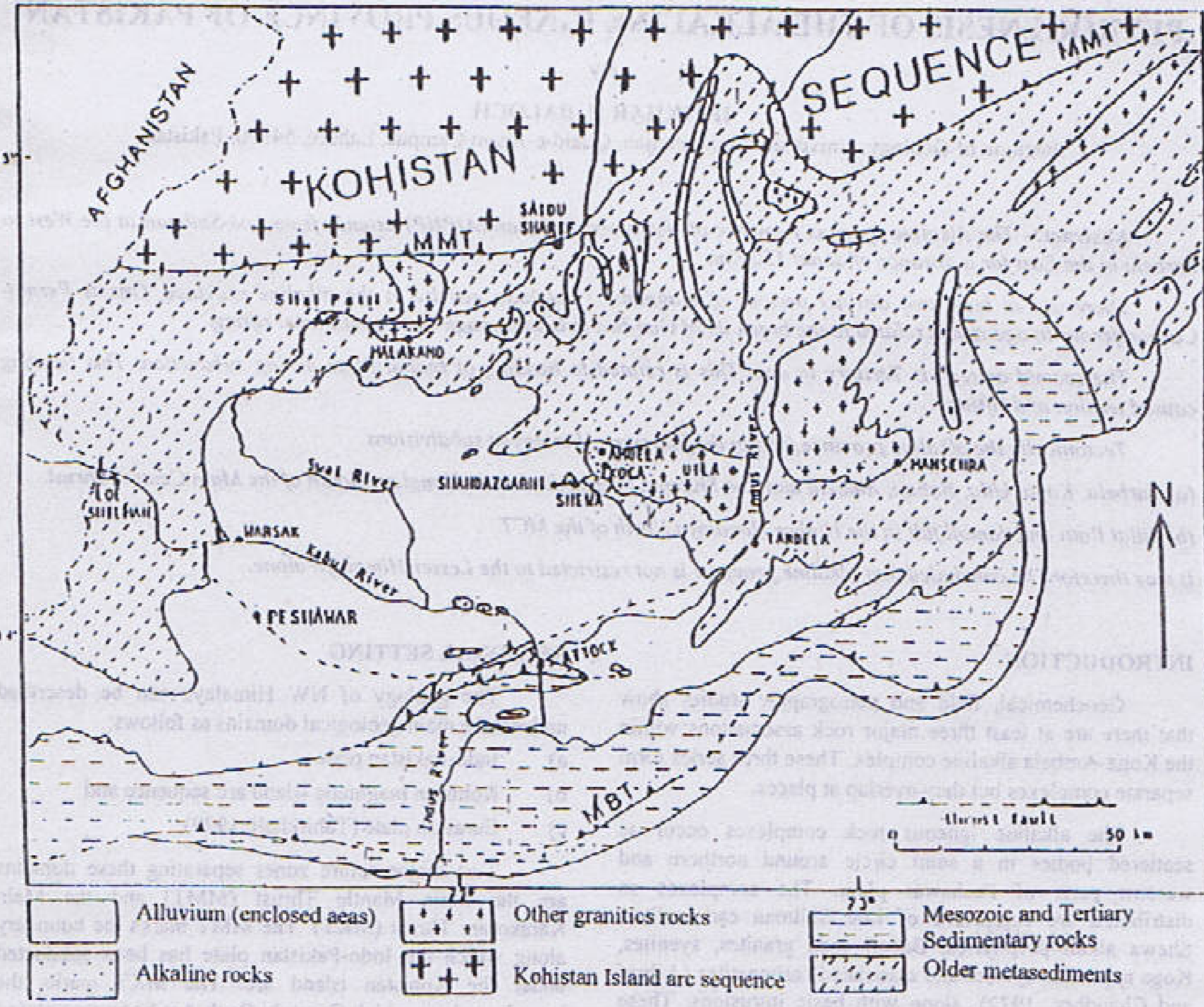


Fig. 1 Alkaline and carbonatite complexes of NW Pakistan.

## ORIGIN OF THE ALKALINE ROCKS AND CARBONATITE COMPLEXES: TECTONIC CONSTRAINTS

Alkaline rocks are commonly associated with rifting (Sorensen, 1974, Smith et al. 1977, Bailey, 1978, and Taylor et al. 1980).

There is a correlation between alkaline magmatism and changes in the direction of plate movements creating reactivation of lithospheric shear zones and rifting within plates from the plate tectonic view point. The associated oblique sets of transcurrent faults originally under compression would open and propagate as tensional faults. This would allow fracturing through the continental lithosphere causing pressure release, channelling of volatiles, partial melting and generation of magma from the asthenosphere. The classic example of African rift related intraplate alkaline magmatism is from Niger - Nigerian alkaline complexes (Bowden et al. 1987)

The overall plate tectonic approach suggests that it is within plate stress fields and fault reactivation which controls the sites of alkaline magmatism in the continental lithosphere. Based on this model the episodic partly mobile thermal anomaly in the mantle is relegated from a plume to a passive hotspot.

The Kohistan sequence interpreted as continental margin or island arc being sandwiched in the Himalayan continent-continent collision provides suitable explana-tion for the origin of carbonatitic bodies only. Kempe and Jan, (1980), suggested that rifting in Peshawar basin was due to relief tension followed by the release of compressional thrusting triggered by collision of Indo - Pakistan and Eurasian plates. This view is applicable to few carbonatitic bodies only which constitute less than 5 % of the alkaline igneous complex. Bulk of the alkaline igneous province developed during Carbiniferous Permian rifting of Gondwanaland.

Rifting is also evident in the Narbada River valley in case of domed Amba Dongar carbonatite and related syenites, ijolite and phonolites, in Gujrat (Sukheswala and Udas, 1964), and may also occur in other Indian alkaline intrusions.

Similar interpretations have been advocated by some authors for the origin of ijolite from the Koga area (Le Bas et al. 1987, Carbonatites from the Silai Patti Butt et al. 1989 and Panjal tholeiitic basalts in Azad Kashmir Butt et al. 1985). Butt et al. (1985) were of the opinion that Panjal basaltic volcanics of Permo-Carboniferous age from Azad Kashmir could be related to rifting of the Indian continent. They considered it to be integral continuation of Panjal traps in Jammu - Kashmir, Raj Mahal traps of West Bengal and Bihar and Sylhet traps of Bangladesh originated with rifting of Gondwanaland, initially proposed by Crawford, (1974). The alkaline and carbonatite magmatism in Koga and Silai Patti may possibly belong to a tensional episode linked with the break up of Gondwanaland. These complexes are now known to be mainly Carboniferous in age. Only Loe Shilman and Jmbil are Tertiary in age and related to plate boundry and rifting associated with India Asia collision sandwiching Kohistan Island Arc.

Alkaline granites of Warsak, Shewa and Shahbaz Garhi, and Koga syenite complex contain pyroxenes as an essential constituent and the field relations show that such bodies are related to faults or rifts as well as areas of cross-folds (Shams, 1980).

## GEOCHEMISTRY

### Major Elements

The Koga feldspathoidal syenites of the project area constitute important rock units of the Koga undersaturated alkaline complex which is generally described as an integral part of the so-called Alkaline Igneous Province of Northwest Pakistan (AIPNP). Current geochemical investi-gations have indicated that at least three major rock associations occur within the Koga - Ambela alkaline complex namely; lamprophyre - carbonatite - fenites, ijolite -feldspathoidal syenites - syenites and syenites - quartz syenites - alkali granites. These three series generally form separate intrusions.

In order to visualize the petrogenetic evolution of the feldspathoidal syenite rocks, it is necessary to consider overall aspects of the nature of mantle source, degree of partial melting of plausible magma and subsequent fractional crystallisation, and the extent of involvement of both lithospheric mantle and lower crust beneath the Koga - Ambela region.

The analysed feldspathoidal rocks exhibit a strong to moderate alkali enrichment and undersaturated character with slightly higher $SiO_2$ content than in other agpaitic and miaskitic syenite suites. They are strongly depleted in $TiO_2$, MgO, CaO and $P_2O_5$ The overall major element chemistry suggests that at least the feldspathoidal syenites, pulaskitic feldspathoidal syenites, garnet bearing feldspathoidal syenites and alkali syenite suites may have been primarily derived directly from a more mafic or trachytic magma. Some of the foyaites particularly sodalite/cancrinite rich foyaites are late stage differentiates emplaced as dykes and pegmatite bodies. The present analytical data (including unpublished results of the associated ijolites, Babaji syenites and alkali granites strongly indicate that the feldspathoidal syenite suites are not formed from a single undersaturated magma series. In this respect the Koga undersaturated alkaline complex has similar genetic evolutionary history to typical rift related alkaline provinces of India and Africa.

The analyses of the rock samples of different groups of the Koga feldspathoidal syenite complex are plotted with their averages in Figs. 2 and 3 respectively as CIPW normative wt. % in the nepheline-kalsilite-silica system after Hamilton and MacKenzie, (1965) at 1 Kb pressure, Taylor and MacKenzie, (1975) at 2 Kb pressure and Morse, (1970) at 5 Kb pressure.

All groups from the Koga complex plot at a pressure > 1 and < 5 Kb, except the sodalite rich foyaites. Hamilton and Mark, (1965) showed that rocks having 80 % or more normative nepheline, albite and orthoclase plot close to the 1 Kb nepheline-syenite minimum. The leucite field becomes contracted with increasing pressure.

The alkali syenite plots on the Ab - Or join, whereas, majority of the rock groups plot near the minima. The feldspathoidal foyaites are the most evolved rocks while the alkali syenite the least evolved, with the means of the foyaitic analyses plotting almost on the minima at 1 and 2 Kb $P_{H2O}$. The final stage of crystallisation is represented by the cancrinite and sodalite rich foyaites. Although a trend from the ternary minima in the water saturated system from cancrinite to sodalite rich foyaite involves a rise in temperature. It may be that the high concentration of $SO_3$, Cl and $CO_2$ alter the phase diagram, causing a shift of the minima towards the nepheline-quartz side of the diagram. A second possibility might involve the autometasomatism of foyaites by their own residual fluids.

It can be concluded from the petrography that the feldspathoidal syenite rocks of the Koga complex started as normal syenites with homogeneous feldspar and then exsolved and recrystallised. These feldspars may have formed at high temperature and then they attained a stable, low-temperature composition each containing little of the other in solid solution. Electron microprobe data also shows that the nephelines cluster tightly close to the nepheline - kalsilite line (Fig. 4), also indicates a low final equilibration temperature.

Chaudhry et al. (1981), outlined the differentiation sequence for the Koga complex, starting from Babaji soda granite. Through progressive evolution alkali enrichment resulted in the formation of Babaji nordmarkite, pulaskite and nepheline syenite. They argued that the evolution of these rocks due to crystallisation differentiation and alkalis were distributed due to the concentration of volatiles. According to Chaudhry et al. (1981), soda granite and nepheline syenite was emplaced first, followed by the western body of pulaskite and nepheline syenite. At this stage pulaskitic pegmatites with either microcline only and or microcline albite - nepheline and pyroxene developed, and then the nepheline syenite. In this intrusion, nepheline syenite pegmatites consisting of nepheline and microcline developed due to enrichment of alkalis.

Chaudhry et al. (1981), proposed the process of alkali volatile enrichment after the formation of nepheline syenite proper which resulted in the generation of different dikes, rich in nepehline and pegmatites. These dikes and pegmatites followed the development of melanite and biotite bearing nepheline syenite of Koga, Bibi Dherai, Agarai and Sura. These dikes are aplitic which could be due to pressure quenching. This was followed by the formation of dikes near Agarai, Namdar, Landi Patao and Miani Kandao. These were formed due to alkalis and volatile enrichment. These dikes are coarse grained to pegmatitic and the main intrusion forming activity came to an end. Finally after this, a rapid concentration of alkalis and volatiles formed the feldspathoid rich pegmatites. Sodalite pegmatites with sodalite-nepheline-cancrinite-microcline-biotite and pyrite. In the end pegmatites with nepheline cancrinite-albite-biotite-calcite formed due to alkalis and F, $H_2O$, $SO_3$, $CO_2$ and S enrichment.

The above differentiation is possible but the mineralogy of the Koga feldspathoidal syenite does not totally confirm this. First of all the mafics i.e. pyroxenes and biotites were not formed in the Koga feldspathoidal syenite. The very nature of their occurrence as aggregate and clots in thin sections reveals that they were carried from the source magma. Secondly the nepheline-cancrinite-albite-pyroxene-calcite pegmatites are not the last stage of formation but the pegmatites of sodalite-nepheline-cancrinite-microcline-biotite and pyrite formed last of development of various rocks.

It is therefore suggested that the sequence may be as follows:

Babaji soda granite → Babaji nordmarkite → alkali syenite → garnet bearing feldspathoidal syenite → pulaskitic feldspathoidal syenite → feldspathoidal syenite → foyaitic feldspathoidal syenite → feldspathoidal foyaites miaskitic → feldspathoidal foyaites agpaitic → sodalite - cancrinite rich foyaites and finally sodalite rich foyaites.

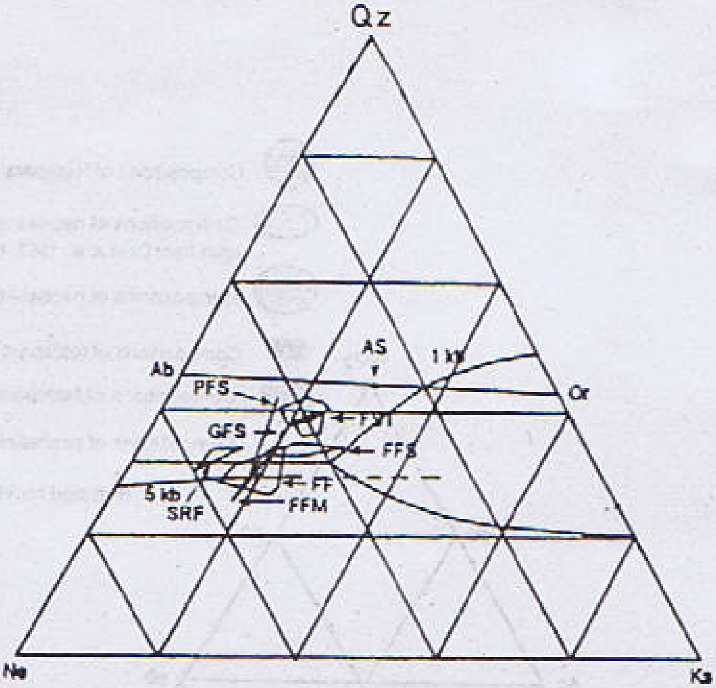


**Fig. 2** Normative nepheline of different groups of the Koga complex rocks plotted on Ne - Qz - Ks, SRF=sodalite rich foyaites, FF and FFM=feldspathoidal foyaite agpaiticand miaskitic, FFS=foyaitic feldspathoidal syenite, PFS=phonolitic feldspathoidal syenite, FST=feldspathoidal syenite trachytic, GFS=garnet feldspathoidal syenite and AS=alkali syenite.

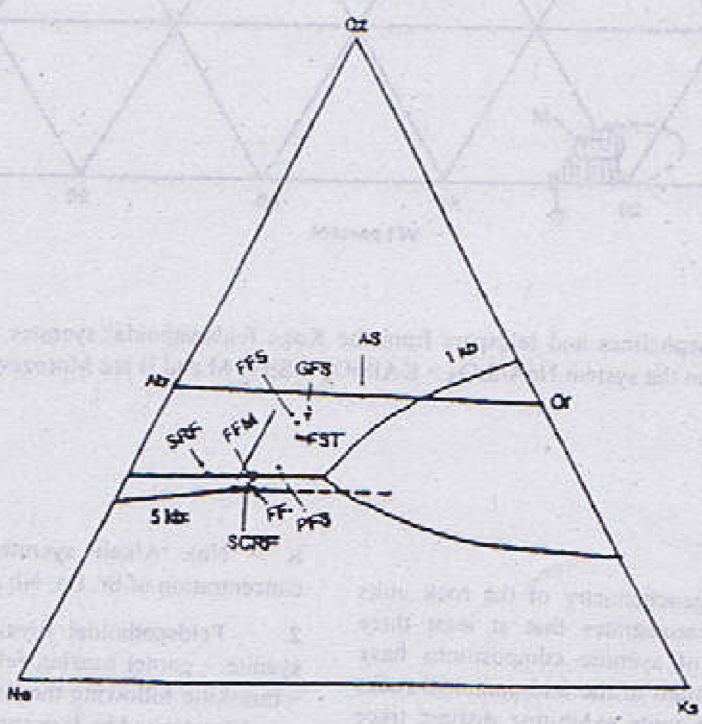


**Fig. 3** Average normative nepheline of different groups of the Koga complex rocks plotted on Ne -Qz - Ks system, symbols as above and SCRF=sodalit-cancrinite rich foyaites.

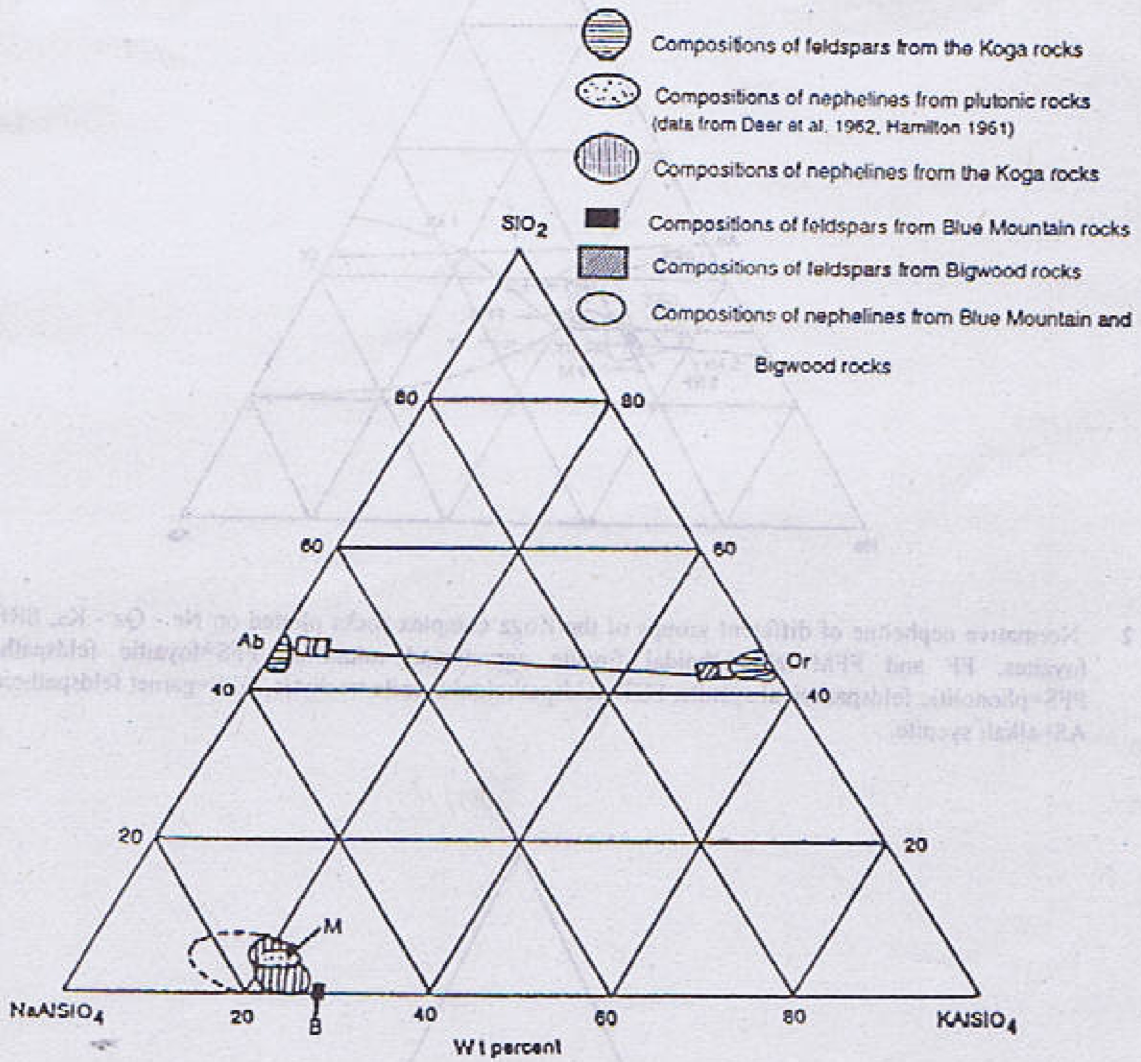


**Fig. 4** Compositions of nephelines and feldspars from the Koga feldspathoidal syenites, Blue Mountain and Bigwood complexes plotted on the system $NaAlSiO_4 - KAlSiO_4 = SiO_2$ M and B are Morozewics and Buerger compositions.

## Trace Elements

The trace element geochemistry of the rock units discussed here broadly demonstrates that at least three distinct primary magmas of syenitic compositions have been involved in the generation of the feldspathoidal rocks of the Koga complex. The units exhibiting distinct trace element signatures may be grouped accordingly as follow:

1. Alkali syenite – alkali granites (high potassic trend, K > Na). Alkali syenites are characterised by high concentration of Sr, Ba, Nb and high K/Rb ratios.

2. Feldspathoidal foyaites – pulaskitic feldspathoidal syenite – garnet bearing feldspathoidal syenites (Trachytic – miaskitic following the pulaskitic – foyaitic trend). These are characterised by low concentrations of Rb, Cr, Sc, Y, Nb, Zr, Th and LREE and high Sr and Ba and relatively high ratios of K/Rb, Ba/Sr, Cr/Sc, Zr/Y and Ba/Nb.

3. Foyaites - foyaitic feldspathoidal syenites feldspathoidal syenites (phonolitic – agpaitic following ijolitic – nepheline syenite trend with sodium enrichment towards sodalite / cancrinite rich foyaites differentiates). The rock units are characterised by relatively high contents of Rb, Zn, Y, Nb, Zr, Th and LREE and strong depletion of Sr and Ba with relatively low Ba/Nb and Y/Nb.

### Rare Earth Elements

The distinct variable trace element abundances and very interesting complex REE distribution patterns (strong LREE enrichment without Eu anomaly, significantly marked negative Ce anomaly and kinked HREE pattern with distinct positive Gd and Er anomalies) strongly indicate the complex magmatic evolutionary history of the Koga feldspathoidal syenite rocks.

The dual behaviour of LILE and HFSE (incompatible as well as compatible trend) within the analysed suite suggest both partial melting and fractional crystallisation processes were involved in the magmatic evolutionary trends leading to the variable trace element geochemistry. The REE patterns, Zr - Y, Nb - Ba and Nb - Y characteristics and Cr/Sc - Cr are consistent with the partial melting of the mantle sources. Both the deep asthenospheric source and shallow lithospheric mantle may have been involved through varying degrees of melting. The strongly undersaturated melts were probably produced by a small degree of partial melting of the deepest source of garnet lherzolite facies in the asthenospheric mantle. The observed variations in the trace elements and REE patterns perhaps suggest the complex processes of assimilation and contamination during the production of trachytic magmas and subsequent differentiation and emplacement of feldspathoidal rocks.

The source enrichment of LREE could be due to mantle metasomatism as well as involvement of oceanic crust subduction during the underthrusting of the Indo-Pakistan plate. The Ce and Eu negative anomalies in the REE patterns of feldspathoidal syenites strongly suggest this phenomenon. Alternatively, the REE characteristics in combination with Cr/Sc - Cr may be interpreted by the involvement of lower crust (granulite and eclogite facies) in the shallow level lithospheric mantle source melts (Neal and Taylor, 1989).

To proceed further with the investigation of the petrogenesis of the Koga complex requires an investigation of Sr and Nd isotopes.

## DISCUSSION

The Alkaline Igneous Complex of Northwest Pakistan was generally considered Tertialy in age and formed ue to Plate bending following India-Asia collision (Kempe and Jan, 1980 Chaudhry and Shams 1983). However recent geochrono-logical studies (in press) clearly show that most of the rocks of this province are carboniferous-Permain in age and were formed due to rifting and dismemberment of Gondwanaland. These rocks originated from metasomatised mantle with subduction influence (Ce and Eu negative anomalies).

This view is contrary to the view of crustal derivation (Ashraf and Chaudhry, 1977) though Cr/Sc-Cr values could be interpreted to involve granulite to eclogite facies lower crustal contribution.

Chaudhry et al. (1981), proposed alkali and volatile enrichment for evolution of various rocks like sodalite syenite cancrinite sodalite syenite and equivalent pegmatites from nepheline syenites and syenites. While that may be partially correct, the ultimate origin of these rocks lies in derivation from enriched mantle.

The pattern of rare earth elements, Zr-Y, Nb-Ba and Nb-Y, Cr/Sc-Cr are consistent with partial melting of the mantle. The Tertiary rocks so far discovered are only carbonatites near Loe Shilman. These are related to plate bending and rifting caused by India-Asia collision sandwiching Kohistan Island Arc.

The tholeiitic Punjal Volcanics within the alkaline province and in nearly areas of Kaghan and Azad Kashmir (Butt et al. 1985, 1989) are complimentary to the alkaline province. Although these (Punjal) volcanics and the alkaline province are both related to the break up of gondwanaland yet their exact relationship is not known. This would require detailed field work, isotopic, geochemical and geochronalogical investigations.

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