The
GEOLOGICAL BULLETIN
of the
PUNJAB UNIVERSITY

Number 33 & 34 *December 1999*

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Geol. Bull. Punjab Univ., 33 & 34 1999.

EVIDENCE FOR PRE-MESOZOIC AFFINITY OF THE KARAKORAM HIMALAYA TO THE INDIAN PLATE, NORTHERN PAKISTAN

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Abstract:- *Recent geological studies in the Karakoram Himalaya and the Indian Plate (NW Himalaya, Pakistan) lead us to suggest that the pre-Mesozoic stratigraphy and associated mineralisation in both of the plates are comparable. Infact, the similarities are so strong that the possibility is here considered that the Indian Plate and the Karakoram Microplate were, until the Mesozoic, joined as part of the same plate until the early Mesozoic. The Karakoram Microplate extends to the Lhasa Block (Tibet) in the east and the Helmand Block in the west (Afghanistan). Moreover, evidence is given to make tectonostratigraphic correlations between the units within the Karakoram Himalaya and the Indian Plate, allowing us to define a Higher- and Lesser Karakoram that can be related to their Indian Plate Himalaya equivalents.*

INTRODUCTION

The Karakoram Himalaya form a distinctive topographic and mountainous range in Central Asia. Geologically, they are classified as part of the Eurasian Plate, a collage of terranes into which the Indian Plate collided to form the Himalayan mountain range at times estimated to range from 65 to 45 Ma (Fig. 1). This continent-continent collision was preceded by an earlier arc-continent collision, associated with the final closure of the Neo-Tethyan ocean. During the Cretaceous, oceanic crust was subducted below Eurasia and resulted in its subsequent melting and production of I-type granites that intruded along the length of Eurasia (Trans-Himalayan Batholith). Recent mapping and traverses of the Karakoram Himalaya lead us to suggest that there is a distinctive stratigraphical correlation between the units of the Karakoram Himalaya (Eurasian Plate) and the Himalaya (Indian Plate). In fact, we suggest that these similarities are so strong that the likelihood should be considered that the Karakoram Himalaya and the Indian Plate were, until the early Mesozoic, attached as part of the same block or plate. With the closure of Paleo-Tethys and the opening of Neo-Tethys, a rifted piece of the Indian Plate (the Karakoram Block or microplate, now called the Karakoram Himalaya) subsequently broke away from Gondwanaland (and the juvenile Indian Plate) and was subjected to a passive (?) collision, with eventual suturing, to Eurasia.

The fact that the pre-collisional history of the Karakoram Himalaya is known to be correlatable to the Lhasa block of southern Tibet in the east (Chen-fa and Yu-shen, 1981; Searle, 1991) and the Helmand Block of eastern Afghanistan in the west (Blaise et al., 1977; Stocklin, 1977; Wolfart and Wittekindt, 1980), suggests that a distinctive belt with a similar pre-Mesozoic stratigraphy can be traced, north of the Indus Suture, both to the east and to the west of the Karakoram. Here we provide evidence of a north to south correlation of the Karakoram Himalaya with the Indian Plate. For discussion purposes, we also suggest a new terminology for the Karakoram Himalaya with the implications that this has for its tectonic history. The classification that we have used is based on that of the Himalayan subdivisions (i.e. Higher Himalaya and Lesser Himalaya). We suggest that in the Karakoram Himalaya, the distinctive units of the Higher Karakoram and Lesser Karakoram can be found and, more importantly, be correlated to their Pre-Mesozoic Indian Plate stratigraphic equivalent (Tables 1 and 2).

Table 1
Stratigraphic correlation between the Higher Himalaya (Lower Swat and Besham, Kaghan and Azad Kashmir) and the Higher Karakoram (Hunza Valley).

Higher Himalaya (Indian Plate)		Higher Karakoram
Lower Swat & Besham	**Kaghan & Azad Kashmir**	**Hunza Valley**
Alpurai Group	***Burawai Group***	***Baltit Group***
Tilgram Formation: Calc-pelite, marble with minor pelite	*Bans Formation:* Pelites	*Ganesh Formation:* Marble, calc-pelite, pelite and amphibolite
	Seri Formation: Thick sequence of calc-pelite and marble with amphibolites	
Salampur Formation: Pelite psammite; Turbidites with amphibolite sheets	*Old Battakundi Formation:* Pelite psammite; Turbidites with amphibolite sheets	
Pacha Group	***Purbinar Group***	***Baltit Group***
Swat Granite, Manglaur Formation: Pelite-psammites, Turbidites, Migmatites, minor marble, calc-schist and graphitic schists	*Saiful Muluk Granite* *Lulu Sar Formation:* Pelite-psammites, minor marbles and graphitic schists	*Minapin Formation:* Pelite-psammites with minor marbles and graphitic schists
Kolangi Formation: Migmatites	*Gittidas Granite* *Jalkhad Nar Formation:* Migmatites and enclaves	
Targhao Granite Gneisses: Granite gneisses and Migmatites	*Ratti Gali Granite* *Lulu Sar Formation:* Granite gneisses and Migmatites	*Hasanabad Granite* Migmatites with meta-sedimentary enclaves

Table 2
Stratigraphic correlation between the Lesser Himalaya (Peshawar Basin) and the Lesser Karakoram (Western Pakistan).

Lesser Himalaya (Indian Plate)	Lesser Karakoram
Peshawar Basin	**Chitral**
Bampokha Formation: Dolomitic limestone / limestone *Carboniferous/Triassic?*	***Zait and Parpish Formation:*** Dolomitic limestone / limestone *Carboniferous to Triassic?*
Jaffer Kandao Formation: Limestone, Dolomite and quartzite *Devonian*	***Lun Shales:*** Shale, sandstone and dolomite *Late Devonian*
Panj Pir Formation: Slate, Limestone and dolomite *Silurian*	***Broghil Formation:*** Slate, limestone, dolomite and quartzite *Ordovician/Silurian?*
Misri Banda Quartzite: Quartzite *Ordovician-Cambrian?*	
Attock Slates: Slate, wacke, quartzite and minor marbles *Precambrian*	***Chitral Slates:*** Slate, wacke, quartzite and minor marbles *Precambrian*

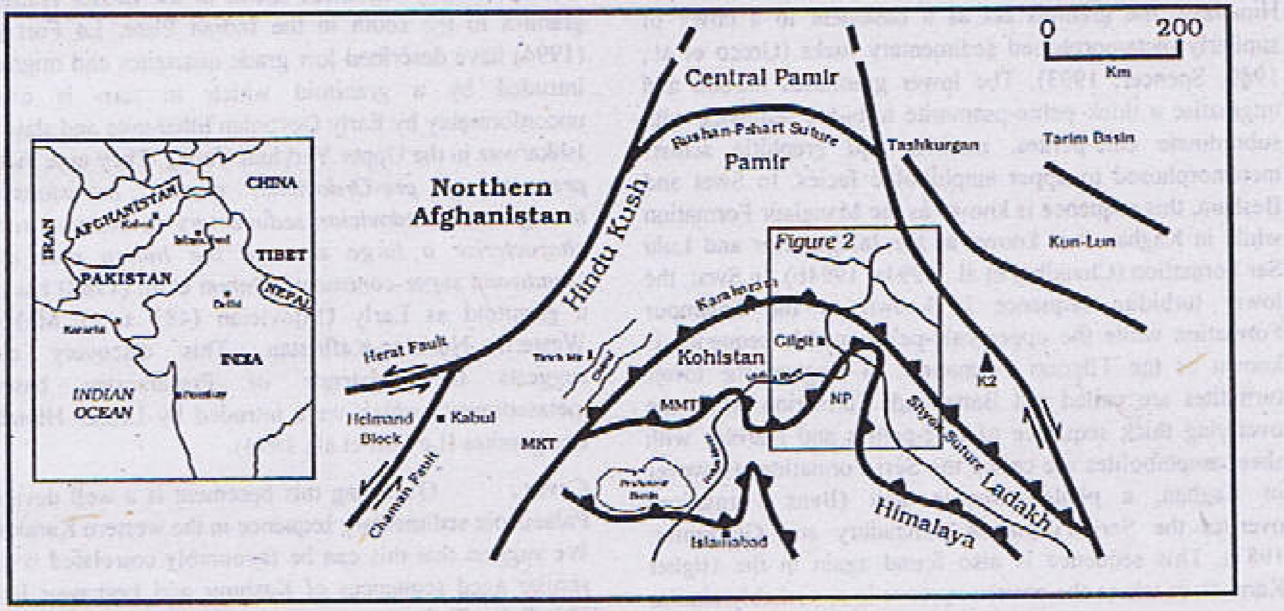

Fig. 1 Tectonic sketch map of Northern Pakistan and the surrounding regions (redrawn from Zanchi, 1993). MMT - Main Mantle Thrust; MKT - Main Karakoram Thrust; NP - Nanga Parbat.

GEOLOGICAL SETTING

Higher Himalaya (HH) and Higher Karakoram (HK)

Basement : The Higher Himalaya (HH) of the Indian Plate forms the distinctive metamorphic core of the Himalayan mountain range and is usually associated with a topographical high. We suggest that the high grade metamorphic rocks of the Central Karakoram, which form north of the Northern Suture and south of the Karakoram Axial Batholith can be directly correlated (Chaudhry et al. 1995). We designate this northern unit as the Higher Karakoram (HK) which is well exposed in its type section along the Hunza Valley (Fig. 2). Here it consists of a lower S-type granitoid-migmatite complex with metasedimentary enclaves. These garnet-tourmaline-bearing two mica granitoids and migmatites (locally called the Hassanabad Granitoid and Migmatite Complex) can be compared with very similar garnet-tourmaline-bearing two mica granitoids and migmatite rocks exposed in the Higher Himalaya south of the Indus Suture. Therefore, a direct correlation of the Higher Karakoram (HK) is made with the Higher Himalaya (HH) in Swat (Targhao Granite Complex and migmatites of Kolangi Formation), in Besham (Lahor Granitoids and Migmatite Complex) and in Kaghan (lower part of the Purbinar Group composed of a granitoid migmatite complex with abundant metasedimentary enclaves and septa). The correlation is given in Table 1.

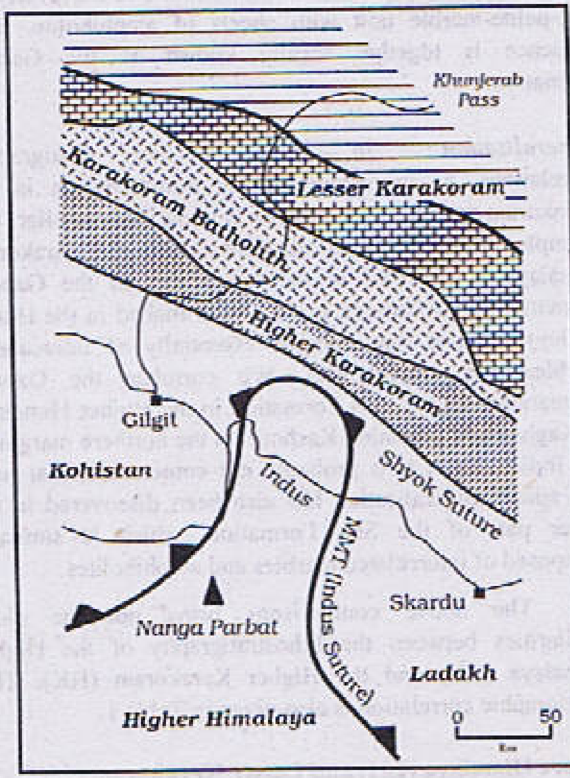

Fig. 2 Simplified tectonostratigraphic map of the Karakoram Himalaya showing the subdivisions of the Higher Karakoram and the Lesser Karakoram. The Karakoram Axial Batholith has intruded along the line of weakness that was originally the Main Karakoram Central Thrust (redrawn from Gaetani, 1994).

Cover : In is now established that, in the Northwest Himalaya, the granites act as a basement to a cover of similarly metamorphosed sedimentary rocks (Greco et al., 1989; Spencer, 1993). The lower granitoids intrude and migmatise a thick pelite-psammite turbidite sequence with subordinate calc-pelites, marbles and graphitic schists metamorphosed to upper amphibolite facies. In Swat and Besham, this sequence is known as the Manglaur Formation while in Kaghan it is known as the Jalkhad Nar and Lulu Sar Formation (Chaudhry et al., 1994a, 1994b). In Swat, the lower turbidite sequence is known as the Salampur Formation while the upper calc-pelite marble sequence is known as the Tilgram Formation; in Kaghan the lower turbidites are called old Battakundi Formation while the overlying thick sequence of calc-pelites and marbles with sheet amphibolites are called the Seri Formation. However in Kaghan, a pelite-psammite unit (Bans Formation) overlies the Seri Formation (Chaudhry and Ghazanfar, 1987). This sequence is also found again in the Higher Karakoram where the cover sequence is remarkably similar to that known in the Higher Himalaya. The cover sequence, similarly metamorphosed with the basement to upper amphibolite facies, is therefore composed of a lower poorly developed pelite-psammite turbidite unit and the overlying calc-pelite-marble unit with sheets of amphibolite. This sequence is together locally known as the Ganesh Formation.

Mineralisation : In addition to these stratigraphic correlations, a comparison of the mineralisation in the Karakoram and Indian Himalaya is remarkably similar. For example, ruby and spinel mineralisation in the Karakoram Himalaya is confined to the lower part of the Ganesh Formation (near Ganesh, north of Karimabad in the Hunza Valley), a zone that consists essentially of intercalated marbles and amphibolites. We correlate the Ganesh Formation with the Seri Formation in the Higher Himalaya of Kaghan and adjoining Kashmir on the northern margin of the Indian Plate. It is probably not coincidental that ruby and spinel mineralisation has also been discovered in the lower part of the Seri Formation, which is similarly composed of intercalated marbles and amphibolites.

The above comparisons bring out the close similarities between the lithostratigraphy of the Higher Himalaya (HH) and the Higher Karakoram (HK). This stratigraphic correlation is also given in Table 1.

Lesser Himalaya (LH) and Lesser Karakoram (LK)

Basement : In the Western Karakoram, there is a very well developed Palaeozoic sedimentary sequence which extends into Afghanistan. It has a basement composed of Precambrian metasediments that are intruded by lowermost Palaeozoic (or older) granitoids. These age relationships are exactly the same as those found in the Lesser Himalayan granites to the south in the Indian Plate. Le Fort et al. (1994) have described low grade quartzites and migmatites intruded by a granitoid which in turn is overlain unconformably by Early Devonian litharenite and slate from Ishkarwaz in the Upper Yarkhun Valley. They note that *"the presence of pre-Ordovician granite intrusions and transgressive Ordovician sedimentary successions seem to characterize a large area of the Indian part of the Gondwana super-continent."* Debon et al. (1987) has dated a granitoid as Early Ordovician (483 ± 21 Ma) from Western Nuristan-Kafiristan. This discovery clearly suggests the existence of Precambrian basement metasediments which were intruded by Lesser Himalayan age granites (Le Fort et al., 1994).

Cover : Overlying this basement is a well developed Palaeozoic sedimentary sequence in the western Karakoram. We suggest that this can be favourably correlated with the similar aged sequences of Kashmir and Peshawar Basins. This Paleo-Tethyan sequence in Chitral overlies the Chitral Slates which we consider, on the basis of superposition, as Eo-Cambrian. In the past they have been considered as Permian (Hayden, 1915) or even Cretaceous (Calkins et al. 1981). This litho-stratigraphic correlation is given in Table 2.

The discovery of the basement in the central and western Karakoram (north of the Karakoram Axial Batholith) by Le Fort et al. (1994) and the knowledge of the Lesser Himalayan aged granites also suggests a similarity. Moreover, there is also a cover correlation of the overlying Karakoram sediments with the sediments of the Lesser Himalaya (Peshawar Basin, Kashmir Basin). This seems to indicate that, during the Palaeozoic, Paleo-Tethys sediments were preserved not only in the Lesser Himalaya, but also in the Karakoram, the Lhasa Block to the east and the Helmand block to the west *(The term Helmand Block, when used alone, refers to Peri Gondwanic elements of Indian Plate affinity in northeastern and southern Afghanistan south of the Herat Fault).* Therefore, at least the upper part of the Lesser Himalaya (LH) (basement and the overlying Palaeozoic sediments in Kashmir and Peshawar Plain) can be correlated with the upper part of the basement and sediments of the what we designate as the Lesser Karakoram (LK) (Fig. 2).

THE MAIN CENTRAL THRUST (MCT) AND THE MAIN KARAKORAM CENTRAL THRUST (MKCT)

The Main Central Thrust (MCT) is a major 5-20 km wide ductile shear zone that separates the Higher Himalaya (HH) from the Lesser Himalaya (LH). It is associated with a distinctive metamorphic break as well as with notable differences in structural style, stratigraphy and tectonic characteristics. Similarly, the Higher Karakoram (HK) and the Lesser Karakoram (LK) in the central Karakoram (Hunza Valley and its surroundings) are separated by a major ductile shear zone which we call the Main Karakoram Central Thrust (MKCT). Across this fault, there is a significant pressure-temperature break with upper amphibolite facies to the south in the Higher Karakoram and lowermost greenschist (slates) in the Lesser Karakoram. A sharp break is also apparent between highly strained ductile deformation in the south to weak brittle deformation in the north. However, it is necessary to point out that this shear zone is only visible in certain parts of the Karakoram, as this line of weakness subsequently became the main fracture for the intrusion of the Karakoram Axial Batholith (Figure 2).

We also note that, in the eastern and western Karakoram, the Higher Karakoram (HK) and the Main Karakoram Central Thrust (MKCT) appears to merge with the Shyok Suture, so cutting out most of the ductily deformed and metamorphosed unit in these areas. Therefore, the Lesser Karakoram (LK) comes directly into contact with the Kohistan Island Arc in the extreme eastern and western parts of the Karakoram. Such a geometry may indicate a rapid domal uplift in the central parts of the Karakoram, possibly comparable with the uplift of Nanga Parbat Haramosh Massif. However, these observations do not necessarily preclude the fact that the high grade basement may be exposed at places in eastern and western Karakoram, as well as Helmand and Lhasa Blocks.

CORRELATION OF THE KARAKORAM-HIMALAYA WITH THE HELMAND BLOCK

According to Wolfart and Wittekindt (1980), southern Afghanistan was affected by two orogenies namely, an early Assyntian or Baikalian (Late Proterozoic) Orogeny and a late Alpine (Oligo-Miocene) Orogeny. We suggest that the Lesser Karakoram Basement, the Helmand Block and the Lhasa Block were consolidated in the Precambrian during the Pan African Orogeny or the Hazaran Orogeny. These orogenies are being used here, as defined by Baig et al. (1988) and Chaudhry et al. (1989) respectively, in the context of Lesser Himalaya of NW Pakistan. The basement was subsequently overlain by a Palaeozoic sequence which, in most parts, was not effected by any subsequent metamorphism. This compares well with the Lesser Himalaya of the Indian Plate where predominant metamorphism is thought to be Pre-Himalayan (i.e., Eo-Cambrian/Pan African or Hazaran). Subsequently, the Karakoram Block (or microplate) separated from the Indian Plate (in the Peri Gondwanic Region) during the Triassic and moved north with the opening of Neo-Tethys and closure of Paleo-Tethys. It was accreted with the central Pamir along the Rushan Pshart Suture. The Karakoram Block may be compared to the Helmand Block to the southwest (Blaise et al., 1977; Stocklin, 1977; Abdullah and Chmyriv, 1980; Girardeau et al., 1989; Wolfart and Wittekindt, 1980). Moreover, according to Wolfart and Wittekindt (1980), the Farah Block and the Helmand Block belong to the eastern Iranian-Central Afghan block. They also suggest that the Nuristan block represents an eastern Afghan-western Pakistan unit, possibly derived from the Indian shield. Finally, the Katawaz block is thought to be a marginal part of the Indian Shield.

Basement: In the Helmand Block, NW of Beshud (Montenat et al., 1981), an age of 502 ± 24 Ma was recorded for a two mica porphyritic granite which intrudes a Pre-cambrian metamorphosed basement consisting of volcano-sedimentary rocks. This granite, according to LeFort et al. (1994), resembles the Early Paleozoic granitoids which are known to extend along the Himalayas from Bhutan to Pakistan.

Cover: The basement of the Helmand Block is overlain by a pelite-psammite succession which may range in age from Cambrian to Silurian (Blaise et al., 1977, 1982). The Palaeozoic sequence is similar to that known in the Lesser Himalaya. A strong correlation therefore suggests that the stratigraphy of the Karakoram Himalaya and the Helmand Block are directly related. They both consist of a basement and lower Palaeozoic granitoids which can then be directly compared to the Lesser Himalayan two mica porphyritic granites. This was subsequently covered by an ensialic Paleo-Tethyan basin. This is comparable and correlatable to the Kashmir-Peshawar Basin of the Lesser Himalaya.

CORRELATION OF THE KARAKORAM-HIMALAYA WITH THE LHASA BLOCK

Like the Helmand Block, the Tibet Plateau (Qinghai-Xizang Plateau) has been formed due to the continental or arc fragments which were successively accreted between the Late Palaeozoic and Late Cretaceous. The sequence of collisional events and their subsequent suturing has been discussed by Cheng-fa and Yu-shen (1981). The Lhasa block (or Northern Xizang Structural Region) is the southernmost block that was passively sutured to the Eurasian Plate along the Bangong Lake Nu Jiang Suture Zone at times estimated to range from Triassic to Middle Jurassic age. In the Northern part of Lhasa Block, Xu et al. (1985) have reported an U-Pb age of 539 ± 14 Ma in a granite. Yin et al. (1988) have described unmetamorphosed sediments of Ordovician age. Therefore, a Precambrian basement overlain by lower to upper Palaeozoic sediments appears to exist. These Lower Palaeozoic sediments have been compared, and considered broadly similar to, those found in the Himalayan Region by Cheng-fa and Yu-shen (1981).

PALEO-TETHYAN AND NEO-TETHYAN PALEOGEOGRAPHY

The simplest interpretation of the above correlations is that the Karakoram Himalaya, Helmand Block and Lhasa Block are broadly correlatable from east to west. A strong similarity also exists between lithologies north of the Indus Suture and south of the Indus Suture with respect to their pre-collisional history. Indian Plate basement and Pre-Mesozoic cover rocks are found in the Higher Himalaya and Lesser Himalaya and can be directly related to their equivalents in the Higher Karakoram and Lesser Karakoram. This suggests that the Lhasa-Karakoram-Helmand Region was part of the Gondwanaland domain until the Permo-Triassic when Neo-Tethyan rifting subsequently separated the Karakoram Plate (or Lhasa-Karakoram-Helmand Block) from the juvenile "Indian Plate" and accreted it to Eurasia. Subsequently, with the continuing break up of Gondwanaland, the Indian Plate separated from this southern hemisphere landmass and moved northwards. It rejoined the Lhasa-Karakoram-Helmand Block in the Paleocene after the closure of the Neo-Tethyan ocean. Therefore, the Paleo-Tethyan history of the Indian Plate and the Lhasa-Karakoram-Helmand Block are sugges-ted to be very similar. By contrast, the subsequent Neo-Tethyan and post-collisional histories of the two terranes are very different. Nevertheless, this interpretation seems to indicate that both the Indian Plate and the Lhasa-Karakoram-Helmand Block have the same Pre-Mesozoic origin: Gondwanaland.

ACKNOWLEDGEMENTS

Nawaz and Munir thank the Pakistan Science Foundation for support for fieldwork in the Pakistani Himalaya. They also acknowledge receipt of a field grant from the University of the Punjab, Lahore. David was financially supported by a Swiss Federal Institute of Technology Grant (Nr. 0.20.367.89), an ETH-Imperial College Scholarship (Nr. 0.330.028.02/8) and a Swiss National Science Foundation Research Fellowship (Nr. 2100-039080.93/1). SSH and HD thank the Pakistan Museum of Natural History for logistical support.

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Geol. Bull. Punjab Univ. 33 & 34, 1999.

THE GEOLOGICAL CHARACTER AND PROBLEMS OF THE LESSER HIMALAYA IN NE PAKISTAN

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Abstract:-*With the delineation of the Main Central Thrust in the Northwest Himalaya of Azad Kashmir and Pakistan, the Lesser Himalayan slab stands defined. The Lesser Himalaya of Pakistan and Kashmir are divided into a 'Northern Metamorphic Zone' and a 'Southern Sedimentary Zone'. The Northern Metamorphic Zone is overlain by the Peshawar Basin in the west of Pakistan and also includes Northern Hazara and the middle parts of Kaghan and Neelum valleys to the east. Whilst the Kashmir and Peshawar Basins are characterized by a Tethyan stratigraphic sequence deformed by simple folding, the intervening middle Kaghan and Northern Hazara areas are highly deformed schuppen structures on the limbs of the Hazara-Kashmir Syntaxis. The Kashmir and Peshawar Basins are limited to the south by the sedimentary zones of the Pir Panjal in the east and the Attock-Hazara Fold-and-Thrust Belt in the west. Both these sedimentary belts are marked by numerous closely spaced ramp faults. The Attock-Hazara Fold-and-Thrust Belt is marked by a polyphase sequence of deformation. At least one phase is Precambrian The occurrence of Pre-Himalayan/Pre-Cambrian metamorphism in the Lesser Himalaya is now well established. The Himalayan overprint is missing or at best limited. The Tanol-Tanawal controversy regarding age and correlation of these formations in Kashmir and Hazara is discussed and it is here suggested that among the Pre-cambrian formations the Tanawals of Hazara are in fact older than the Hazara slates.*

INTRODUCTION

Like all major mountain belts, the Himalayas are divisible into genetically distinct longitudinal zones (Fig. 1). These zones were first proposed in the Central and the Eastern Himalaya and have been named from north as the Tethys Himalaya, Higher Himalaya, Lesser Himalaya and the Sub-Himalaya. From the south, away from the foreland, these zones mark an increase not only in metamorphism, but also in age from Quaternary to Proterozoic (and perhaps even Archaean). This trend, however, reverses north of Higher Himalaya across which the Tethyan Himalaya mark a sudden decrease in deformation and metamorphism. During the course of collisional evolution, the Himalayan belt has been telescoped into a much shorter section by numerous faults and folds. Because of these attenuations, the tectonostratigraphic changes are no longer gradual but sudden and abrupt across major faults. Four or five such faults, the so-called boundary faults, mark the limits of the relatively wide Himalayan tectonic belts.

From south to north the Sub-Himalaya (comprising of the Murree Formation and Siwalik Group) is a clastic wedge which was deposited to the south of the emerging Himalayas in the Upper Tertiary. In the Kumaun and Nepal Himalaya the Lesser Himalaya are low grade Precambrian and Lower Palaeozoic metasediments overridden, at places, by high grade nappes and klippen (e.g. Simla, Garhwal and Almora nappes). The Higher Himalaya is a high grade terrane with Precambrian granite gneisses as well as subordinate leucogranites of Himalayan age. The northernmost zone, the Tethyan Himalaya, is the Phanerozoic, Cambrian to Eocene sedimentary cover overlying the high grade slab of Higher Himalaya, with a normal fault at their base. The identification of the boundary faults implies the limitation of the Himalayan zones; similarly the determination of the distinct tectonic zones implies the existence of their boundary faults. These faults, and the tectonic zones, have thus become interdependent in the classification and subdivision of the Himalaya. From north to south, the boundary faults of the Himalaya are

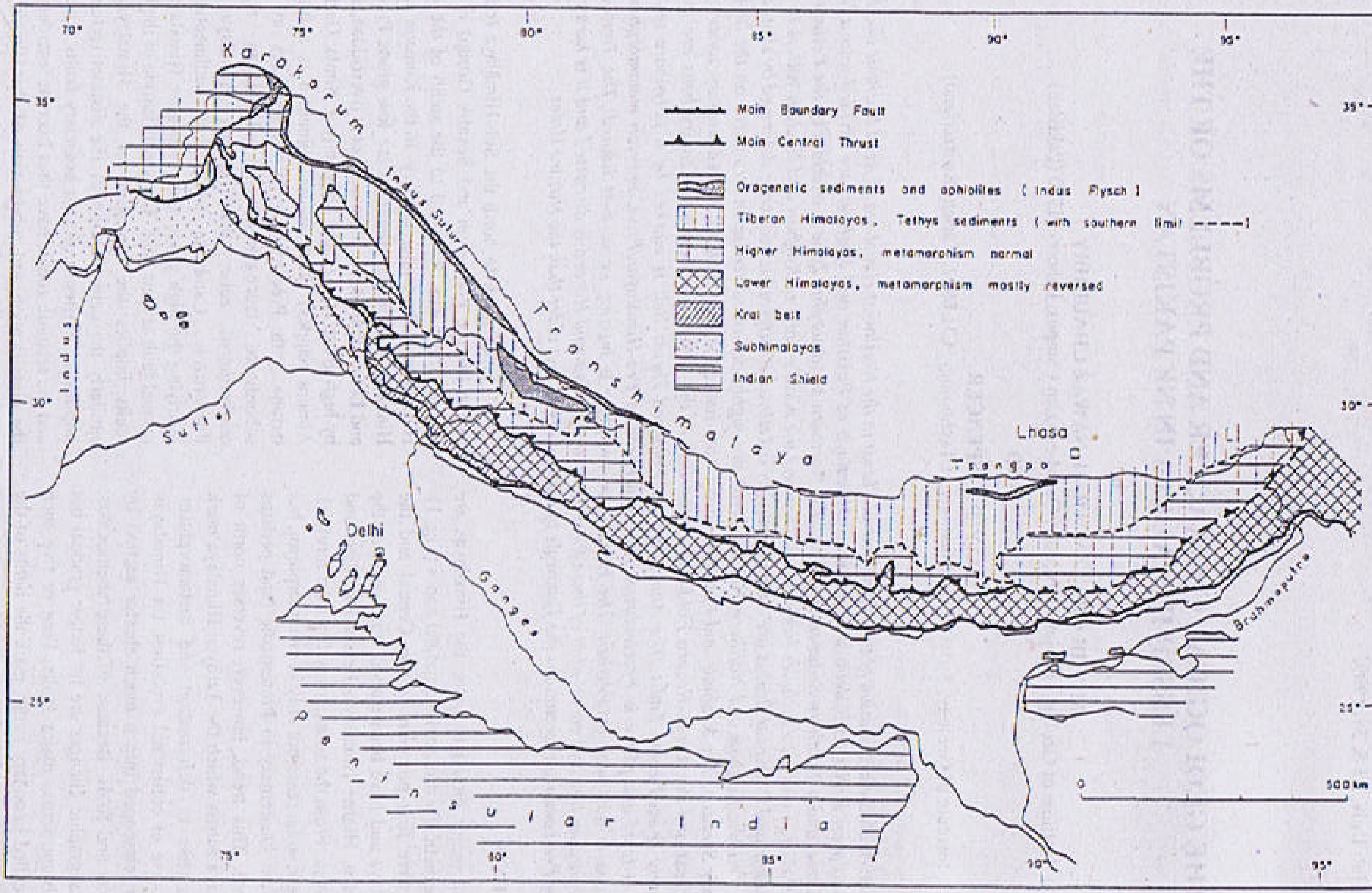


Fig.1. Subdivision of the Himalaya as shown by Gansser (1964).

known as the Trans-Himadari Fault (THF), separates Tethyan Himalaya from Higher Himalaya, the Main Central Thrust (MCT), Higher Himalaya from Lesser Himalaya, the Main Boundary Thrust (MBT) Lesser Himalaya from Sub-Himalaya and the Himalayan Frontal Thrust (HFT) which thrusts the deformed foredeep deposits over the undeformed Indo-Gangetic alluvium of the foreland.

EXTENT OF THE LESSER HIMALAYA IN PAKISTAN AND KASHMIR

In the Northwestern Himalaya (Kashmir and Pakistan), the Himalayan tectonic belts, especially the northern ones, were not so easy to trace as in the Central Himalaya. Reasons include the physical lateral distance from the last known subdivisions in the Central Himalaya, as well one of political inaccessibility for researchers in the Kashmir region. This, combined with the relative lack of geological mapping on Pakistan side, syntaxial deformation and the presence of Kashmir and Peshawar basins, complicated any proposed extension of the Himalayan subdivisions towards the west from India. Some workers, in fact, suggested that the geology of the Pakistan Himalaya was unique and should be subdivided on their own (Yeats and Lawrence, 1984), with no reference to the Himalayas to the east.

Despite previous assertions of the non-Himalayan conformity of the Pakistan region, initial geological mapping of Neelum and Kaghan valleys (Ghazanfar et al., 1983; Ghazanfar and Chaudhry, 1985; Chaudhry and Ghazanfar, 1987) led to the significant delineation of the Main Central Thrust in this area (Ghazanfar and Chaudhry 1986; Chaudhry and Ghazanfar, 1990). The delineation of this fault, therefore, implied a subdivision of this area, into the Higher and the Lesser Himalaya. It also allowed for the tectonic-stratigraphic correlation of the Pakistan Himalaya with Kashmir and the Central Himalaya of Kumaun and Nepal.

This paper, therefore, aims to review this controversial upper boundary and the character of the Lesser Himalaya, as well as its relationship to the Higher Himalaya. The extent of the Lesser Himalaya in Pakistan and Kashmir clearly relates to the demarcation of the Main Central Thrust as the structurally upper boundary and the Main Boundary Thrust as the structurally lower boundary. The delineation of Main Boundary Thrust has been relatively simple and was achieved long ago (Middlemiss, 1896; Wadia, 1931). This boundary fault is traditionally placed at the clearly recognisable contact between the older shelf sediments and the distinctively red coloured Upper Tertiary molasse deposits of the foreland. In fact, this contact is so clear that the nature of the Main Boundary Thrust was not properly investigated for a long time in Pakistan. To date, numerous questions remained to be answered such as the amount of translation it involved and whether or not the basement was involved in the deformation. McDougall et al. (1994) have discussed some such questions related to MBT in a section across the Peshawar Plain.

THE NORTHERN LIMIT OF THE LESSER HIMALAYA - THE MAIN CENTRAL THRUST

The problem of delineating the Main Central Thrust (i.e., the northern limit of the Lesser Himalaya) has been a far more difficult task compared to the southern boundary fault. Between the Lesser Himalaya and the Higher Himalaya, there is no clear change of rock colour or lithology, nor readily applicable geomorphic criteria. Furthermore, the terrane is difficult for traversing and the relief high. Only after detailed geological mapping and subsequent tectono-stratigraphic and tectono-metamorphic studies along the valleys of Neelum, Kaghan, Indus, Swat and Dir, have the distinctive character of Lesser and Higher Himalayas in Pakistan been established with the placing of the Main Central Thrust between them (Ghazanfar and Chaudhry, 1986; Chaudhry and Ghazanfar, 1990; Chaudhry et al. 1994a, 1997).

While delineating the Main Central Thrust, it is important to realise that the concept of this boundary fault is one that has resulted from the strikingly different character of its footwall and hanging wall. Thus, unless there is a major contrast of stratigraphy, metamorphism and structural style in the terrains across the fault, the Main Central Thrust cannot be proved nor delineated. Secondly, there is need for consistency in the definition of Higher and Lesser Himalaya, if indeed these belts continue laterally along the Himalaya. Third, it must be realised that the major boundary faults serve only to accentuate the differences of geology across, which otherwise would be a continuum. Each block shares, to a certain extent, the history of the other block but differs owing to its position in time and space and of course owing to its different uplift and erosion. Thus the differences we are looking for in slabs across a boundary fault are not absolute but relative. For example sediments of Tethyan affinity can be found in the Lesser Himalayan domain. It is therefore the predominant features that determine of the character of any particular Himalayan tectonic zone. Now there are a host of thrusts associated with the Himalayan deformation in the Kaghan Valley. However, it becomes clear that only across the Batal Fault near Naran (Fig. 2), the character of the terrain changes suddenly resulting in the relative uniformity of the stratigraphy, metamorphism and structure of the Lesser Himalaya altering to a different terrain which continues for many miles further towards the north and northeast upto the Indus Suture or MMT. Similar observations can also be

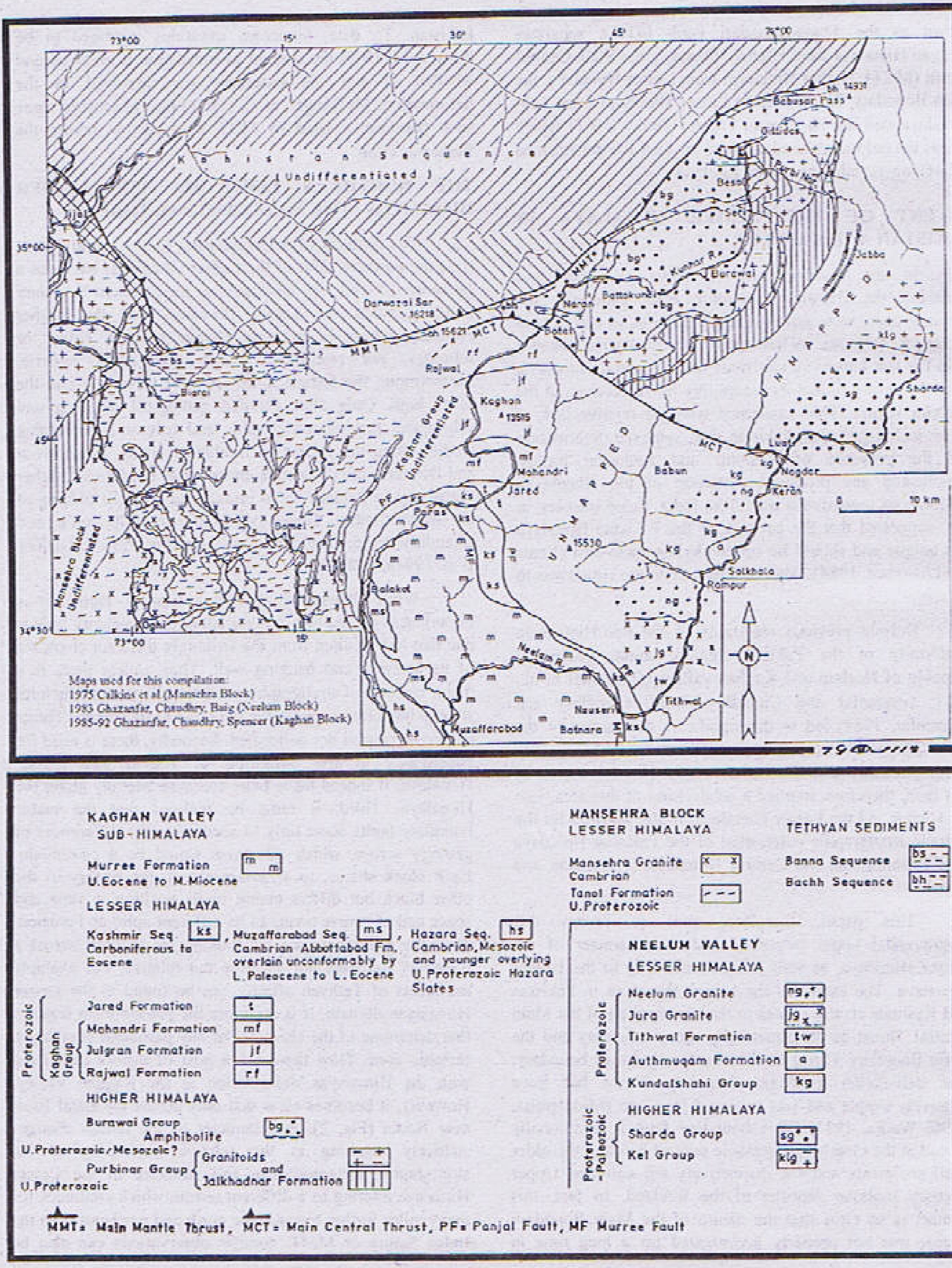
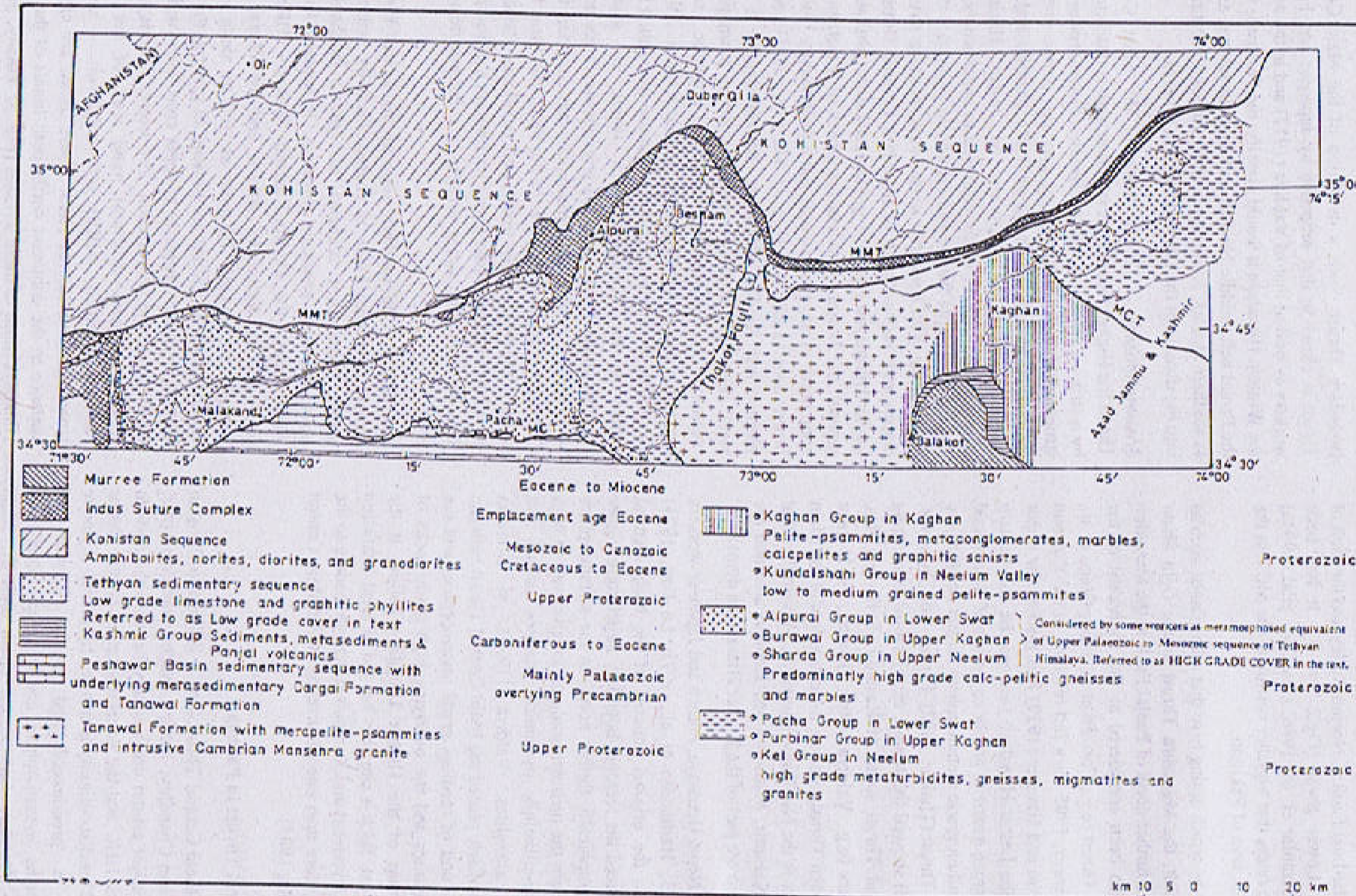


Fig.2. Position of MCT in Kaghan and Neelum Valleys (Ghazanfar and Chaudhry, 1986).



Simplified from a detailed geological map by M.Nawaz Chaudhry, S. Shahid Hussain, Hamid Dawood, David A. Spencer and M. Ghazanfar

Fig.3. Geologic map of the Higher Himalaya Crystalline in the areas of Kaghan Besham and Lower Swat showing MCT in the south.

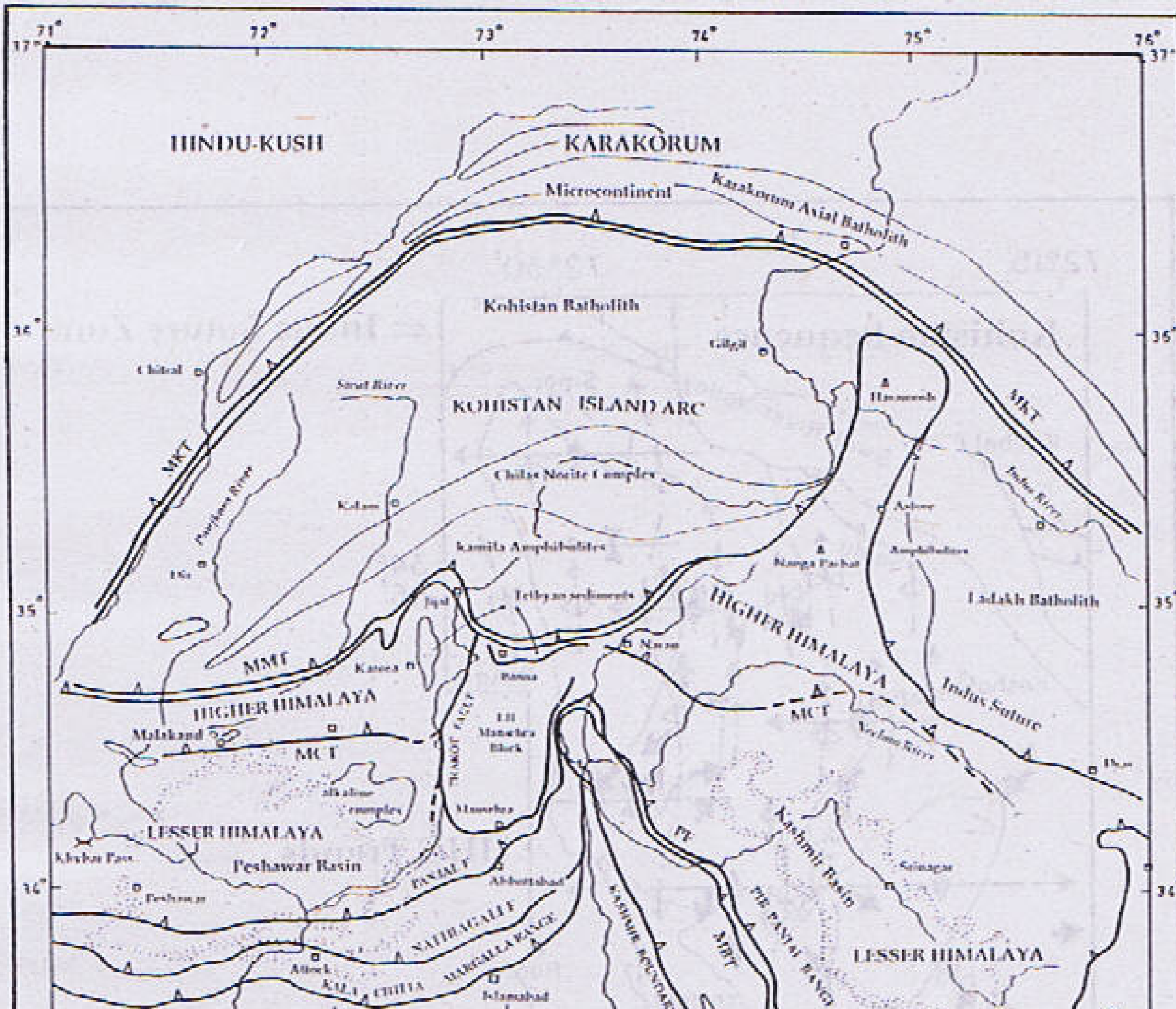


Fig.4. Location of the Main Central Thrust and subdivision of the Himalaya in Pakistan and Western Kashmir.

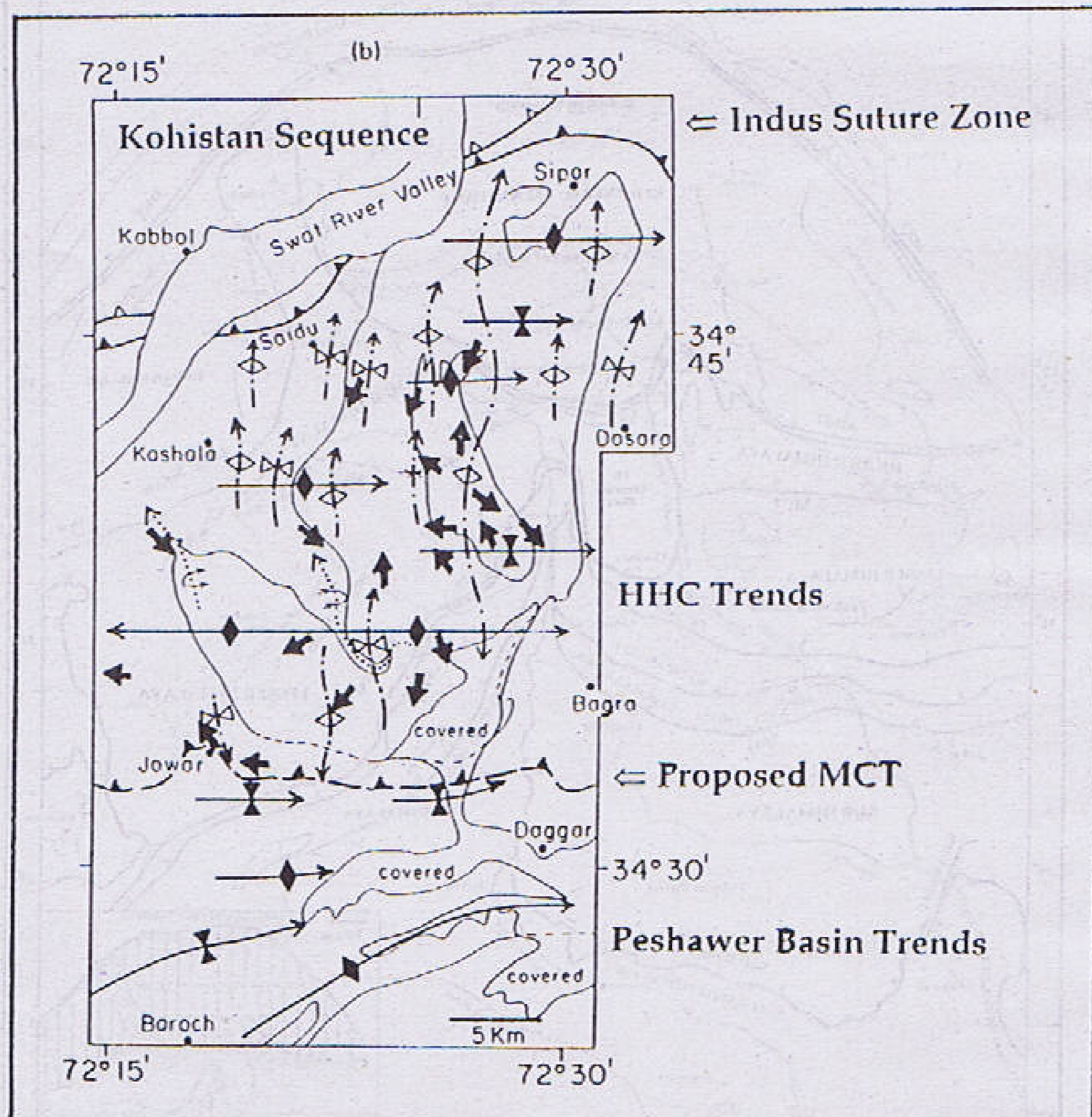


Fig.5. Structural trends in lower Swat and the Peshawar plain (DePietro, 1991). Superimposed on the Fig. are the proposed portion of MCT and subdivision into Higher and Lesser Himalaya.

Central Thrust itself is also marked by a zone, a few kilometers wide, of mylonites which can occur in granite, gneisses, or in the low grade metasediments to the south.

THE GEOLOGIC CHARACTER OF LESSER HIMALAYA IN PAKISTAN

In the classic locations of the Lesser Himalaya (in Kumaun and Nepal), the stratigraphy consists of a Cambrian sequence underlain by thick Proterozoic metasediments. There is a very limited and restricted development of Permian, Cretaceous and Eocene. (Table 1). In addition to the overlying nappes and klippen of medium-high grade metasediments and granite gneisses, a number of small Pliocene to Quaternary basins also exist. The character of the Lesser Himalaya in Pakistan is, however, in some respects different. Although the lateral continuity of the Himalayan subdivisions along its length is remarkable, it is not considered unusual that lateral variations within the tectonic units do occur. We shall look at these along - strike tectonostratigraphic variations with reference to different geographic regions referred to here as the Neelum section, the Kaghan section, the Hazara section and the Peshawar Plain. Their geology is summarized below.

Neelum Valley Section

The Lesser Himalaya of Neelum Valley occurs on the eastern limb of Hazara-Kashmir Syntaxis and extends between Nauseri and Luat (Fig. 6). The southernmost part of the section around Nauseri comprises of Triassic to Eocene sediments which overlie Carboniferous to Permian volcanics and metasediments. This sequence is more or less the same that is exposed south of the Kashmir Valley in the Pir Panjal Range as also in the valley itself where the stratigraphic column extends downwards and where it is overlain by the Plio-Pleistocene Karewas, now uplifted. In the Pir Panjal, this sequence was called the Autochthonous and Parautochthonous Folded Belt by Wadia (1931). Further northeast in the Neelum Valley for some 50 Km between Tithwal and Luat, a long section of greenschist facies metasediments intruded by major granitoid bodies is found. The older porphyritic Jura Granite intrudes the southern part of this section and the younger non-porphyritic Neelum Granite at Keran further north. The Jura Granite is considered correlatable with the Cambrian Mansehra Granite (Schouppe et al. 1994), whilst the fresher and younger Neelum Granites may be homotaxial with the Carboniferous granite bodies like the Malakand Granite west of Indus near the Peshawar Plain Alkaline Complex.

The country rock is characterized by a meta-pelitic - psammite sequence which increases in metamorphic grade towards the higher structural levels in the northeast towards Luat where garnet grade greenschist facies rocks are abruptly truncated by the Higher Himalaya Crystallines across the Main Central Thrust. These Lesser Himalayan metasediments in the Neelum Valley may be termed as the Kundalshahi Group and correlated with the Tanawal Formation of Mansehra-Tarbela area (Ghazanfar et al., 1983). At Authmuqam in the Neelum Valley this sequence is overlain by a still lower grade slate sequence, the Dogra slates of Kashmir. In summary the Lesser Himalaya of Neelum Valley in Western Kashmir comprises a narrow sedimentary zone, the Autochthonous Folded Belt of Wadia (1931) in the south and a much larger Proterozoic to Eo-Cambrian metasedimentary belt intruded by granitoids to the north between Tithwal and Luat. This is shown in Table 2.

More recently Schouppe et.al. (1994) and Schouppe (1995) mapped the entire Neelum Valley section between Tithwal and Tarli Domel. Their colour map is reproduced as Fig. 7. Their tectonic interpretation of various units is incorporated in black and white in the legend.

Kaghan Valley Section

The Kaghan Valley occurs to the northwest of Neelum Valley. The section is similar to that in the Neelum Valley, in so far as there is the autochthonous sedimentary zone in the south and a much wider metamorphic zone to the north. In fact, the narrow sedimentary belt near Paras (Fig. 8) is simply a continuation of the so-called Carboniferous to Eocene Kashmir sequence from the Neelum Valley. The metamorphic zone in Kaghan Valley, which follows north across the Malkandi Fault, however shows a completely different facies from that in Neelum Valley. In Kaghan after a short, pelite-psammite (possible extension of Kundalshahi Group from Neelum Valley) at Jared, the metamorphic zone extends between Mahandri and Batal (near Naran) and has been called the Kaghan Group (Ghazanfar and Chaudhry, 1985; Chaudhry and Ghazanfar, 1987). The Kaghan Group consists of calc-pelites, marbles, quartzites and meta-conglomerates with pelitic and graphitic horizons (Fig. 9). An interesting feature of the stratigraphy of this zone at Kaghan is the presence of gypsum in the Julgran Formation close to the small town of Kaghan. The lithology of the Kaghan Group, occurring south of the Main Central Thrust in Kaghan, is in sharp contrast to the pelite-psammite Kundalshahi group which lies below the Main Central Thrust in Neelum Valley. It appears that the Kundalshahi Group is more or less truncated northwestwards, close to the apical part of Hazara-Kashmir Syntaxis in the Kaghan Valley. However, it possibly reappears on the western limb of the syntaxis in the Mansehra area as the Tanawal Formation. Likewise, the calcareous Kaghan Group is truncated both in the east (Mansehra area) and to the west of Hazara-Kashmir Syntaxis (Neelum valley). The stratigraphic sequence of Lesser Himalaya in Middle Kaghan Valley is given in Table 3.

Table 1.
Stratigraphic Sequence of the Lesser Himalaya (from Thakur, 1992).

Age	Stratigraphic Unit	Thickness	Lithology	Environment of Deposition
Cenozoic	Dharamsala/Siwalik	7000m		Deltaic Lagoonal/continental
-----MBT-----				
Lower Eocene	Subathu,	500m		Shallow marine Lower Eocene Subathu Transgression fairly extensive in Lesser Himalaya
-----Unconformity-----				
Upper Cretaceous	Shell Limestoe			Shallow marine
-----Unconformity-----				
Lower Permian	Boulder slate (rarely exposed)			Turbidite
-----Unconformity-----				
Lower Cambrian	Tal	200m	Lower Tal black shale deposits	Tidal flat, protected lagoon and embayments
Early Cambrian	Krol	950m	Carbonate	
Vendian	Blaini			Glaciomarine
-----Unconformity-----				
Upper Riphean	Jaunsar (Simla)	4000m	Platform Cambrian sediments of Deoban-Shali followed by predominantly clastic sediments of Simla and Jaunsar groups	Coastal sand bar-shale complex prograding muddy delta
Upper-Middle Riphean U/Pb dt on Galena, 967 Ma	Deoban (calc zone of Tejam, Shali)	3300m	Purple clastics in Lower part and platform Met Carbonates in upper. Algal and salt beds	Subtidal to lower intertidal
-----Unconformity-----				
Lower Riphean	Damta (Rautgara, Flysch and Chakrata)	2200m	Shaly turbidites	Distal flysch
-----Unconformity-----				
2510 Ma Proterozoic	Sudernagar - Rampur, Kishtwar, Berinag, Garhwal) including Mandi-Darla volcanics	1200m	Dominantly clastic sediments with penecontemporaneous flows	Rift sedimentation with penecontemporaneous volcanism
-----Unconformity-----				
(Basement for Lesser Himalaya)				
Lower Proterozoic 1800-2000Ma dated gneisses and	Chail		Phyllite, quartzite, basics and mylonite gneiss with Lower Palaeozoic granites	
500 Ma dated granites	Jutogh and Vaikrita		Gneisses, calcsilicate quartzite deformed granites and basic dykes	

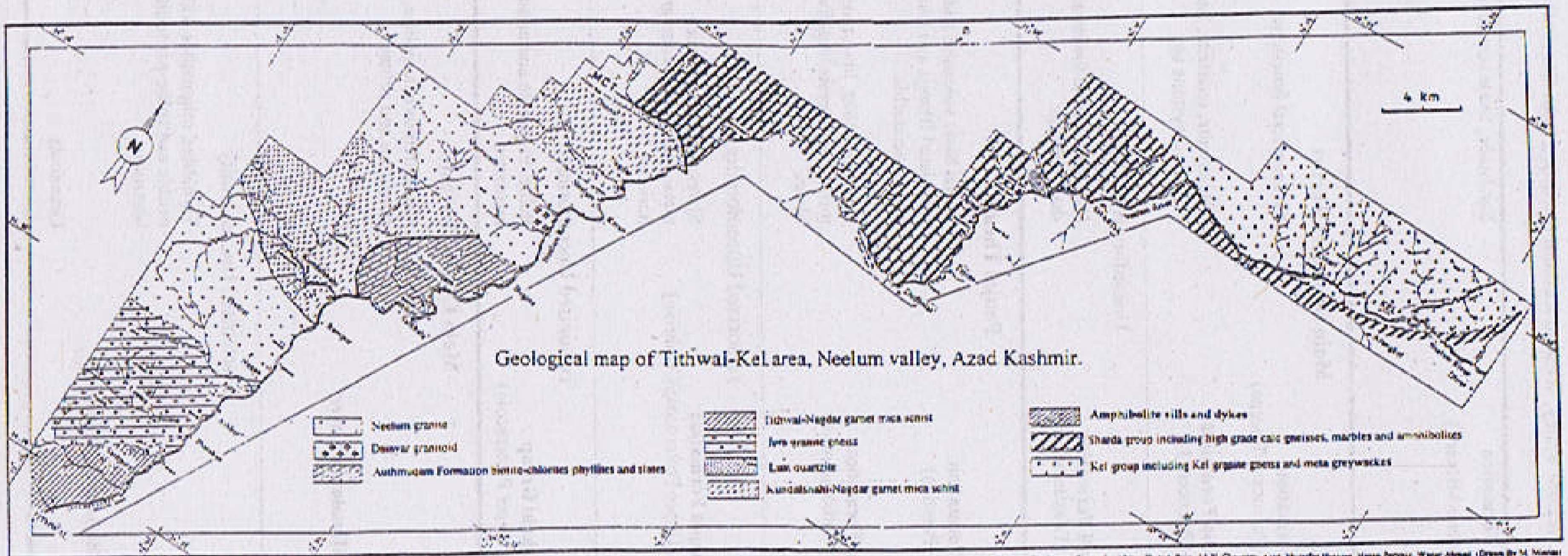


Fig.6. Geological segment of Neelum Valley between Tithwal and Kel.

Table 2.
Stratigraphic sequence in Neelum Valley, Western Kashmir (modified from Ghazanfar et al., 1983).

Sub Himalaya		**Murree Formation** (Mid Eocene-Miocene)	Sandstone, Shale sequence	Unmetamorphosed
Lesser Himalaya	Lesser Himalayan Sedimentary Zone	**Main Boundary Thrust**		Lower Greenschist Facies Chlorite Grade
		Paras Formation (Paleocene/Eocene)	Foraminiferal limestone	
		Rosachcha Formation (Paleocene)	Calc-arenite, quartzite, lateritic/ pisolitic claystone etc.	
		Unconformity		
		Malkandi Formation (Trias/Jurassic)	Dark grey oolitic limestone with shale partings	
	Lesser Himalayan Metamorphic Zone	**Panjal Thrust**		Middle-Upper Greenschist Facies Biotite-Garnet Grade
		Panjal Formation (Permian)	Panjal basic volcanics and associated Bhunja and Ling bands of limestone/marble	
		Chushal Formation (Carboniferous)	Graphitic schist, limestone/marble, metaconglomerate, Agglomeratic Slates	
		Tectonised Unconformity		
		Authmuqan Formation (Upper Proterozoic/Cambrian)	Slates, phyllites, minor metaconglomerates and graphitic horizons	
		Tectonised Unconformity		
		Kundalshahi Group (Upper Proterozoic)	Pelite, Psammite and minor quartzites	
Higher Himalaya	Sharda Group (Upper Proterozoic or U.Palaeozoic/L.Mesozoic)	**Main Central Thrust**		Upper Amphibolite to Eclogite Facies Kyanite-Sillimanite Grade
		Higher Himalayan Cover	Garnetiferous calc-pelites, marbles, dolomites and pelites	
		Tectonised Unconformity		
	Kel Group (Proterozoic or L.Paleozoic)	**Higher Himalayan Basement**	Turbidites, migmatites with minor marble and pelite-psammite horizons	
			Granitoids	

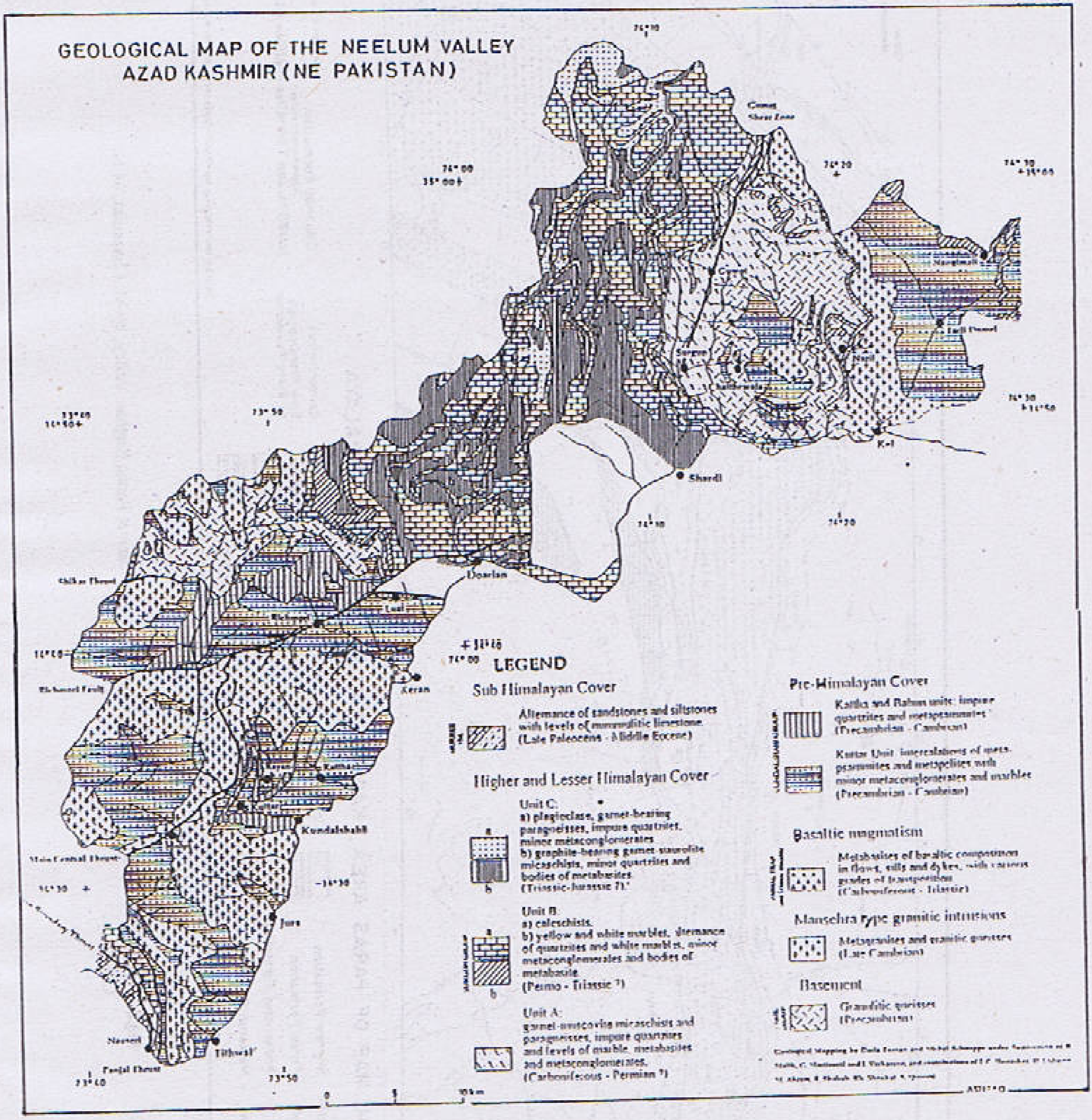


Fig.7. Geological map of Neelum Valley (Schouppe et al., 1994).

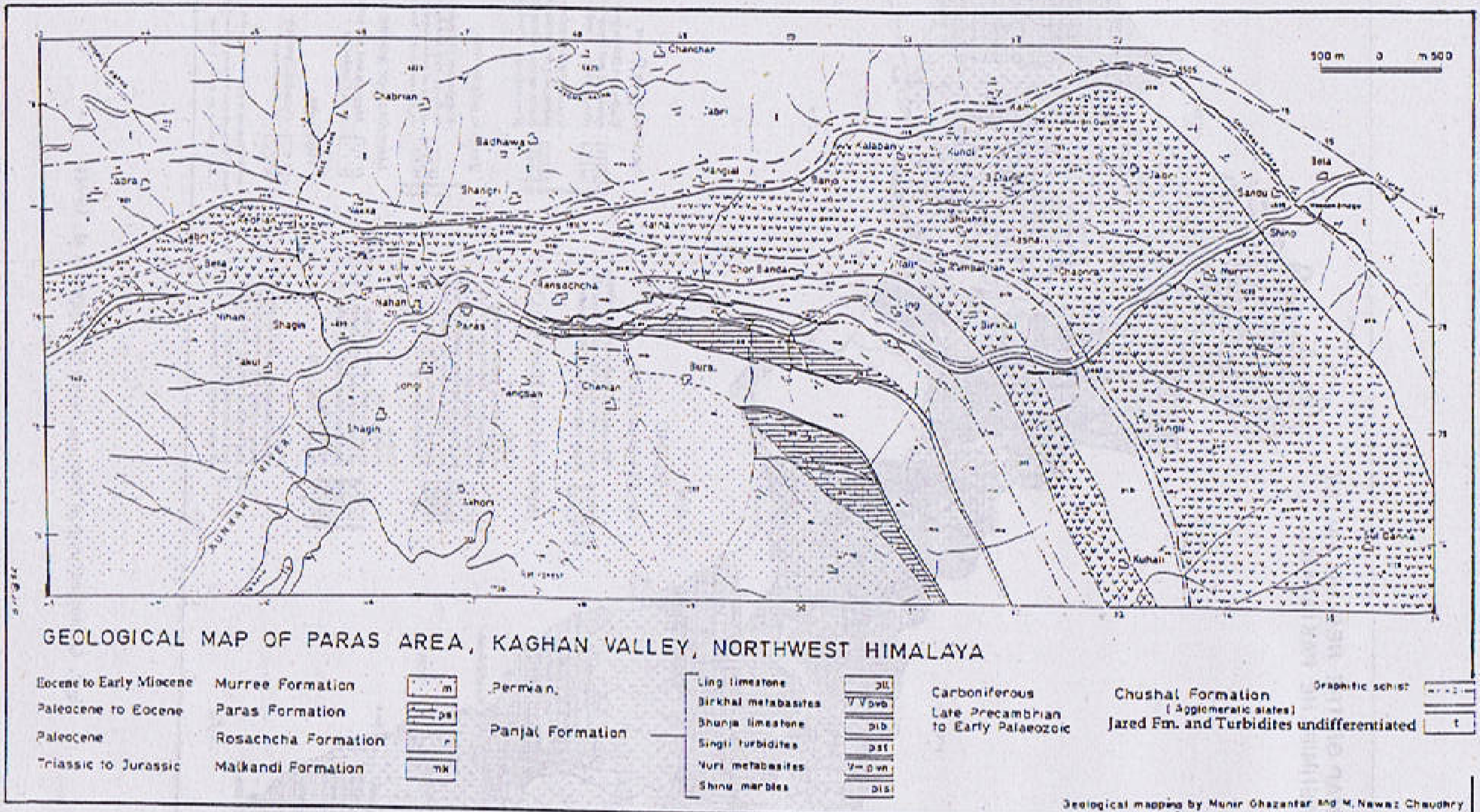


Fig.8. Geological map of the Lesser Himalayan sedimentary zone at Paras, Kaghan Valley, by M. Chazanfar, M.N. Chaudhry.

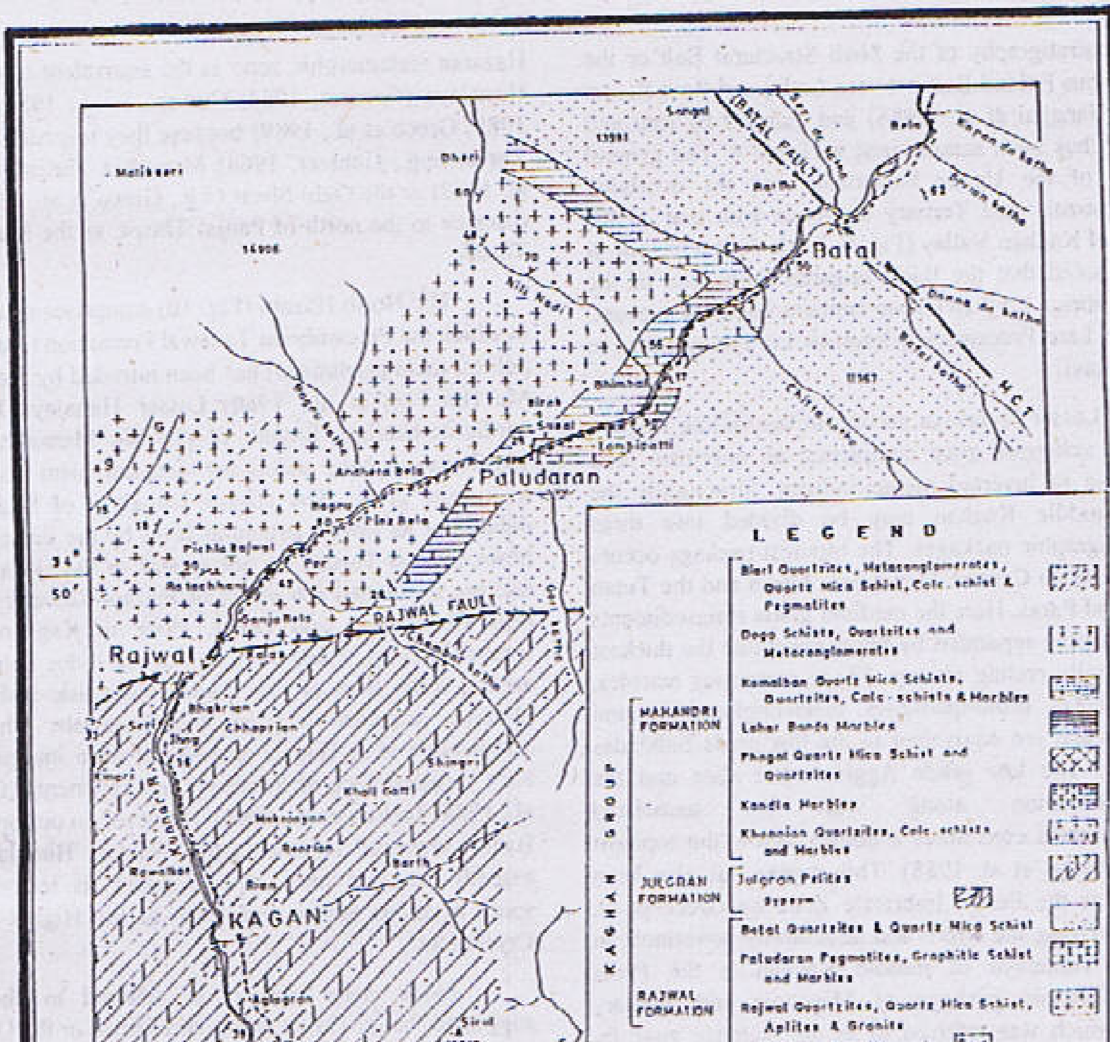


Fig.9. Geological map of the Lesser Himalayan metamorphic zone in middle Kaghan valley (From Ghazanfar and Chaudhry, 1985).

The stratigraphy of the Shali Structural Belt or the Autochthonous Folded Belt between Satluj and Ravi Rivers studied by Jangpai et al. (1986) and mapped by Rao and Rao (1979) has been summarized in Table 4. The general correlation of the Upper Palaeozoic and the overlying limited Mesozoic and Tertiary sequence with that of the Paras area of Kaghan Valley (Fig. 9, Table 3) is apparent. It should be noted that the thick Julgaran Formation of the Late Precambrian Kaghan Group contains bands of gypsum, as does the Late Precambrian Ramban Formation between Satluj and Ravi.

The Lesser Himalaya section in the middle Kaghan Valley is a schuppen zone comprising an imbricate fault stack leading to inverted metamorphism. Structurally the rocks of middle Kaghan may be divided into three tectonostratigraphic packages. The topmost package occurs between the Main Central Thrust near Naran and the Tutan Fault north of Paras. Here the medium grade metasediments of Kaghan Group separated by faults constitute the thickest slab structurally resting on top. These comprises marbles, meta-calc-pelites, ortho-quartzites, metaconglomerates and meta-pelites and are equivalent to the low grade Salkhalas of Kashmir. The low grade Agglomeratic slate and the Panjal Formation along with the associated limestone/marbles constitutes a duplex below the topmost package (Bossart et al. 1988). This duplex has also been referred to as the Panjal Imbricate Zone by Greco et al. (1989). Overlying the MBT and structurally lowermost in the Lesser Himalaya of middle Kaghan is the Paras tectonostratigraphic package of Mesozoic and Tertiary sediments which was referred to as the melange zone by Bossart et al. (1988).

Hazara Section

The Hazara section comprise the areas of Batgram, Mansehra, Abbottabad, Haripur and Murree. Stratigraphically, these areas are the most studied sections (Middlemiss, 1896; Latif, 1970; Calkins et al., 1975; Ghazanfar et al., 1990), as well as being the most accessible. This section comprises of two clearly defined zones separated by the Panjal Thrust, the sedimentary belt of southern Hazara (Table 5) between Islamabad and Abbottabad in the north and the metamorphic belt of northern Hazara (commonly known as the Mansehra area) between Abbottabad in the south and Banna/Biari near the Indus Suture in the north. The South Hazara comprises of an interrupted but well developed Phanerozoic sedimentary sequence unconformably overlying a low grade slate basement. Sedimentary belt of Hazara comprises, the eastern part of the Attock Hazara Fold and Thrust Belt. Laterally the northern Hazara extends between HKS, the Hazara Kashmir Syntaxis, on the east and the River Indus in the west. Many workers have tended to regard this northern Hazaran metamorphic zone as the equivalent of the Higher Himalaya (Gansser, 1964; Coward et al., 1988, Windley, 1988; Greco et al., 1989) because they regarded the Panjal Thrust (e.g., Gansser, 1964) Mansehra Thrust (Coward et al. 1988) or the Oghi Shear (e.g., Greco et al., 1989), some distance to the north of Panjal Thrust, as the Main Central Thrust.

The North Hazara (Fig. 10) comprises of a sequence in which the Precambrian Tanawal Formation (mainly meta-pelites, meta-psammites) has been intruded by the 516 ± 16 Ma (Le Fort et al., 1980) Lesser Himalaya two mica, cordierite-bearing, S-type, porphyritic Mansehra Granite. The Tanawals have undergone metamorphism from chlorite to kyanite grade. The Higher Himalaya of Kaghan, now defined at its lowest structural level by the demarcation of Main Central Thrust, do not appear in the Hazara section and are attenuated (an effect of Hazara-Kashmir Syntaxis) near Chhalayyan and Dheri, close to Kaghan-Kohistan watershed (Figs. 2 and 4). South of the Indus Suture in this area, a thick slice of low grade calc-pelitic and graphitic phyllitic sequence overlies the Tanawals. This Banna sedimentary slice (Fig. 2 and 4) has been interpreted as a back thrusted slice of South Hazara sediments (Coward et al., 1988; Treloar et al., 1989). However, in our opinion, the Banna sequence represents the Tethyan Himalaya which extends eastward into Upper Kaghan. as tectonic slices, south of Indus Suture and north of the Higher Himalaya Crystalline.

Since many workers as referred to above have suggested Panjal Thrust, Mansehra Thrust or the Oghi Shear Zone as coeval to MCT they imply that northern Hazara is part of the HHC. However, the Lesser Himalayan character of northern Hazara section is supported by the following observations.

1. The Tanawals of Mansehra are correlatable to the Chails of the Kumaun Lesser Himalaya (Thakur 1992) and extend into Kashmir, as well as below the Peshawar Plain (Pogue et al. 1992).

2. Not only are the Tanawals similar in lithology to Hazara slates, a Lesser Himalayan formation, but also a gradation between the slate and Tanawal sequences can be observed between Abbottabad and Mansehra.

3. The Tanawals are intruded by the 516 ± 16 Ma (LeFort et al., 1980)Mansehra Granite, a characteristic similar to the 500 Ma granites of the Lesser Himalaya, south of Kashmir and Chamba basins and further east into Nepal (Kaphle, 1992).

4. The North Hazara is predominantly a low grade greenschist facies terrain with high grade metamorphism affecting only a subordinate northern part. The Higher Himalaya Crystalline on the other hand are uniformly

Table 3.
Stratigraphic sequence in Kaghan Valley (modified from Ghazanfar and Chaudhry, 1985; Chaudhry et al., 1994b).

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
Lesser Himalaya	Lesser Himalayan Sedimentary Zone		Rosachcha Formation (Paleocene)	Calc-arenite, quartzite, lateritic/pisolitic claystone etc.	Unmetamorphosed
				Unconformity	
Lesser Himalaya	Lesser Himalayan Sedimentary Zone		**Malkandi limestone** (Trias/Jurassic)	Dark grey oolitic limestone with shale partings.	Unmetamorphosed
				Panjal Thrust	
Lesser Himalaya	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
Lesser Himalaya	Lesser Himalayan Metamorphic Zone		**Chushal Formation** (Carboniferous)	Graphitic schist, limestone/marble, metaconglomerate.	Lower Greenschist Facies Chlorite Grade
				Unconformity	
Lesser Himalaya	Lesser Himalayan Metamorphic Zone		**Jared Formation**	Jared Quartzite and quartz mica Schist.	Lower Greenschist Facies Chlorite Grade
				Jared Thrust	
Lesser Himalaya	Lesser Himalayan Metamorphic Zone	Kaghan Group (Late-Proterozoic)	**Mahandri Formation**	Biari quartzites, metaconglomerate, quartz mica schists, calc-schist and pegmatites. 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 Khanian quartzites, calc-schists and marbles.	Middle Greenschist Facies Biotite Grade
				Khanian Thrust	
Lesser Himalaya	Lesser Himalayan Metamorphic Zone	Kaghan Group (Late-Proterozoic)	**Julgran Formation**	Pelites with subordinate graphitic schist, marble, gypsum.	Middle-Upper Greenschist Facies Garnet Grade
				Rajwal Thrust	
Lesser Himalaya	Lesser Himalayan Metamorphic Zone	Kaghan Group (Late-Proterozoic)	**Rajwal Formation**	Rajwal quartzites, quartz mica schists/gneisses, pegmatites, aplites and granite gneiss. Paludaran graphitic schist. Batal quartzites and quartz mica schist/gneiss.	Middle-Upper Greenschist Facies Garnet Grade
				Main Central Thrust	
Higher Himalaya	Burawai Group (Upper-Proterozoic or U Paleozoic/L Mesozoic)		**Higher Himalayan Cover**	Marbles, dolomites. Pelites. Garnetiferous calc-pelites. Amphibolites (eclogites) with intercalated marbles.	Upper Amphibolite to Eclogite Facies Kyanite-Sillimanite Grade
				Tectonised Unconformity	
Higher Himalaya	Purbi Na Group (Proterozoic to L Paleozoic)		**Higher Himalayan Basement**	Turbidites, migmatites with minor marble and pelite-psammite horizons. Granitoids.	Upper Amphibolite to Eclogite Facies Kyanite-Sillimanite Grade

Table 4.
General Stratigraphy of the 'Autochthonous Folded Belt' (Jangpangi et al., 1986).

Formation	Member	Lithology	Fauna/Flora	Age
	Variegated shale	Purple-red and green shale and siltstone		
Rajpur				Paleocene to Lower Eocene
	Nummulitic limestone	Hard massive grey to dark grey to sooty black limestone and calcareous shale	Nummulites sp. Assilina sp. Operculina sp	
		---------- Unconformity ----------		
		Light to dark grey shale and slate		
Poonch Mandi		Gritty limestone, silty shale and yellowish weathered buff coloured limestone	Paleonopsis sp Palaeomacula sp Trigonia sp	Jurassic
		Grey sandy limestone, fine to medium grained quartzite	Rhynchonella sp	Triassic
		--------------------		
		Dark grey ferruginous shale, slate, grey to buff coloured limestone	Fenestella sp. Polypora sp and bivalves	
Zewan		Coral limestone, green and purple coloured tuffaceous shale with bands of quartzite	Productus sp. Waagenophyllum sp bivalves	Upper Permian
		Dark grey to cream coloured semi-crystalline crinoidal limestone	Protoretepora, Fenestella sp	
			Crinoidal stems, cephalopods, gastropods	
		---------- Unconformity ----------		
Panjal Volcanics		Green massive amygdaloidal to vesicular andesitic flows and ash beds		Lower Permian
		---------- Unconformity ----------		
Agglomeratic Slate		Greyish white quartzite, grits and sandstone		? Upper Carboniferous to
		Grey to dark grey diamictite with dense to sparsely distributed clasts		Lower Permian
		---------- Angular Unconformity ----------		
Sincha		Light grey to grey sandy dolomite, pink and grey limestone, lenticular black chert and gypsum 350 m	Primitive microbiota	Upper Precambrian
		--------------------		
	C	Grey-green shale/slate with bands of quartzite 750 m		
		Purple and green shale/slate, micaceous siltstone 200 m		
Bhimdasa	B	Grey pebbly shale/slate (diamictite) and slate with pebble to boulder-size clasts 230 m		
	A			
				Upper Precambrian
		---------- Unconformity ----------		
Ramban		Grey to dark grey shale/slate		Upper Precambrian
		Grey quartzite with shale/slate		
		Bluish grey phyllitic slate with bands of gypsum 1600 m		

Baila		Thin bedded laminate limestone, nodular limestone with shale/slate 290 m		Upper Precambrian
		--------------------		
Gamir		White to bluish grey quartzite, purple and green shale/slate with occasional thin bands of limestone, base not exposed 580 m		

Table 5.
Stratigraphic Sequence in South Hazara (Latif, 1970, Shah, 1977).

Early Miocene	Murree Formation	Grey and reddish sandstone and shales
Middle Eocene	Kuldana Formation	Maroon to variecoloured shales and marl
Early to Middle Eocene	Chorgali Formation	Thinly bedded limestone and marl
Early Eocene	Margala Hill Formation	Nodular foraminiferal grey limestone
Late Paleocene	Patala Formation	Greenish grey/Khaki shales with limestone beds
Middle Paleocene	Lockhart Formation	Nodular foraminiferal grey limestone
Early Paleocene	Hangu Formation	Sandstone, claystone, laterite
	---------------------------Disconformity---------------------------	
Late Cretaceous	Kawagarh Formation	Fine grained light grey limestone
Early Cretaceous	Lumshiwal Formation	Grey to brownish coarse sandstone
Late Jurassic to Early Cretaceous	Chichali Formation	Dark grey shales with sandstone beds
	---------------------------Disconformity---------------------------	
Middle Jurassic	Samana Suk Formation	Limestone with dolomitic patches, and oolites
Early Jurassic	Datta Formation	Sandstone, quartzite, microconglomerates
	---------------------------Disconformity---------------------------	
Early Cambrian	Hazira Formation/Galdanian	Calcareous siltstones and shales/Quartzites
Cambrian	Abbottabad Formation	Dolomites with sandstone, shale in lower part and boulder bed at base
	---------------------------Unconformity---------------------------	
Late Precambrian	Hazara Formation	Slates, pelites sandstones and quartzites with a horizon of gypsum and two algal limestone bands
Late Precambrian	Tanawal Formation	Quartzite and quartz mica schists with a 500 Ma intruded granite

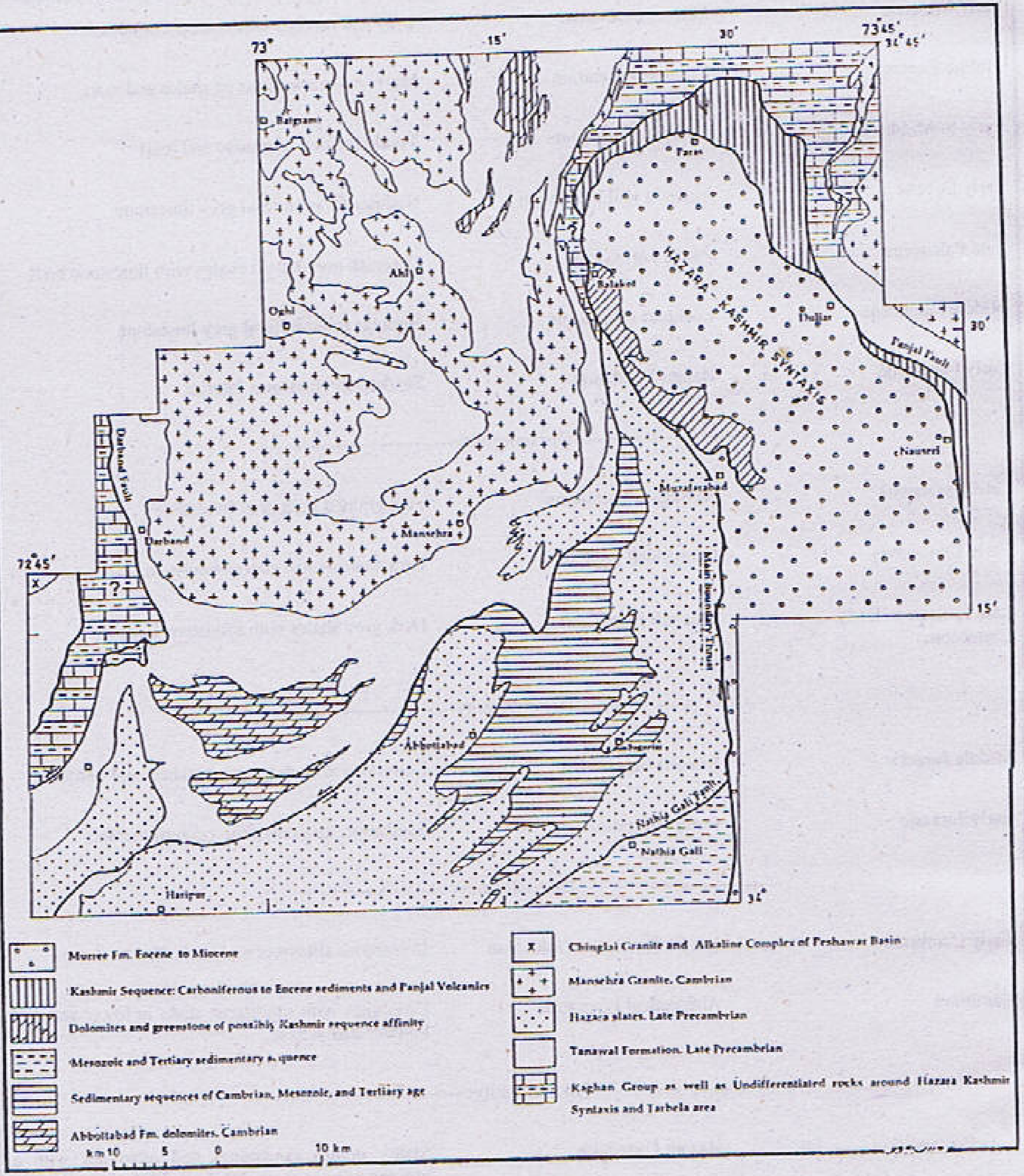


Fig.10. Simplified geological map of Lesser Himalaya metamorphic zone in the Mansehra area, Northern Hazara (After Calkins et al., 1975).

metamorphosed in the upper amphibolite facies throughout NE Pakistan (Chaudhry and Ghazanfar, 1987; Chaudhry et al. 1994) except around Besal in Upper Kaghan where the grade rises to eclogite facies (Spencer et al. 1990).

5. The stratigraphy, metamorphism and structure in Northern Hazara is markedly different from that of the (Higher Himalaya) in Nanga Parbat, Kaghan or Swat. There is also evidence to suggest that the metamorphism in the Higher Himalaya of Upper Kaghan and Swat took place under different condition than that in Northern Hazara. Treloar et al. (1989) calculated temperatures of 600-650° C with pressures of 7 to 11 Kbars in the Higher Himalaya Alpurai schists of Lower Swat. Dipietro and Lawrence (1991) give main phase of metamorphism (of the Higher Himalaya) from Lower Swat at 600-700° C at 9-11 kbars. However, the conditions of metamorphism in the adjacent Hazara region were markedly different from the above mentioned estimates for the Higher Himalaya. While the temperature showed an increase from 430° C at garnet isograd to 650-700° C in the sillimanite-K-feldspar zone, the pressure-temperature estimates for the garnet sillimanite zones show metamorphic pressures of 5-9 kbar in the staurolite zone to kyanite-sillimanite in the kyanite-sillimanite zones. Thus metamorphism in the Hazara region was at significantly lower pressures compared to that for the Higher Himalaya (Treloar et al., 1989).

6. Hornfelsing is well developed on the southern margin of the Cambrian Mansehra Granite and the discordant relationship with the country rock, evident at places, indicates a meso-zone intrusion in contrast with the keta-zone relationship of the Higher Himalaya older granites (Chaudhry and Ghazanfar, 1987).

7. The Mansehra area of Northern Hazara is characterized by the typical inverted matamorphism seen elsewhere below the MCT in the LH of India and Napal.

The sedimentary belt of southern Hazara is apparently an extension of the Pir Panjal belt from Kashmir and Kaghan over the Hazara-Kashmir Syntaxis, but represents a different basin. This is invoked due to the presence of a wider and somewhat different Phanerozoic sequence. Not only is no volcanism reported in Hazara but the middle and the upper Palaeozoic are absent here altogether, in marked contrast to the middle and upper Palaeozoic sedimentary and volcano-sedimentary sequence of Kashmir to the east.

Structurally, South Hazara comprises of two synclinorial complexes, Dor Depression and the Harno Trough (Latif et.al. 1995), on two sides of the the Nathia Gali Thrust (Fig. 11). Each of these structures comprises of numerous anticlines and synclines, in the cover. The folds show opposing vergence on two sides of the major anticlinal structures in which basement Hazara slates are involved. Structurally upwards the vergence is generally southeast. In general the folds are tight to isoclinal and high angle imbricate strike faults are ubiquitous especially associated with the anticlines. The earliest deformation phase in South Hazara is Precambrian, during which the Hazara slates were deformed and metamorphosed. The second deformation phase relate to the main phase of Himalayan folding and imbrication of the Phanerozoic cover ending in relaxation. The final phase of deformation relates to the formation of the Hazara-Kashmir Syntaxis, which resulted in a fold interference pattern (doubly plunging folds and cross folds with NW-SE axes).

Across the Panjal Thrust the metamorphic zone of the Hazara area comprises of the region west of Hazara-Kashmir Syntaxis upto the River Indus (i.e., the areas of Mansehra, Shinkiari, Batgram, Oghi and Tarbela). Coward et al. (1988) and Treloar et al. (1989) have described three main phases of deformation for the area of Northern Hazara. According to them, the main metamorphism took place after the thrust stack thickening that followed the initial collision at 50-55 Ma (Patriat and Achache, 1984). Later the metamorphosed middle crust was imbricated, leading to an inverted metamorphic sequence. Finally, under a changed direction of stress, north-south folds were transposed. Northern Hazara, on the other hand, has also yielded geological evidence of Pre-Himalayan metamorphism (Chaudhry, 1964; Baig et al., 1987, 1988; 1989; Williams et al., 1988; Chaudhry et al., 1989). This evidence has been especially preserved in the low grade metasediments of the Lesser Himalaya and in the thermal aureole of the Cambrian Mansehra Granite in the Northern Hazara area. The problem of metamorphism, and the relationship between Tanawal Formation (the main country rock of the Northern Hazara area) and the Hazara slates, are discussed in a separate section below.

Peshawar Plain Section

The Lesser Himalaya, south of the Main Central Thrust at Malakand (Chaudhry et al. 1994a) continue through Nowshera down to the Main Boundary Thrust south of Kalachitta range. The Lesser Himalaya of Western Kashmir-Kaghan section, thus, after telescoping around the apex of the Hazara-Kashmir Syntaxis and passing through Mansehra area expands expands to a full width in the Peshawar Basin areas (Fig. 12). The Panjal thrust (Khairabad Fault in this region) subdivides the Lesser Himalaya into a Northern Metamorphic Zone and a Southern Sedimentary Zone. The area of the Peshawar basin, overlain by a low grade metasedimentary cover, correlates with the metamorphic zone. The Attock-Cherat-Kalachitta Fold-and-Thrust Belt to the south of Peshawar basin represents the sedimentary zone of the Lesser

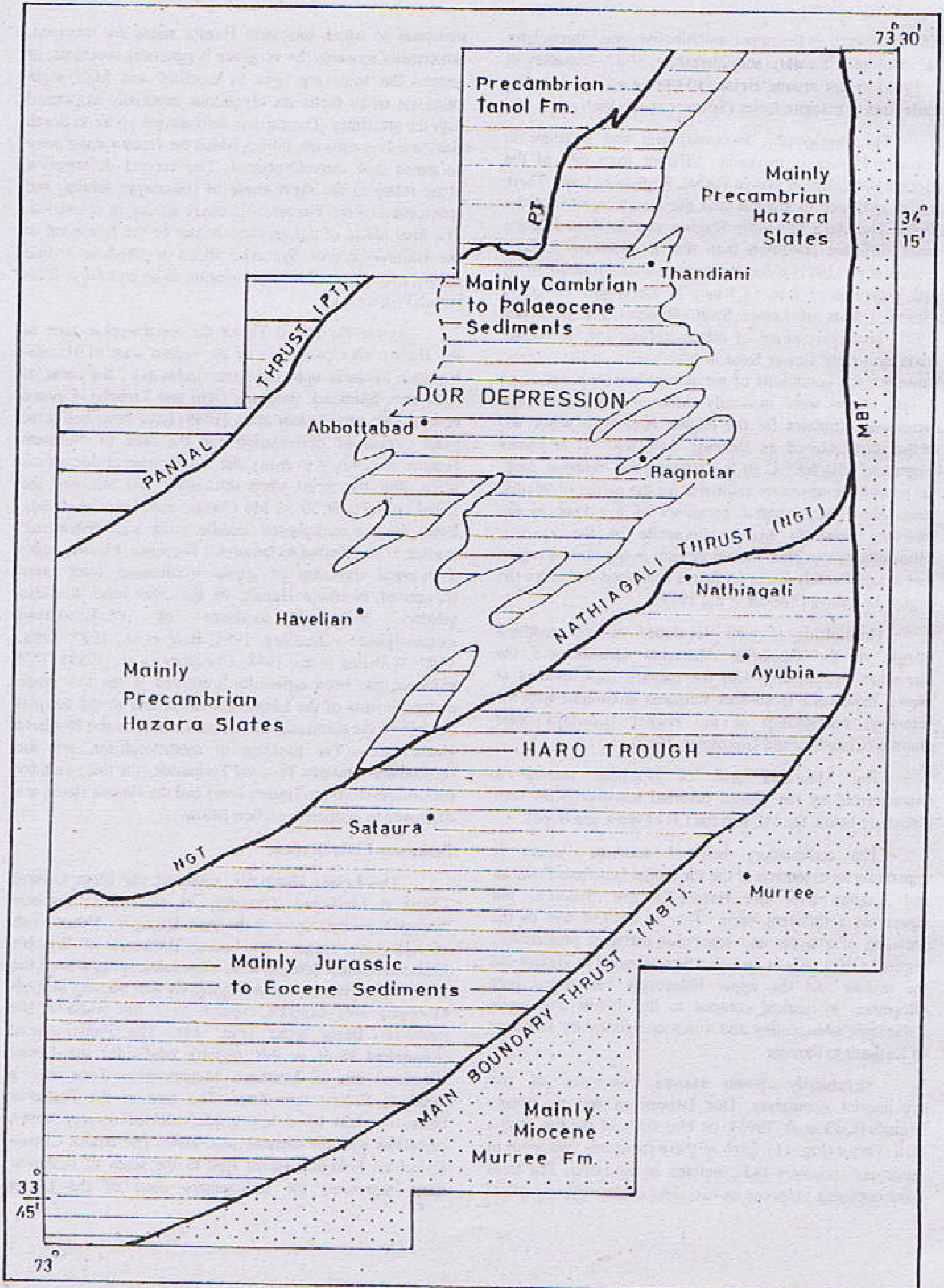


Fig.11. Sketch of the Lesser Himalaya sedimentary zone, south Hazara (after Latif, 1970; Latif et al., 1995).

Himalaya in this region. This sedimentary zone is an extension of South Hazara sedimentary belt and is comparable to the Panjal Range Authochthonous Folded Belt of Wadia (1931) or the Panjal Imbricate Zone of Greco et al. (1989) which is the southernmost part of the Lesser Himalaya in Kashmir and Kaghan.

The area between the Main Central Thrust and the Panjal Fault (Khairabad Fault) mainly comprises of the fringe ranges and the rest of the Plio-Pleistocene Peshawar basin. Numerous workers have made contributions to the stratigraphy of Peshawar basin (Martin et al. 1962, Stauffer, 1968, Burbank and Tahirkheli, 1985 Hussain et al. 1989, 1990; Pogue and Hussain 1986; Pogue et al.,1992]. Perhaps the best developed Palaeozoic sequence in Pakistan is found in the Peshawar basin. Nearly the entire low grade metasedimentary/sedimentary sequence is fossiliferous. A brief summary is given in Table 6 (after Hussain et al. 1989 and Pogue et al. 1992). The fossiliferous sequence has been intruded by the alkaline igneous rocks. These alkaline rocks can be broadly grouped into the plutonic Ambela Granite Complex and the Shewa Volcanic Complex. These complexes constitutes part of the much larger Peshawar Plain Alkaline Complex or the Koga Feldspathoidal Syenite Complex (Baloch, 1994) which actually extends westwards outside the confines of Peshawar basin with bodies occurring as far as Warsak (near Peshawar), Loe Shilman (Dir) and possibly beyond into Afghanistan. It has also been recognised that the igneous rocks of the Peshawar basin are rift related and their age is constrained between Carboniferous and Early Permian (Kempe, 1986; Le Bas, 1987).

Table-6

Stratigraphic sequence in the Peshawar Basin (after Hussain et al., 1989; Pogue et al., 1992).

Jurassic	Nikanai Ghar/Saidu Formation Tursak
Upper Triassic	Kashala Carbonates/Girarai Formation
Permian	Karapa greenschist.
Carboniferous	Jafar Kandao Formation. Shales, limestone.
Devonian	Nowshera Formation. Limestone, quartzites, sandstone, dolomites.
Silurian	Panjpir Formation. Agrillites and phyllites with crinoidal limestone.
Cambro-Ordovician	Misri Banda Quartzite.
Cambrian	Ambar Formation. Dolomite dominated carbonate sequence.
Late Proterozoic to Cambrian	Tanawal Formation. Interbedded quartzites and metapelites near Swabi >3000 m. Intruded by 516±16 Ma Mansehra Granite.
Late Proterozoic	Shekhai Formation. Quartzite overlain by a thick sequence of thin bedded to massive dolomite and arenaceous limestone and marble.
Late Proterozoic	Utch Khattak Formation. Basal conglomerate, overlain by shale and argillite.
Late Proterozoic	Shahkotbala Formation. Basal cherty limestone with shales. Gradational contact with Manki slates.
Late Proterozoic	Manki Formation over 1000 m thick. Dark low grade metapelite.
Late Proterozoic	Gandaf Formation Carbonaceous calc-phyllite, schist and carbonaceous marble with interbedded quartz schist. Correlated to Salkhala Formation.

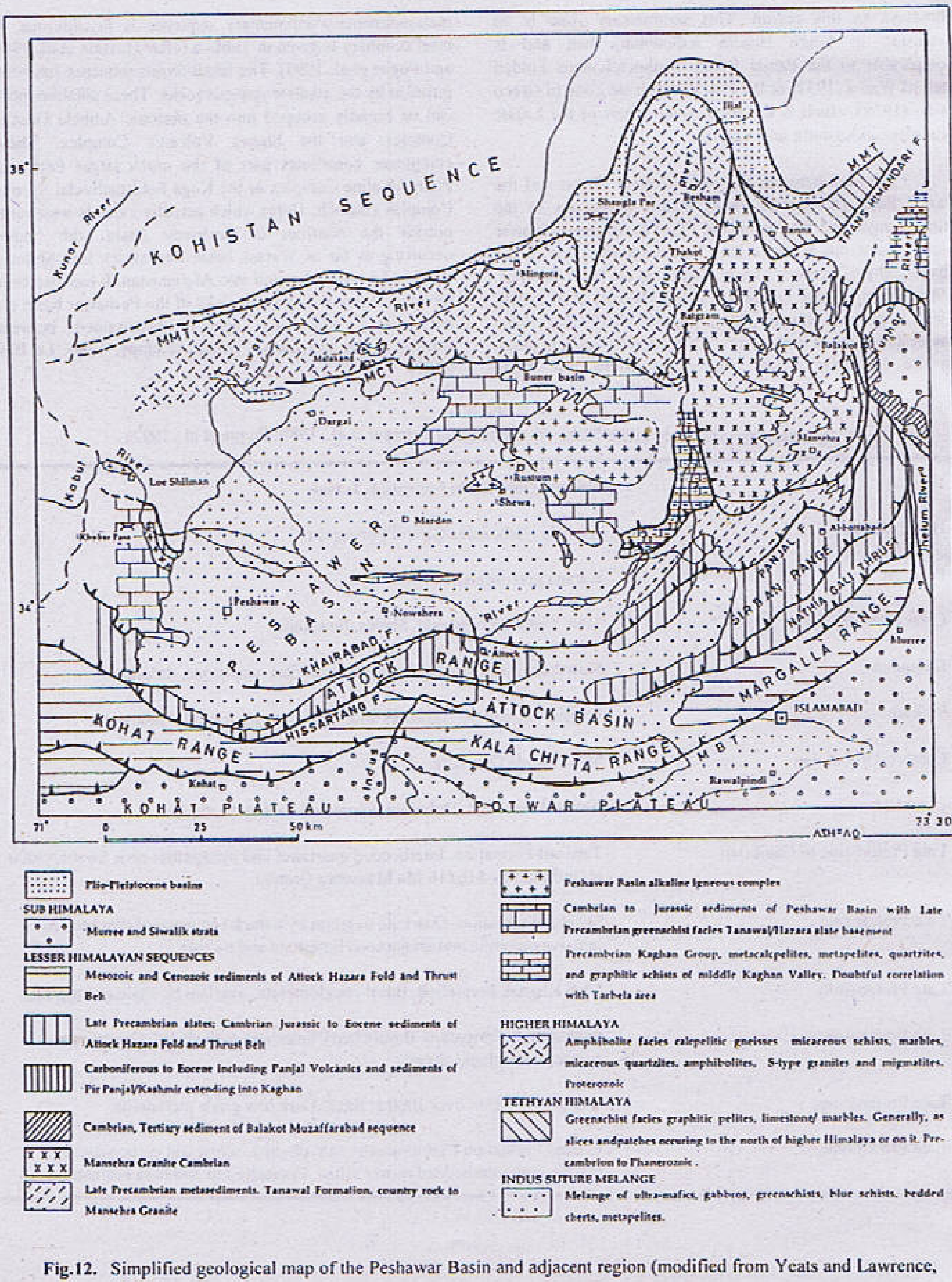


Fig.12. Simplified geological map of the Peshawar Basin and adjacent region (modified from Yeats and Lawrence, 1984).

Apart from the alkaline complex, the 516 ± 16 Ma (Le Fort et al., 1980) Mansehra Granite also extends into the Peshawar Plain to the west of River Indus. Here, however, it has been called the Chinglai Granodiorite Gneiss (Siddiqui et al., 1968). Like in Mansehra area, it intrudes the Tanawal Formation of Precambrian age, which forms the basement to Peshawar basin. The situation in the Peshawar basin section of the Lesser Himalaya of Pakistan is very different from that in Kaghan. Here, there is no schuppen zone structurally underlying the Main Central Thrust. The situation in many ways actually resembles the Kashmir basin. The Tethyan Palaeozoic-Mesozoic sequence, with generally open to tight simple folds and a lack of major thrusts, overlies a low grade Tanawal basement. The relatively low deformation of the Peshawar basin is partly a function of its distance from the Hazara-Kashmir Syntaxis and may partly be due to the presence of a decollement, like the one under Potwar Plateau further to the south where most of the strain has been taken and absorbed by the slip surface developed in the Salt Range Formation bearing rock salt. A comparison of the Peshawar basin with Kashmir basin is discussed in a separate section below.

The less deformed, mainly Palaeozoic Peshawar basin overrides the Attock-Cherat sedimentary zone along the Khairabad Thrust, the equivalent of the Panjal Thrust (Pogue et al. 1992). The Attock-Cherat sedimentary zone being the structural equivalent of southern Hazara sedimentary belt and of the Autochthonous Fold Belt of the Pir Panjal (Wadia, 1931) is an imbricate zone that comprises two major duplexes (McDougall et al., 1994). The Cherat Fault and the Hissartang Fault merge eastwards to become the equivalent of the Nathiagali Fault of southern Hazara.

DISCUSSION

Tanawal Formation

The unfossiliferous, generally low grade pelitic-psammitic Tanawal Formation, has been one of the most controversial formations of the Lesser Himalaya. Following points are worth mentioning in this regard: The original name of the Tanawal Formation was the 'Tanol' Formation, after the Tanol area. The name was given by Wynne (1879) to a sequence of metamorphosed pelite-psammites occurring mainly in the Mansehra, Oghi and Tarbela-Swabi areas. Later, the name Tanawal Formation was given by Wadia (1928) to a formation from Kashmir of Carboniferous age. Calkins et.al. (1975) renamed the Tanol Formation as Tanawal Formation to bring the name in conformity with spellings printed on topographic map. This added to the confusion as Wadia had already used this name for a a formation of Carboniferous age in Kashmir as mentioned above. Although the name Tanawal Formation is now widely used for Precambrian metasediments of Mansehra/Hazara area, the readoption of the name Tanol Formation for the same would clear much confusion. The Tanawals (Tanols) of Hazara once believed to be Carboniferous like the Tanawals of Kashmir are now known to be Precambrian.

The Tanawal (Tanol) Formation has always been considered younger than the Hazara Slate Formation since the work of Wynne (1879). Middlemiss (1896) also distinguished the Tanol Quartzites of Hazara as the lower part of his Infra-Trias Series, now known as the Abbottabad Formation. Ali (1962) endorsed the stratigraphic views of the above workers. Ali (1962) published a map of the area east and northeast of Tarbela in which he showed the Tanakki boulder bed, now dated as Cambrian, overlying the Tanawals (Tanols). The Tanawals (Tanols) themselves, with their biotite grade metamorphism, were shown to overlie the Hazara slates. The sequence established that the Tanawals (Tanols) were younger than Hazara slates. Such an order of superposition for this unfossiliferous formation, however, raises important questions. First, if Tanawal Formation of Northern Hazara is younger than Hazara slates why does it not appear between the Precambrian Hazara and the Cambrian Abbottabad formations anywhere in the Hazara trough south of the Panjal Thrust. Second, how is it that the sequence overlying the Hazara slates has been more metamorphosed while the older Hazara slates are less metamorphosed. Finally, why is the Cambrian Mansehra Granite intruding the so-called overlying Tanols but not the underlying Hazara slates?

These facts suggest that the Tanawal Formation is, in fact, older and not younger than the Hazara slates. The Tanawal and Hazara formations are, for the most part, very similar in lithology and even the metamorphism can actually be seen to gradually increase structurally upwards towards north on the Abbottabad-Mansehra road. Therefore, the lower part of Hazara slates has been interpreted as the Tanawal Formation and separated from it mainly on the basis of a higher grade of metamorphism. A Precambrian age for Tanawals of Mansehra area is no longer disputed. However, their relationship with Hazara, Manki and Attock slates is still confused. At present the practice is to regard low grade pelite psammite sequence as slates and the relatively higher grade as the Tanawals, both in northern Hazara and the Peshawar basin; and consider the relatively higher grade sequence younger than the slates. It is clear that the younger than Hazara slate stratigraphic position for the Tanawal Formation is at best doubtful and definitely needs further investigation.

Panjal Volcanics

The Panjal volcanics are an important and controversial unit of the area herein classified as the Lesser

Himalaya. The Panjal Formation consisting of basic lavas and associated metasediments, occurs as a distinct group throughout the length of Pir Panjal range from the Hazara-Kashmir Syntaxis in the northwest to Beasavi in the southeast, as well as in the Kashmir Valley. In fact the spread of Panjal flows has been considered so widespread as to include the basic bodies of Higher Himalaya also as Panjal lavas (Honegger et al. 1982; Greco and Spencer, 1993). However, the possibility of another basic episode may not be ruled out. From the time of Wadia (1928, 1931) who did pioneer work on the Panjal lavas, these flows have been considered continental and subaerial as in Kashmir.

There is now increasing evidence in Pakistan that these lavas, in part, especially in Kaghan and Neelum valleys are oceanic in nature(Sinha, 1976; Chaudhry et al., 1992). The basic volcanics of Kaghan when plotted on discrimination diagrams are seen to be tholeiitic in character. The tholeiites of Kaghan resemble P-type MORB. The relic pillow structures and the oceanic tholeiite affinities of the Panjal volcanics, together with their association with marine turbidites, limestones and other sediments, is a strong evidence in favour of submarine oceanic eruption of the Panjal lavas in Neelum and Kaghan valleys. This is, however, contrary to their subaerial occurrence elsewhere. In Kaghan Valley, the Panjal volcanics which are at other places predominantly rift related assumed a transition to oceanic regime.

Kashmir Basin and the Peshawar Basin

In the tectonic framework of the Himalaya, the position of the Kashmir Basin is not easily correlatable to the fourfold framework as seen in Kumaun and Nepal Himalaya. The division between Higher and the Lesser Himalaya is not as clear in Kashmir. It is unclear whether, for example in the Tso Morari and Zanskar areas, the Higher Himalaya make a distinct unit north of Kashmir. Nevertheless, the situation in the Western Himalaya of Pakistan is different. The Higher Himalaya Crystalline is easily discernable with the Main Central Thrust at its base north of the Peshawar basin. The Phanerozoic sequence correlatable to the the Peshawar basin is underlain by a low grade Lesser Himalayan Proterozoic sequence of slates and the Tanawal Formation. The Peshawar basin, except for the presence of a cover sequence is therefore correlatable as part of the Lesser Himalayan domain. By analogy, the Kashmir Basin south of the Zanskar Higher Himalaya may also be regarded as part of the Lesser Himalaya. The Kashmir Basin includes a well developed Palaeozoic sequence overlying a metamorphosed sequence consisting of the Dogra slates and the Salkhalas further below (Wadia, 1934). The Palaeozoic of Kashmir also includes the well developed Permo-Carboniferous sequence of Panjal volcanics, Agglomeratic slates and the associated Permo-Carboniferous sediments. These are overlain by a relatively less well developed Mesozoic sequence which are, in turn, overlain by the mainly Quaternary fluvio-lacustrine Karewas.

To its south the wide synclinal basin of Kashmir is fringed by a series of thrusts forming the so-called Carboniferous-Eocene Autochthonous or Parautochthonous Folded Belt of Wadia (1931), enclosed by Panjal Thrust to the northeast and the Murree Thrust (Main Boundary Thrust) to the southwest. The Kashmir synclinal basin closes to the northwest and only the plunging tip of the Dogra slates (Authmuqam Phyllites) can be seen at Authmuqam in Neelum Valley (Fig.6). The attenuation of the Kashmir Valley sequence is at its maximum around the Hazara-Kashmir Syntaxis in Kaghan Valley. To the west of the Kaghan Valley syntaxial zone, the Lesser Himalayan sequence opens up again passing through Mansehra-Tanol/Tanawal terrane to underlie the Peshawar Basin further west. The Peshawar basin has a well developed Palaeozoic sequence (Table 6). These Cambrian to Jurassic rocks rest on a basement of the Precambrian slate and the Tanawal Formation. The Palaeozoic sequence is followed by a less well developed Mesozoic sequence. To the south, the parautochthonous fold-and-thrust belt of Pir Panjal and Kashmir, is represented by the Attock-Hazara fold and thrust belt. The synclinal Peshawar basin to the west is thus an analogue of the synclinal Kashmir basin to the east of Hazara-Kashmir Syntaxis (Fig.4). This relationship was earlier noted by other (Yeats and Lawrence, 1984). It may be added that like the Karewas of Kashmir, the Peshawar basin has a thick Plio-Pleistocene to Recent fill of alluvial sediments (Burbank, 1983; Burbank and Tahirkheli, 1985). Again like the Kashmir Basin the Peshawar Basin also has less intense deformation compared to the thrust belt on its southern periphery and shows a rift related plutono-volcanic suite of Upper Palaeozoic age.

Lesser Himalaya and the Karakoram Microcontinent

Like the Kashmir and Peshawar basins, there is a well developed Palaeozoic sequence in the Chitral area of the Western Karakoram (Chaudhry et al., 1996). This sequence overlies the controversial Chitral slates which, we consider as Precambrian to Eo-Cambrian and correlatable with the Hazara slates, being in continuation with slates of the same age further west in Afghanistan (Wolfart and Wittekindt, 1980). A possible correlation between the Palaeozoic Peshawar basin and the Western Karakoram is given below in Table 7. Interestingly, a similar correlation can also be made between the Himalaya and Karakoram for the Proterozoic basement which is exposed as the Higher Himalaya on the Indian Plate and as the Baltit Group and the Hasanabad Group in the Middle Hunza Valley of the Karakoram (Table 8). The correlation of these Proterozoic and Palaeozoic sequences of Higher and Lesser Himalaya with the sequences of Western and Central Karakoram shows that in continuation of the rifting initiated in Upper Palaeozoic times (Peshawar basin alkaline assemblage is Carboniferous) on the northern margin of India a rifted slice of Gondwanic affinity (Gaetani, 1991;Gaetani and Garzanti, 1991) moved north in Permo- Triassic times eventually closing the Palaeo-Tethys and colliding with the Asian continent. Thus, the stratigraphy, structure and metamorphism of Western Karakoram appear to correlate with that of Lesser Himalaya much to the south.

Table 7.
Stratigraphic correlation between the Lesser Himalaya (Peshawar Basin) and the Western Karakoram.

Higher Himalaya (Indian Plate)		**Central Karakoram**
Lower Swat & Besham	**Kaghan & Azad Kashmir**	**Hunza Valley**
Alpurai Group	**Burawai Group**	**Baltit Group**
Tilgram Formation: Calc-pelite, marble with Minor pelite	*Bans Formation:* Pelites	*Ganesh Formation:* Marble, calc-pelite, pelite And amphibolite
	Seri Formation: Thick sequence of calc-pelite And marble with Amphibolite	
Salampur Formation: Pelite psammite; Turbidites With amphibolite sheets	*Old Battakundi Formation:* Pelite psammite; Turbidites With amphibolite sheets	
Pacha Group	**Purbinar Group**	**Hasanabad**
Swat Granite, Manglaur Formation: Pelite-psammites, Turbidites, Migmatites, Minor marble, calc-schist And graphitic schists	*Saiful Muluk Granite* *Lulu Sar Formation:* Pelite-psammites, minor Marbles and graphitic Schists	*Minapin Formation:* Pelite-psammites with minor Marbles and graphitic Schists
Kolangi Formation: Migmatites	*Gittidas Granite* Jalkhad Nar Formation: Migmatites and enclaves	
Targhao Granite Gneisses: Granite gneisses and Migmatites	*Ratti Gali Granite* Lulu Sar Formation: Granite gneisses and Migmatites	*Hasanabad Granite* Migmatites with meta- Sedimentary enclaves

Table 8.
Stratigraphic Correlation Between the Higher Himalaya of Indian plate and the Central Karakorum of Hunza Valley.

Lesser Himalaya (Indian Plate)	Western Karakoram
Peshawar Basin	**Chitral**
Bampokha Formation: Dolomitic limestone/limestone **Carboniferous/Triassic?**	***Zait and Parpish Formation:*** Dolomitic limestone/limestone **Carboniferous to Triassic?**
Jaffer Kandao Formation: Limestone, Dolomite and quartzite **Devonian**	***Lun Shales:*** Shale, sandstone and dolomite **Late Devonian**
Panj Pir Formation: Slate, Limestone and dolomite **Silurian**	***Broghil Formation:*** Slate, limestone, dolomite and quartzite **Ordovician/Silurian?**
Misri Banda Quartzite: Quartzite Ordovician-Cambrian?	
Attock Slates: Slate, wacke, quartzite and minor marbles **Precambrian**	***Chitral Slates:*** Slate, wacke, quartzite and minor marbles **Precambrian**

Metamorphism in the Lesser Himalaya

Based on cooling ages (Treloar et al., 1989) many modern workers have tended to regard regional metamorphism of Higher and Lesser Himalaya as Tertiary or Himalayan in age (Frank et al. 1973; Le Fort, 1975; Bird, 1978; Bard 1983; Treloar et al., 1989). Metha (1980) summarised published K-Ar, Rb-Sr and fission track mineral ages of Himalaya in India. According to this study more than 75% of these ages range from Late Cretaceous to Neogene although Rb-Sr whole rock ages range from Precambrian to Early Proterozoic (upto 1840 Ma).

Geological evidence was however, relied upon more heavily in the past. Gansser (1964), for example, regarded most of the Himalayan metamorphism as Precambrian. His view relied on the fact that most of the overlying Palaeozoic and younger succession is hardly affected by metamorphism. Chaudhry (1964) based on the evidence of presence of chips of Hazara slate in the overlying sedimentary Tanakki boulder bed regarded Carboniferous at that time proposed a Palaeozoic orogeny. Baig et al. (1987, 1988) for the first time properly documented the evidence of Precambrian metamorphism from Tanakki boulder bed of Hazara now known to be Cambrian. Baig (1990) also reported not one but many Precambrian events, from the Besham area further north, based on isotope dating.

Chaudhry et al. (1989) pointed out further field evidence from the Mansehra area in favour of Precambrian metamorphism in the Lesser Himalaya. The Cambrian Mansehra Granite does not follow the thermal axis but rather intrudes all metamorphic zones of the country rock ranging from chlorite grade to sillimanite grade and the metamorphic isograds of the regional metamorphism are abruptly truncated by the granite body at many places. Not only that but also the thermal metamorphic event associated with the emplacement of Mansehra Granite has been superimposed on the regional metamorphism, at places, at an angle. Development of contact migmatites and andalusite, sillimanite and cordierite bearing hornfelses is common. Regional metamorphic minerals like almandine, staurolite and kyanite tend to break down leaving recognisable relics or disappear altogether in the thermal aureoles. Overprinting of an earlier fabric by chiastolite and cordierite porphyroblasts in the aureole of Mansehra Granite was also reported by Treloar et al (1989). The above field and petrographic relationship is enough to suggest that the emplacement of the Cambrian Mansehra Granite is younger than the age of regional metamorphism and that one phase of the Precambrian metamorphism in the Himalaya reached upto at least the amphibolite facies. The Precambrian metamorphism of Lesser Himalaya is thus well established. Proterozoic dates are likewise widespread on the S-type granites of Higher Himalaya (Bhanot et al., 1977; Singh et al., 1986; Pandey et al., 1981; Zeitler et al., 1989). Apart from the evidence directly in favour of Precambrian metamorphic event a Pre-Himalayan relic schistosity was also recognized by Greco et al. (1989) in the Lesser Himalayan terrane of Middle Kaghan, and by Treloar et al. (1989) in the rocks of Northern Hazara.

The Jura Granite in Neelum Valley (Fig. 6)like the Mansehra Granite is two mica, S-type porphyritic granite which has an intrusive relationship with the country rock. The contact, however, is now disturbed by faulting. The Jura Granite is a typical deformed granite like the 500 Ma granites of the Lesser Himalaya seen in the Central Himalaya to the east and Mansehra to the west. Furthermore the Jura Granite contains large screens of country rock (correlatable to the Tanawal Formation) showing pre-inclusion regional metamorphism.

A thermal metamorphism is superimposed on regionally metamorphosed rocks in the aureole of Neelum Granite (Fig. 6) (again considered Mansehra Type and of Late Cambrian age by Schouppe et al. 1994, Fig.7) further northeast of Jura Granite but again in the Lesser Himalayan domain of Neelum Valley. Near Rampura-Dhanabela the aureole is about 120 m thick and contains biotite hornfelses, andalusite-cordierite hornfelses and banded andalusite-biotite hornfelses. The relationships establish that not only the country-rock is older than the granites but also they were already metamorphosed when the granites intruded and at least one phase of regional metamorphism is Pre-Himalayan. However, there have been more than one phase of metamorphism as indicated by growth of garnet on garnet in Nagdar Schists and the growth of chlorite porphyroblasts enclosing biotite near Kundalshahi in Neelum Valley(Ghazanfar et al. 1983).

The problem in the Lesser Himalaya, in fact, relate mainly to the degree of Tertiary reheating. Such Tertiary reheating or Himalayan metamorphism has indeed been intense in the HHC as is evidenced by presence of Tertiary leucogranites and cooling ages (Metha, 1980; Treloar and Rex, 1990, Chamberlain et al., 1991). This metamorphism reached eclogite facies in the Besal area of Kaghan (Spencer et al., 1990; Pognante and Spencer, 1991) However, the Himalayan metamorphism has not been equally intense everywhere and at all levels. The Mansehra area was hardly affected. Furthermore Permian dated (270 Ma, Baig, 1990) unmetamorphosed dolerites have been reported from Mansehra Granite in Northern Hazara.

It may be mentioned that although we are of the opinion that the Pre-Himalayan metamorphism was the main metamorphism as seen in the Northern Hazara, Treloar et al. (1989) take an opposite view. They are of the opinion that the Himalayan regional metamorphism clearly overprints contact metamorphic assemblages related to the intrusion of Mansehra Granite. According to them, although the cordierite andalusite hornfels assemblages are essentially unaffected in the southern part of the area, to the north they reacted to produce assemblages more typical of the Himalayan regional metamorphism, the replacement of andalusite by regional kyanite as reported by Shams (1964) being the only incidence mentioned. This evidence, it may be noted relates to the northernmost fringe of the Mansehra area.

In the Kaghan Valley (Fig. 8), an interesting relationship is again exhibited by rocks of the Kashmir sequence. Here the Permian Panjal Formation and the underlying Chushal Formation (Bossart et al., 1984) i.e., the Agglomeratic Slate is metamorphosed to greenschist facies while the overlying Triassic/Jurassic Malkandi Formation is unmetamorphosed. This could be interpreted as a minor Hercynian Permo- Trias event probably related to the opening and closing of the small Panjal ocean created by rifting (which ultimately failed in this area) on the Indian plate margin.

We may conclude that although no one can deny the presence of Himalayan regional metamorphism an overemphasis can lead to the downplaying of the significance or even ignoring the presence of Pre-Himalayan metamorphism. It is now increasingly becoming clear that the view of an omnipresent Himalayan main metamorphism cannot explain many tectonostratigraphic relationships and related questions.

CONCLUSION

The extension of the Himalayan subdivisions to the Western Himalaya of Kashmir and Pakistan has been a source of much debate. The most difficult problems related to the character and extent of the Higher Himalaya and Lesser Himalaya and the presence or absence of the Tethys or the Tibetan Himalaya. This presentation outlines the character and problem of the Lesser Himalaya in Pakistan, which may now be summarised as follows:

The first problem relates to the extent and boundaries of the Lesser Himalaya. The Lower boundary of Lesser Himalaya is well defined by Main Boundary Thrust in Pakistan as in India. It is the upper boundary which remained elusive and led to great confusion between the HHC and the Lesser Himalaya and in matters of lateral correlation. Now the delineation of the Main Central Thrust in Pakistan determines the northern boundary and the extent of Lesser Himalaya in Pakistan.

What we are calling Lesser Himalaya in Pakistan is different from what is known as the Lesser Himalaya in Kumaun and Nepal in the sense that the Pakistani Lesser Himalaya has still preserved patches of Tethyan sediments on top of the low grade basement sequences that predominate in the Lesser Himalaya of Kumaun and Nepal Although we can generally say that the Lesser Himalaya in Pakistan is characterised by a metamorphic zone to the north and a sedimentary zone to the south of the Panjal Thrust the metamorphic zone in the Peshawar basin area has a well developed Palaeozoic- Lower Mesozoic Tethyan sedimentary sequence. On the basis of significant lateral variations and complexities the Lesser Himalaya slab in Pakistan can be studied with reference to a number of sections. From east to west we may relate to these as the Neelum section, the Kaghan section, the Hazara section and the Peshawar basin. Occurring east and west of the Hazara Kashmir Syntaxis respectively the Kashmir and Peshawar basins are analogous and both have well developed Palaeozoic sequence and upper Palaeozoic rift related magmatism.

The Neelum and Kaghan valleys have different lithostratigraphic packages in their respective Lesser Himalayan metamorphic zones, calcareous in Kaghan, pelite psammite in Neelum. The metapelitic-psammitic Kundalshahi group of Neelum Valley nearly disappears in Kaghan but reappears west of Hazara-Kashmir Syntaxis in Mansehra area as Tanawals. These Tanawals in the Mansehra and and Peshawar basin areas as apparently of Neelum valley too, are intruded by Cambrian and Palaeozoic granites and alkaline suites. Apart from the pelitic psammitic Tanawal Formation the dominantly calcareous Kaghan Group previously described as part of the much larger Salkhala Formation is the other major basement formation of the Lesser Himalayan metamorphic zone. Apparently the Kaghan group is older than Tanawals although both are unfossiliferous.

The southern Sedimentary Zone of the Lesser Himalaya occurs in the form of a fringe along Pir Panjal, Kaghan, and over the Hazara-Kashmir Syntaxis and as a wider belt in the area of Southern Hazara, Kalachitta and Attock Cherat ranges. From Pir Panjal to Parachinar over the Hazara-Kashmir Syntaxis this belt comprises different stratigraphic provinces with variations in basinal history. Three such stratigraphic sequences of Kashmir, Hazara and Muzaffarabad occur close to each other in the area of Hazara-Kashmir political boundary (Ghazanfar et al. 1987).

Stratigraphically, at present the more metamorphosed unfossiliferous Precambrian Tanawals of Hazara and Peshawar basin are considered younger than the Hazara, Attock and Manki slates. It is, however, more likely that Tanawals in fact represent the lowermost metamorphosed part of the Hazara slate group but structurally, they overlie the Hazara slates in the inverted metamorphic sequence.

The Permo-Trias Panjal Formation with basic volcanics and the associated limestone horizons are another enigmatic formation of the Lesser Himalaya. These continue for some 400 km from Hazara-Kashmir Syntaxis southeast along the strike of the Himalayas and their spread has been claimed in the HHC north. They have been considered rift related continental on geologic and geochemical basis. In Kashmir, continental Gondwana fossils are reported from the associated beds. Along a long rift opening tectonic variations could naturally be expected. In Peshawar basin there is a well developed alkaline plutono-volcanic suite occurs along this rift . The chemical and geologic evidence in Kaghan and Neelum valleys point towards a P-type MORB affinity of homotaxial metabasites (Chaudhry et al., 1992). There is thus reason to believe that in the Kaghan and Neelum areas, at least, a small ocean the Panjal Sea, did develop in Permian times.

Many workers especially recently have tended to regard regional metamorphism of both Higher and Lesser Himalaya as Tertiary or Himalayan in age. There is now abundant documented evidence of Precambrian main metamorphism in the Lesser Himalaya. The importance of the Pre-Himalayan events has not however, has been properly emphasised. This has been partially due to the fact that the HHC domainof Himalayan metamorphism had not been recognized as different from that of Lesser Himalaya in Pakistan.

Well developed Palaeozoic basins existed on Gondwanaland margin in Salt Range, Kashmir, Peshawar basin and what is today Karakoram. The close correlation of both the Palaeozoic sequences and the underlying basement in regions now hundreds of kilometers apart, with an intervening island arc, in Lesser Himalaya to the south and in Western and Central Karakoram to the North is remarkable. There is now an increasing evidence to suggest that Karakoram was a part of the Indian Plate that rifted and separated from India in Permo-Triassic times closing the Paleotethys in front (Gaetani and Garzanti, 1991; Chaudhry et al. 1996).

ACKNOWLEDGEMENTS

MG and MNC thank the Punjab University, Lahore, for research grant and logistic support for work in the Lesser Himalaya. DAS was financially supported by a Swiss Federal Institute of Technology Grant (Nr. 0.20.367.89), an ETH-Imperial College Scholarship (Nr. 0.330.028.02/8) and a Swiss National Science Foundation Research Fellowship (Nr. 2100-039080.93/1).

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Geol. Bull. Punjab Univ. 33 & 34, 1999.

THE NATURE AND PROBLEMS OF THE TETHYAN HIMALAYA IN PAKISTAN AND WESTERN KASHMIR

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Abstract: *This paper aims to define, describe and discuss the occurrence of the tectonic subdivision of the Tethyan Himalaya in northern Pakistan and western Kashmir. With the demarcation of the Main Central Thrust in the Neelum and Kaghan valleys (western Kashmir and Pakistan), the Higher Himalaya and the Lesser Himalaya have now been differentiated in these areas. In the NW Himalaya, two domains of the Tethyan sedimentary rocks have been recognised, both north and south of the Main Central Thrust. To the south, the Lesser Himalaya in Pakistan and Kashmir is overlain by a sedimentary sequence of Tethyan affinity. The relationship of this 'Southern Tethyan Sequence', incorporated as part of the Lesser Himalaya, is interpreted to be analogous to that of the cover sediments in Kashmir and the autochthonous fold belt of Pir Panjal. To the north of the Higher Himalaya and directly underneath of the Indus Suture, the 'Northern Tethyan Sequence' possibly consists of low grade sediments which are found in Upper Kaghan, Banna, Karora and Lower Swat. These sediments can be interpreted to be analogous to the Tethyan Himalaya. Other interpretations of these sediments (i.e., their suture zone affiliation) are also discussed. Finally, the high grade metasedimentary cover of Higher Himalaya is also regarded as being the equivalent of the Tethyan Himalaya in the 'Northern Tethyan Sequence'. The role and significance of these Tethyan sequences, in the subdivision terminology of the Himalaya, is assessed with the other known subdivisions of the Pakistani Himalaya and western Kashmir.*

INTRODUCTION

Extra-peninsular India is composed of the more than 2,800 Km long Himalayan mountain ranges which occur to the north of the Indian craton and platform. The Himalayan mountain range has traditionally been considered to extend for 2,400 Km between the Arakan-Yoma ranges in the east and Nanga Parbat in the west. However, recent work in the western Himalaya of Hazara and Swat now geologically extends the Himalayan mountain range west of Nanga Parbat for a further distance of some 400 Km to the border of Afghanistan (Shroder, 1984; Butt, 1988; Chaudhry et al., 1994a) Based on early work in the Central and Eastern Himalaya, the Himalaya have been subdivided into four major longitudinal tectonic belts which, from south to north, have been called the Sub-Himalaya, Lesser Himalaya, Higher Himalaya and the Tethyan (or Tibetan) Himalaya (Gansser, 1964; Fig. 1). The northern limit of the Himalayas is marked by the Indus-Tsangpo Suture Zone. These tectonic belts of the Himalaya are separated from each other by major boundary thrusts and show a remarkable continuity for nearly 2,000 Km from the eastern Himalaya across to the Central Himalaya of Kumaun (India). Further west, however, the situation becomes complicated due to the syntaxis of the northwest Himalaya. With increasing geological mapping by both local and foreign geological teams, combined with correlations to known areas in the east (Kashmir and India), the geology of the Pakistani Himalaya has now become more understandable.

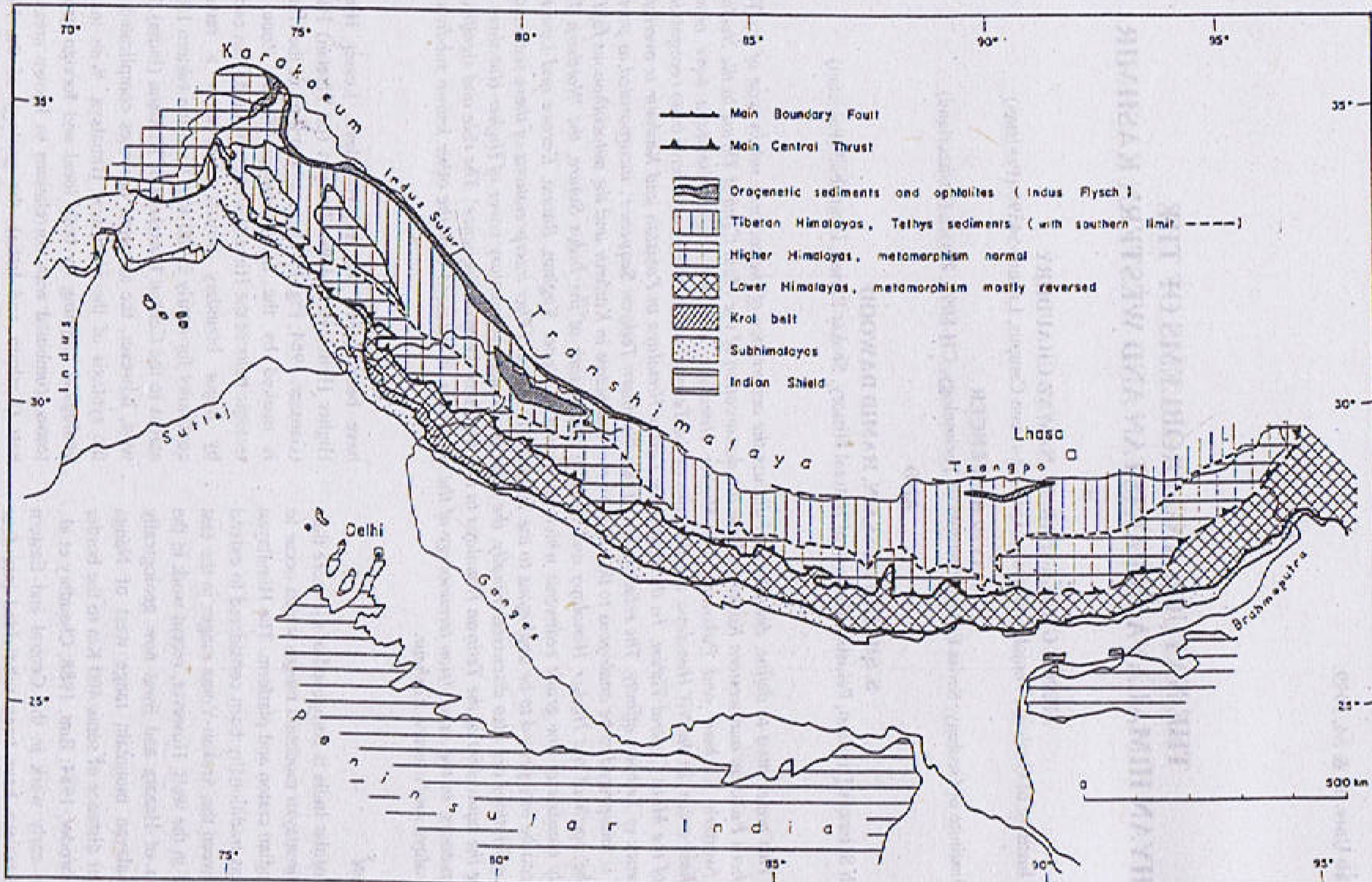

Fig.1. Subdivision of the Himalaya as shown by Gansser (1964).

SUBDIVISIONS OF THE HIMALAYA

The Sub-, Lesser- and Higher Himalaya

The Sub-Himalaya (also known as the Outer Himalaya, Siwalik Belt and the Molasse Zone) is the southernmost tectonic unit of the Himalaya. It is a foredeep folded belt whose boundary with the Tertiary fold belt of the Lesser Himalaya is marked by the Main Boundary Thrust (MBT). The Lesser Himalaya in Kumaun and Nepal mainly comprises of thick Precambrian low grade sequences reaching up into Cambrian. The sequence is tectonically inverted and, in the Kumaun Himalaya, is overridden locally by high grade crystalline Precambrian rocks. Westwards into Kashmir, however, the low grade Precambrian rocks are overlain by a well developed Palaeozoic to Jurassic sedimentary sequence and, at places such as Kishtwar, by nappes of the Higher Himalaya. The Lesser Himalaya is separated from the Higher Himalaya further north by the Main Central Thrust. The Higher Himalaya (also known as the Central Crystalline or the Great Himalaya) consists of a high grade Precambrian basement intermixed with granitic plutons and migmatites of Tertiary age. Classically, it is separated from the Tethyan Himalaya (discussed below) further north by a once controversial tectonic contact that is now generally considered extensional. This fault has been variously termed as the South Tibetan Detachment System (Burg et al., 1984), the Zanskar Shear Zone (Herren, 1987) or the Trans-Himadri Fault (THF) (Valdiya, 1989).

The Tethyan (-Tibetan) Himalaya

The Tethyan (or the Tethyan-Tibetan) Himalayan zone occurs north of the Higher Himalaya. It is composed of a fairly continuous marine succession of Palaeozoic and Mesozoic rocks resting with a tectonised unconformity over the Precambrian basement of the Higher Himalaya. The Tethyan Himalaya are limited to the north by the Indus Tsangpo Suture Zone (ITSZ), known as the Indus Suture in the NW Himalaya. The Tethyan sequence has developed as a continental margin shelf deposit on the northern edge of the Indian Plate. Although calling it the "Tethyan Himalaya" or the "Tibetan Himalaya", Gansser (1964) recognised that vast tracts of this northerly Himalayan unit were not in Tibetan Territory. Also, he suggested that not all of the rocks found in this northern belt were of *"Tethys type of deposits"*. Gansser preferred, however, to use the term Tibetan Himalayas for this northern region, meaning the part of the Himalayas north of the main range which slopes into or towards Tibet. The Tethyan Himalaya are best differentiated as a distinct tectonic belt in the central and eastern Himalaya. The Zanskar Himalaya can be regarded as the currently known western limit of this well marked and recognized subdivision of the Himalayas. The stratigraphic sequence of the Tethyan sediments in the Malla Johar area of Kumaun and in Kashmir is given in Table 1,2.

Table-1

Stratigraphic subdivision of the Tethys Himalaya zone in Malla Johar, Garhwal (after Shah and Sinha, 1974; from Thakur, 1992).

Division	Lithology	Characteristic Fossils	Age
	Greenish shales with bands of radiolarian cherts		Lower Eocene
Sangeha Malla Formation	Greenish-grey, greywackes and dark shales; Purple marly shale with foraminiferal ooze	Radiolaria, fucoid markings, *Globotruncana, Heterohelix, Plummerita, Shackoina, Eouvigerina*	Upper Cretaceous
	Dark greenish shale with greywacke bands		
Giumal Sandstone	Greenish-grey sandstone and sandy shale with thick bands of massive radiolarian cherts	Not determinable fossils except radiolaria	
	Thick bedded glauconitic sandy shales and sandstones		
Saligram member (Spiti Shale)	Black shales with phosphatic, ferruginous and calcareous concretions	*Belemnopsis gerardi, Perisphinctes (Virgatosphinctes) fregens, Lytoceras sp. Hoplites, etc.*	Portlandian
Sulcacutus Member	Ferruginous oolite with conquina	*Belemnopsis sp., Reineckites sp., Mucrocephalites, etc.*	Callovian
Lapthal Formation	Dark-blue to grey limestone with bands of coquina	*Pecten sp., Astarte sp., Curdium sp., Trigonia sp., Arca sp., Avicula sp., Belemnites sp.*	Lias

Kioto Limestone	Grey limestone with numerous bands of coquina, Nodular and oolitic limestone. Cross-bedded calcarenite and arenaceous limestone. Grey and blue dolomitic limestone	*Megalodon, Spiriferina, Pecten, etc.*	Rhaetic
Kuti Shale	Alternating bands of black shale and limestone	Few pelecypod shells	Noric
Kalapani Limestone	Nodular limestone, grey massive limestone	*Prychites, Gymnites, Halobia, Arcestes, etc.*	Camic-Ladinic
Kuling	Black crumply shale with thin beds of limestone with concretions towards the top	*Paramarginifera himalayensis, Cleiothyriduim roysii, etc.*	Upper and Middle Permian
Muth Quartzite	White sugary orthoquartzite with bands of dirty white quartzite	*Schellwienella williami, Leptaena rhomboidalis, Strophomcna sp.*	Devonian
	Chocolate brown quartzite and dolomitic limestone	Pentamerus sp., Camarophoria sp., Leptaena rhomboidulis, etc.	
Variegated Formation	Purple limestone and shale with bands of quartzite	*Atrypa reticularis, Strophonella sp., Orthis (Dalmanella) basalis, Favosites sp., Leptaena rhomboidalis*	Silurian
Yong Formation	Green nodular biohermal and biostromal limestone	Calostylis? dravidiana, Streptelasma sp. and massive stromotoporids	
Shiala Formation	Grey to pinkish sandstone and quartzite with bands of limestone at the top	Rafinesquina alternata, Leptaena halo, Favosites sp., ? Saffordia sp., Monotrypa sp., Strophomena sp.	Ordovician
	Alternating bands of sandstone and shale	Chacmacrops, Laptacna? trachealis, ? Rhinidictya sp., Asaphus sp.,? Lioclema sp.,	
	Alternating bands of greenish shale and biostromal limestone. Green splintery shale with thin bands of arenite	Rafinesquina aranca, R.muthensis, Triplccia sp., Skendium sp., etc.	
Garbyang Formation	Green needle shales with occasional bands of limestone		
	Alternating bands of sandstone and shale with graded bedding	Eccliopteris kushanensis	Cambrian
	Cross-bedded calcareous sandstone		
	Greyish green graded bedded sandy shales, crinoidal and oolitic limestone, brown marl		
	Brown dolomitic limestone with alternating bands of shale		
Ralaam Formation	Arenaceous shale		Precambrian
	Dark coloured quartzite		
	Conglomeratic alternating with quartzite		
Martoli Formation	Graded bedded greyish black shales, slates and phyllites		
Vaikrita Group	Quartzite, quartzite schist, calcsilicates, kanite and sillimanite gneisses, migmatites and granites		Proterozoic

Table-2
Stratigraphic succession in Liddar Valley, Kashmir
(after Middlemiss, 1910, Wadia, 1934; Shah, 1972 and Fuchs, 1975).

Plio-Pleistocene	Karewa Formation	Lacustrine mudstones, lignites, deltaic siltstones, sandstones with subordinate conglomerates.
Lower Jurassic	Megalodon Limestone	Upper part of Megalodon Limestone, shales and sandstone of restricted distribution.
Triassic	Megalodon (Kioto) Limestone	Fossiliferous blue grey limestone.
Permian	Zewan Series	Fossiliferous shales below and limestones above.
Permian	Gangamopteris beds	Cherts, siliceous shales, carbonaceous shales and quartzites, plant fossils.
Upper Carboniferous/Permian	Panjal Volcanic Series	Tuffs, slates, andesites and basic lava flows.
Upper Carboniferous	Agglomeratic Slate Series	Pyroclastic slates, conglomerate and agglomeratic products thousands of m thick. Fossiliferous.
Middle Carboniferous	Fenestella shales	Fossiliferous shales and quartzites above, unfossiliferous quartzites and limestones below.
Early Carboniferous	Syringothysis limestone	Limestones with minor shales and quartzites.
Devonian Upper Silurian Lower Devonian	Murth Quartzite Naubug beds	Quartzites. Fossiliferous. Fossiliferous shales and siliceous limestone.
Upper silurian	Harpatner beds	Fossiliferous mustone and shale
Lower to Middle Silurian		Unfossiliferous shales
Ordovician	Gauran Beds	Shales, silts and limestone, fossiliferous in upper part.
Cambrian		Lower Cambrian comprises fossiliferous imperfectly cleaned clays, impure sandstones and greywackes, with few lenticular beds of limestone, upper Cambrian comprises fossiliferous ferruginous slates, greyish limestones.
Precambrian	Dogra Slates	Slates and phyllites with few bands of quartzites and sltered lavas.
Precambrian	Salkhala series	Slates, schist, carbonaceous schist, marble and granitoids.

Southern Contact of the Tethyan Himalaya - The Trans-Himadri Fault

According to Gansser (1964), a sharp division does not exist in the Kumaun Himalaya (of India) between the Higher Himalaya and the northern Tethyan Himalaya. He regarded the sedimentary sequence as transitional from the Cambrian into the younger deposits. Recent investigations in the Nepal, Kumaun and Zanskar regions however, demonstrate that the boundary between the Higher Himalaya and Tethyan Himalaya is demarcated by a large detachment fault of regional dimensions (Kumar et al., 1972; Shah and Sinha, 1974; Burg et al., 1984; Herren, 1987), that is as crucial in importance as the Main Central Thrust and the Main Frontal Thrust (Valdiya, 1989). According to Valdiya (1989), it is obvious that a regional fault extending more than 1,600 Km from north of Nun Kun (Zanskar) to the east of Sagarmatha (Everest), marks the boundary between the Higher Himalayan metamorphic terrane and the Tethyan sedimentary rocks. Therefore, between the Main Central Thrust and Indus Tsangpo Suture Zone, the Trans-Himadri Fault separates the Higher Himalayan basement slab from its sedimentary cover.

Subdivisions of the Himalaya in Pakistan

In the Central and Eastern Himalaya, the tectonic setup that formed as a result of the collision is relatively simple. The tectonic slabs are well defined, in part due to the marked uplift along the Main Central Thrust during the Himalayan period, but also because of the difference in facies of the Phanerozoic sedimentary cover which constitutes the Tethys Himalaya in the north that is largely missing from the low grade basement south of the MCT. The transition area between the Central Himalaya and the Pakistan Himalaya is Kashmir and it is here that the classical Himalayan subdivision is uncertain. Therefore, it is not surprising that further westwards into Pakistan, the situation is complicated and not all workers agree on whether the Himalayan subdivision terminology should be extended at all (Yeats and Lawrence, 1984). This situation is not helped by the relative lack of geochronological ages that, for example, could be used to define the ages of the Higher Himalayan metamorphosed cover in Kaghan and Swat areas of Pakistan (Burawai and Alpurai groups) and the overlying low grade sediments. Finally, instead of a typical Kumaun type Lesser Himalayan sequence, south of the Higher Himalaya in Pakistan, we have the development of lithologies of clear Tethyan affinity which overlie the Lesser Himalayan sequence in areas like Hazara and the Peshawar Basin. However, many of the above complications are beginning to be resolved now that the Main Central Thrust and the Higher/Lesser Himalaya have been defined (Ghazanfar and Chaudhry 1986, Chaudhry et al. 1997).

Therefore, the subdivision of the Pakistani Himalayas and Western Kashmir is a problem that has not been properly researched until fairly recently. However, some units have been delineated for some time and a move has gradually been made towards a tectonic classification. For example, the foreland belt of the Sub-Himalayas, with its northern contact the Main Boundary Thrust, has been long known. Work by Misch (1936, 1949) in the Nanga Parbat had indicated that this region had affinities with the Higher Himalaya in India and Nepal. Finally, the recognition and delineation of the Main Mantle Thrust (MMT) and the Kohistan Island Arc (Tahirkheli et al., 1979) delimited the northern extent of the Indian Plate in the Pakistani Himalaya. More recently, Ghazanfar and Chaudhry (1995, 1986) and Chaudhry and Ghazanfar (1990), on the basis of extensive mapping in Neelum and Kaghan valleys, placed the Main Central Thrust in these areas and so defined a Lesser- and Higher Himalaya. It has now been extended (Chaudhry et al., 1994b, 1997) west of the Indus River through the region of Lower Swat close to the border with Afghanistan.

Tethyan Himalaya in Pakistan and Western Kashmir

Thus it has now become possible to further extend Himalayan the subdivisions into the Northwest Himalaya of Pakistan and Kashmir (Fig. 2) and correlate these with the known subdivisions to the east in Kumaun and Nepal. With the Lesser- and Higher Himalaya now defined (Ghazanfar et.al. 1997, Chaudhry et.al. 1997) and available for evaluation, attention can be turned to the Tethyan Himalaya in Pakistan and Western Kashmir. In Pakistan, in contrast to India and Nepal, two regions instead of one or the Tethyan Sequence with lithologies of 'Tethyan' affinity can be found which we may refer to as the "Southern Tethyan Sequence", and the "Northern Tethyan Sequence", which is akin to the Lesser Himalayan Tethyan Sequence and the Tethyan Himalaya respectively.

The Southern Tethyan Sequence of the Lesser Himalaya in Pakistan

Many workers since Gansser (1964) have recognized Tethyan affinity rocks in the southern part of the Himalaya in Pakistan including the fold and thrust belt of Hazara, Attock-Cherat and Kala Chitta. This sedimentary belt in the Pakistani Himalaya, with a well developed Phanerozoic stratigraphic sequence, is enclosed between the Panjal Fault and the Main Boundary Thrust and is, in many ways, analogous to the Pir Panjal autochthonous fold belt south of Kashmir. The latter extends through Neelum and Kaghan valleys and then is deformed by the Hazara-Kashmir Syntaxis until it gets truncated near Balakot. It then starts again a short distance further southwest at Garhi Habibullah expanding into the Attock Hazara Fold and Thrust Belt (AHFTB). North of the Attock-Cherat ranges of AHFTB is the Peshawar Basin which in Pakistan is analogous in structure, metamorphism, stratigraphy and geomorphology to the Kashmir basin where Tethyan affinity rocks are well recognized (Gansser, 1964; Wadia, 1957; Thakur, 1992). The stratigraphy of the various segments of the southern Tethyan sequence of Pakistan is given in Tables 3 to 8. These rocks of Tethyan affinity in Kaghan (Table 3) and Neelum (Table 4) valleys as well as those at Hazara (Table 5), Peshawar Basin (Table 6), Kala Chitta (Table 7) and Attock-Cherat (Table 8) all lie to the south of the Main Central Thrust and therefore to the south of the Higher Himalaya. However, it must be noted that in these areas Tethyan sediments with close affinities to Kashmir and Spiti overlie the basement sequences of Lesser Himalayan affinity. For example, the Precambrian Tanawals which have a wide exposure in the Mansehra area have correlatives in the Neelum Valley and form the basement to the Peshawar Basin. These have been correlated with the Chails of Simla area while, the overlying Hazara, Manki and Attock slates from this part of Pakistan have been correlated to the Dogra and Simla slates. We, therefore, are

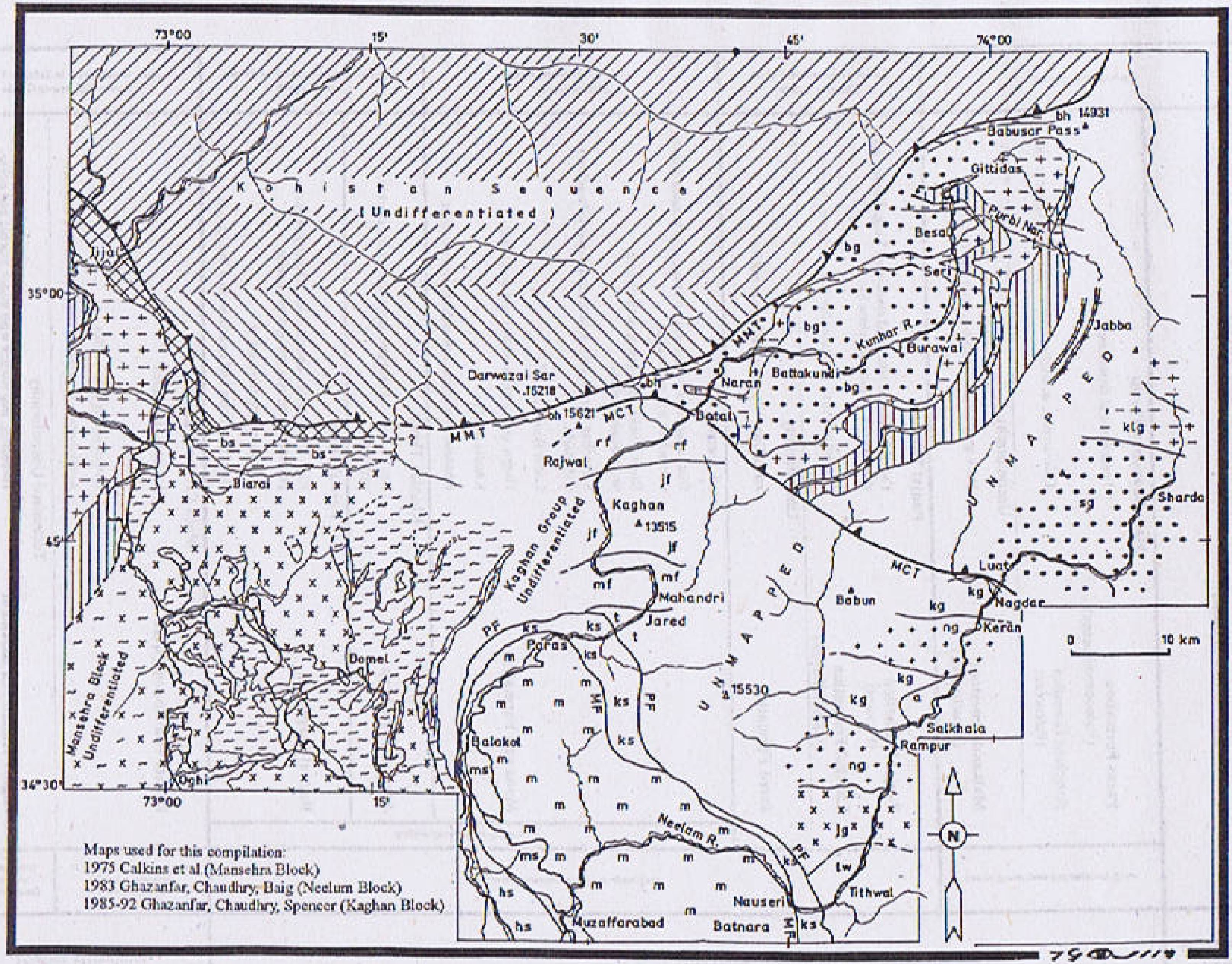

Fig.2. Location of the Main Central Thrust and subdivision of the Himalaya in Pakistan and Western Kashmir.

Table 3.
Stratigraphic sequence in Kaghan Valley (modified from Ghazanfar and Chaudhry, 1985; Chaudhry et al., 1994a, 1997).

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

Table 4.
Stratigraphic sequence in Neelum Valley, Western Kashmir (modified from Ghazanfar et al., 1983).

Sub Himalaya		**Murree Formation** (Mid Eocene-Miocene)	Sandstone, Shale sequence	Unmetamorphosed
Lesser Himalaya	Lesser Himalayan Sedimentary Zone	**Main Boundary Thrust**		Lower Greenschist Facies Chlorite Grade
		Paras Formation (Paleocene/Eocene)	Foraminiferal limestone	
		Rosachcha Formation (Paleocene)	Calc-arenite, quartzite, lateritic/ pisolitic claystone etc.	
		Unconformity		
		Malkandi Formation (Trias/Jurassic)	Dark grey oolitic limestone with shale partings	
	Lesser Himalayan Metamorphic Zone	**Panjal Thrust**		Middle-Upper Greenschist Facies Biotite-Garnet Grade
		Panjal Formation (Permian)	Panjal basic volcanics and associated Bhunja and Ling bands of limestone/marble	
		Chushal Formation (Carboniferous)	Graphitic schist, limestone/marble, metaconglomerate, Agglomeratic Slates	
		Tectonised Unconformity		
		Authmuqan Formation (Upper Proterozoic Cambrian)	Slates, phyllites, minor metaconglomerates and graphitic horizons	
		Tectonised Unconformity		
		Kundalshahi Group (Upper Proterozoic)	Pelite, Psammite and minor quartzites	
Higher Himalaya	Sharda Group (Upper Proterozoic or U.Palaeozoic/L.Mesozoic)	**Main Central Thrust**		Upper Amphibolite to Eclogite Facies Kyanite-Sillimanite Grade
		Higher Himalayan Cover	Garnetiferous calc-pelites, marbles, dolomites and pelites	
		Tectonised Unconformity		
	Kel Group (Proterozoic or L.Paleozoic)	**Higher Himalayan Basement**	Turbidites, migmatites with minor marble and pelite-psammite horizons	
			Granitoids	

of the opinion that areas south of the Higher Himalaya (i.e., between Main Boundary Thrust and the newly demarcated Main Central Thrust) in Pakistan should be classified as the Lesser Himalaya (as in Kumaun and Nepal) even though in Pakistan there is a substantial cover of Tethyan affinity overlying it.

Lithostratigraphy of the Lesser Himalaya

Since the Lesser Himalaya of Pakistan is different in so far as it supports a major cover of Tethyan affinity, it may be useful to discuss the lithostratigraphy of the Lesser Himalaya of Kumaun and look for their correlatives between the Main Boundary Thrust and the Main Central Thrust in Pakistan. The Lesser Himalaya of Kumaun with its unfossiliferous packages, klippes, nappes, tectonic windows and its westward extension into Kashmir has remained for years one of the most complicated tectonic problems of the Himalayas. Thakur (1992) has presented a tectonic synthesis of this region and its relationship with the neighbouring areas especially to the west. This may be summarized as follows: Four mega-sedimentary cycles are recognised in the Lesser Himalaya basin (Srikantia, 1977; Valdiya, 1980). These are: (1) the Sundernagar - Damta cycle; (2) the Deoban - Shali cycle; (3) the Jaunsar - Simla cycle and (4) the Krol cycle. Each cycle is separated from the overlying one by an epeirogenic break, marked by an unconformity. This stratigraphic sequence of the Lesser Himalaya is given in Table 9.

It now appears possible to trace this Lesser Himalayan stratigraphy laterally to the west to see its continuity and transition into Pakistan. According to Thakur (1992), the Lesser Himalaya formations like Shali, Deoban and Sundernagar, and the Mandi Darla volcanics extend west of Satluj to Ravi, from where they have been further traced along the strike to Poonch area. In Poonch area, the Lesser Himalaya formations of Upper Precambrian age are overlain unconformably by the Agglomeratic Slate, Panjal volcanics, and then by the Zewan and Rajpur formations (Lower Permian to Triassic). Further west, this belt continues through Neelum Valley into Kaghan and around the Hazara-Kashmir Syntaxis to Balakot. In Kaghan, the Upper Carboniferous-Lower Permian Agglomeratic Slate/Chushal Formation (Bossart et al., 1988) is overlain by the Panjal Formation comprising of basic volcanics and associated limestones. This is followed by the Triassic/Jurassic Malakandi (limestone) Formation and then the foraminiferal Paras (limestone) Formation (Eocene) with an underlying microconglomerate sequence of Rosachcha Formation (Paleocene?) marking an unconformity at the base (Table 3).

Autochthonous Folded Belt of Kashmir has been mapped between Poonch and River Ravi by Rao and Rao (1970. Its stratigraphy has been dealt with in detail by Jangpangi et.al. (1986) and has been summarized in Table 10. The Triassic Jurassic Poonch Mandi Formation of this section is correlatable with the Triassic Jurassic Malkandi Formation and the Nummulitic limestone of unconformably overlying Rajpur Formation is correlatable with the limestone of Paras Formation of Kaghan Valley (Table 3). Such a correlation of the sedimentary Autochthonous Folded Belt of Kaghan Valley with that in Poonch shall eventually develop further when the biostratigraphy in Kaghan Valley has been worked out. The underlying metamorphosed Panjal Volcanics and Agglomeratic Slates (Chushal Formation) are likewise easily correlated. It should be noted that the thick Julgaran Formation of the Kaghan Group (Table 3) still below contain bands of gypsum as the Upper Precambrian Ramban Formation of the Autochthonous Folded Belt (Table 10).

Further west near Garhi Habibullah, the autochthonous fold belt sequence of Kaghan is replaced by the Hazara sequence and still further west by the sequences of Peshawar Basin, Attock-Cherat Range and the Kala Chitta Range (see Tables 5 to 8). Thakur (1992) suggests that the Hazara Formation, Manki Formation, Dakhner slates, Tanawal Formation, Abbottabad Formation and Hazira Formation of Precambrian and Cambrian age from Hazara and Kala Chitta are the equivalent of the Shimla Slates and the Krol-Tal sequence of the Lesser Himalaya in Simla Hills. The Upper Proterozoic to Cambrian sequences are overlain by a Palaeozoic-Mesozoic sequence in the Peshawar Basin and the Attock-Cherat ranges and by Cambrian and Mesozoic and Tertiary sequences in South Hazara and Kala Chitta Range.

Two more major Proterozoic formations of the Western Himalaya of Pakistan may be correlated with the Lesser Himalaya sequence of India. The pelite psammite sequence of the Kundalshahi Group of Middle Neelum Valley (Table 4) between Tithwal and Luat (except for the Authmuqam slates) and the Tanawals of Hazara can be related to the Chail Formation, as mentioned above, while the Kaghan Group of Middle Kaghan Valley between Mahandri and Batal can be related to the Jutogh or the low grade Salkhalas of Kashmir. The Kaghan Group comprising of pelites, calc-pelites, marbles and quartzites with subordinate graphitic schists may be older than Chail Formation but younger than the high grade Vaikrita.

It may be interesting likewise to look at the correlation of some Lesser Himalayan Formation in a transverse sense. On the basis of lithological comparison of the rock types between the two regions, Holland (1908) suggested that the Vindhyan, Cuddapah and similarly older systems of the Peninsular India continued into the Lesser Himalaya. While the Vindhyan basin extends towards Nepal

Table-5

Stratigraphic sequence in the Hazara region (after Latif, 1970; Shah, 1977).

Early Miocene	Murree Formation	Grey and reddish sandstone and shales
Middle Eocene	Kuldana Formation	Maroon to variecoloured shales and marl
Early to Middle Eocene	Chorgali Formation	Thinly bedded limestone and marl
Early Eocene	Margala Hill Formation	Nodular foraminiferal grey limestone
Late Paleocene	Patala Formation	Greenish grey/Khaki shales with limestone beds
Middle Paleocene	Lockhart Formation	Nodular foraminiferal grey limestone
Early Paleocene	Hangu Formation	Sandstone, claystone, laterite
	---------------------------Disconformity---------------------------	
Late Cretaceous	Kawagarh Formation	Fine grained light grey limestone
Early Cretaceous	Lumshiwal Formation	Grey to brownish coarse sandstone
Late Jurassic to Early Cretaceous	Chichali Formation	Dark grey shales with sandstone beds
	---------------------------Disconformity---------------------------	
Middle Jurassic	Samana Suk Formation	Limestone with dolomitic patches, and oolites
Early Jurassic	Datta Formation	Sandstone, quartzite, microconglomerates
	---------------------------Disconformity---------------------------	
Early Cambrian	Hazira Formation/Galdanian	Calcareous siltstones and shales/Quartzites
Cambrian	Abbottabad Formation	Dolomites with sandstone, shale in lower part and boulder bed at base
	---------------------------Unconformity---------------------------	
Late Precambrian	Hazara Formation	Slates, pelites sandstones and quartzites with a horizon of gypsum and two algal limestone bands
Late Precambrian	Tanawal Formation	Quartzite and quartz mica schists with a 500 Ma intruded granite

Table-6

Stratigraphic sequence in the Peshawar Basin (after Hussain et al., 1989; Pogue et al., 1992).

Jurassic	Nikanai Ghar/Saidu Formation Tursak
Upper Triassic	Kashala Carbonates/Girarai Formation
Permian	Karapa greenschist.
Carboniferous	Jafar Kandao Formation. Shales, limestone.
Devonian	Nowshera Formation. Limestone, quartzites, sandstone, dolomites.
Silurian	Panjpir Formation. Agrillites and phyllites with crinoidal limestone.
Cambro-Ordovician	Misri Banda Quartzite.
Cambrian	Ambar Formation. Dolomite dominated carbonate sequence.
Late Proterozoic to Cambrian	Tanawal Formation. Interbedded quartzites and metapelites near Swabi >3000 m. Intruded by 516±16 Ma Mansehra Granite.
Late Proterozoic	Shekhai Formation. Quartzite overlain by a thick sequence of thin bedded to massive dolomite and arenaceous limestone and marble.
Late Proterozoic	Utch Khattak Formation. Basal conglomerate, overlain by shale and argillite.
Late Proterozoic	Shahkotbala Formation. Basal cherty limestone with shales. Gradational contact with Manki slates.
Late Proterozoic	Manki Formation over 1000 m thick. Dark low grade metapelite.
Late Proterozoic	Gandaf Formation Carbonaceous calc-phyllite, schist and carbonaceous marble with interbedded quartz schist. Correlated to Salkhala Formation.

Table-7

Stratigraphic sequence in the Kala Chitta Range (after Tahirkheli, 1982; Yeats and Hussain, 1987; Hussain et al., 1990).

Lower-Middle Eocene	Marni Khel Clays	Variegated gypsiferous mudstone and clay interbedded with sandstone, conglomerate and marl (eqv.: Kuldana Formation of Hazara)
Lower Eocene	Shekhan Limestone	Limestone
Lower Eocene	Sakesar Limestone	Nodular grey limestone with forams
Paleocene	Patala Formation	Greenish grey shales interbedded with limestone
Paleocene	Lockhart Formation	Nummulitic, nodular grey limestone
Paleocene	Hangu Formation	Claystone and laterite
Upper Cretaceous	Kawagarh Formation	Fine grained light grey limestone
Lower Cretaceous	Lumshiwal Formation	Calcareous sandstone
Upper Jurassic	Chichali Formation	Black shale
Middle Jurassic	Samana Suk Formation	Oolitic grey limestone with yellow dolomitic patches
Upper Triassic	Kingriali Formation	Dolomites
Middle Triassic	Chak Jabbi Limestone	Limestone
Lower Triassic	Mianwali Formation	Thin bedded marl and limestone
	Base Not Exposed	

Table-10
General Stratigraphy of the 'Autochthonous Folded Belt' Jangpangi et al., 1986.

Formation	Member	Lithology	Fauna/Flora	Age
	Variegated shale	Purple-red and green shale and siltstone		
Rajpur				Paleocene to Lower Eocene
	Nummulitic limestone	Hard massive grey to dark grey to sooty black limestone and calcareous shale	Nummulites sp. Assilina sp. Operculina sp.	
		------------ Unconformity ------------		
		Light to dark grey shale and slate		
Poonch Mandi		Gritty limestone, silty shale and yellowish weathered buff coloured limestone	Palemnopsis sp. Palaeonucula sp. Trigonia sp.	Jurassic
		Grey sandy limestone, fine to medium grained quartzite	Rhynochonella sp.	Triassic
		------------------------		
		Dark grey ferruginous shale, slate, grey to buff coloured limestone	Fenestella sp. Polypora sp and bivalves	
Zewan		Coral limestone, green and purple coloured tuffaceous shale with bands of quartzite	Productus sp. Waggenophyllum sp. bivalves	Upper Permian
		Dark grey to cream coloured semi-crystalline crinoidal limestone	Protoretepora, Fenestella sp	
			Crinoidal stems, cephalopods, gastropods	
		------------ Unconformity ------------		
Panjal Volcanics		Green massive amygdaloidal to vesicular andesitic flows and ash beds		Lower Permian
		------------ Unconformity ------------		
Agglomeratic Slate		Greyish white quartzite, grits and sandstone		? Upper Carboniferous to
		Grey to dark grey diamictite with dense to sparsely distributed clasts		Lower Permian
		------------ Angular Unconformity ------------		
Sincha		Light grey to grey sandy dolomite, pink and grey limestone, lenticular black chert and gypsum: 350 m	Primitive microbiota	Upper Precambrian
		------------------------		
	C	Grey-green shale/slate with bands of quartzite: 750 m		
		Purple and green shale/slate, micaceous siltstone: 200 m		
Bhimdasa	B	Grey pebbly shale/slate (diamictite) and slate with pebble to boulder-size clasts: 230 m		
	A			
				Upper Precambrian
		------------ Unconformity ------------		
Ramban		Grey to dark grey shale/slate		Upper Precambrian
		Grey quartzite with shale/slate		
		Bluish grey phyllitic slate with bands of gypsum: 1600 m		

Baila		Thin bedded laminate limestone, nodular limestone with shale/slate: 290 m		Upper Precambrian
		------------------------		
Gamir		White to bluish grey quartzite, purple and green shale/late with occasional thin bands of limestone, base not exposed: 580 m		

and Kumaun Lesser Himalaya, the Lesser Himalaya of Garhwal, Himachal, Kashmir and Salt Range appear to be the northerly extension of the rocks of the Aravalli system. While correlating the Lesser Himalaya basement with that of Tethyan Himalaya, Thakur (1992) notes that no crystalline basement of Lesser Himalaya is exposed anywhere in the Lesser Himalaya. However, it can be inferred that the Chail and the underlying Jutogh and Vaikrita originally constituted the basement both for the Lesser Himalaya as well as for the Tethys Himalaya sequences. This inference is based on the occurrence of 1,800-2,000 Ma granitic gneiss and the 500 Ma granites dated in the Chail and Jutogh groups (Thakur, 1992). The Jutogh and Vaikrita comprise the Central Crystalline over which the Phanerozoic Tethyan sequences lie to the north of the Higher Himalaya. The Haimanta Formation occurs at the base of the Phanerozoic sequence of the Tethyan Himalaya and, according to Thakur (1992), extends southwards to join the Chail Formation of the Lesser Himalaya. The Haimanta and its equivalents (the Phe Formation in Zanskar, the Martoli Formation in Kumaun and the low grade Salkhala Formation in Kashmir) form the base of the Phanerozoic sequence of the Tethys Himalaya Zone. However, it is more likely that the Kaghan Group and its equivalent the low grade Salkhalas underlie the Tanawal Formation of Mansehra and its equivalent, the Chail Formation.

The Lesser Himalayan sequence shows continuous westward lateral variations until their transformation into the stratigraphy of Attock Hazara and Peshawar Basin. The Phanerozoic stratigraphy of the latter region is very close to that of Kashmir and Spiti. It has already been suggested that both the high grade and the low grade basements of the Lesser Himalaya are can be correlated to that of the Tethyan Himalaya up in the north. The similarities show that the regional stratigraphy, in spite of its variations, can be correlated and shows that the Pakistani terrain between Main Central Thrust and Main Boundary Thrust is basically different from Lesser Himalaya of Kumaun in that it has a Tethyan affinity cover which is generally missing in Kumaun. It also shows that stratigraphic variations alone cannot act as sufficient basis for the differentiation of the Lesser and the Tethyan Himalayas. Stratigraphically a somewhat gradual and systematic variation can be traced both laterally, and in a limited way transversely, between what is considered as the Tethyan Himalaya and the Lesser Himalaya.

The Southern Tethyan Sequence

The stratigraphic sequence developed north of the Panjal Fault in the Kashmir Valley has been considered a nappe of the northern Tethyan Himalaya which has moved south to nearly cover and obliterate the Lesser Himalaya sequence, now exposed in the Autochthonous Fold Belt south of Kashmir. Thakur (1992) suggests the narrow width and imbricate nature of the Autochthonous Fold Belt west of Satluj indicates that the greater part of the Lesser Himalaya basin in Kashmir may be concealed under the Kashmir and Chamba nappes. According to Thakur (1992), the concept of a Kashmir nappe as suggested by Wadia (1934) has been vindicated by the discovery of Kishtwar window where Lesser Himalaya sequence is found under the high grade crystalline.

It has to be kept in mind, however, that the Kashmir sequence of the valley is no more different from the sequence of the Authochthonous Fold Belt to the south than it is from the Tethyan sequence of Zanskar and Spiti to the north. The southern Zanskar and Spiti sediments are believed to have moved south along the Zanskar Shear Zone, while on the other side of the Higher Himalaya, the Kashmir nappe moved south along the Panjal Thrust. The southward movement of the Peshawar Basin would be just as likely as the southward movement of Kashmir basin. However, the stratigraphic difference between Kashmir and Pir Panjal, or between the Peshawar Basin and Attock-Cherat areas are not all due to tectonic juxtaposition. In part this could be also due to normal stratigraphic lateral variations because of the distances involved.

One of the main aims of this paper is to suggest that the presence of Tethyan affinity cover rocks in the Lesser Himalaya should not be considered as synonymous with the Tethyan Himalaya as a tectonic unit which has a specific tectonic position. Although there is a well developed Tethyan affinity cover sequence south of the Main Central Thrust in the Lesser Himalaya of Pakistan, these Tethyan affinity cover rocks have developed in an area that mainly represents a continuation of the Lesser Himalaya and, therefore, may be referred to as the 'Southern Tethyan Cover Sequence' of the Lesser Himalaya. In Pakistan and Western Kashmir, the area between the Main Central Thrust and the Main Boundary Thrust, which includes the low to medium grade Upper Proterozoic basement units in the north, the Peshawar Basin sequence and the sedimentary sequences of Autochthonous Fold Belt in Neelum, Kaghan, Hazara, Attock-Cherat and Kala Chitta in the south, constitute the area of the Lesser Himalaya. The stratigraphic package of this area is different from the Lesser Himalaya of Deoban-Simla-Karol area. Nevertheless, the tectonic subdivision of the Himalaya cannot be made dependent on the facies of a certain type. The tectonic position, metamorphism, and structural style justify the inclusion of this area south of the Higher Himalaya in Pakistan as the Lesser Himalaya.

The Northern Tethyan Sequence or the Tethys (Tibetan) Himalaya in Pakistan

In the Central and Eastern Himalaya (of India, Nepal and Tibet), the Phanerozoic Tethyan sedimentary cover has developed only to the north of the Higher Himalaya and is generally though not entirely absent from the Lesser Himalaya. In Pakistan, however, the presence of the Tethyan sedimentary lithologies south of Higher Himalaya has been noted as also in Kashmir. Nevertheless, there is a problem of clearly delimiting the presence (or absence) of the Tethyan Himalaya (i.e., the northern Tethyan stratigraphic sequence in Pakistan). In general, the Tethyan Himalaya tectonic subdivision has developed more or less continuously for over 2,000 Km from Assam in the east to Zanskar-Ladakh in the west. Tectonically, it overlies the Higher Himalaya to the south and is delimited to the north by the Indus Suture. This Phanerozoic cover slab part of the former northern margin of the Indian continental plate, clearly lies to the north of the Higher Himalaya. In Pakistan, the question then arises about the identification of this Phanerozoic sequence.

In Pakistan, the Higher Himalaya has one of the most distinct exposures in the Himalaya. Between the Indus Suture in the north and the Main Central Thrust in the south, a fairly wide Higher Himalayan slab occurs in the areas of Neelum Valley (Kashmir) and Kaghan. West of Kaghan, most probably associated to syntaxial deformation, this slab pinches out. However, west of River Indus and the Thakot Fault, the Higher Himalaya crops out again and extends into Lower Swat and further west across the Afghanistan border. Following the tectonic juxtapositions in Central and Eastern Himalaya, the Tethyan Himalaya would be expected to occur between the Higher Himalaya and the Indus Suture in Pakistan also but no such thick slab of Phanerozoic sediment can be readily detected. We should, therefore, look either for a metamorphosed equivalent or tectonic or erosional remnants. There have been two main suggestions put forward for the existence for the Tethyan Himalaya in Pakistan: either they occur as the relatively limited occurrences of low grade sediments in between the Higher Himalaya and the Indus Suture in upper Kaghan and Swat and the Banna sequence (the Low Grade Cover as the Northern Tethyan Himalaya in Pakistan, Chaudhry et al., 1992; Chaudhry and Ghazanfar, 1993); or the Tethyan Himalaya are represented by the high grade cover that intricately overlies the Higher Himalaya basement (Metasedimentary cover as the Tethys Himalaya in Pakistan) as suggested by Greco et al. (1989), Papritz and Rey (1989), Spencer (1993), DiPietro (1991), DiPietro and Lawrence (1991) and Spencer and Gebauer (1996).

Low Grade Cover as the Northern Tethyan Himalaya in Pakistan

There are a number of occurrences of low grade, slightly metamorphosed sediments just south of the Indus Suture in Pakistan (Fig. 3) (Chaudhry et al., 1992; Chaudhry and Ghazanfar, 1993). These sediments first appear near Babusar Pass (Upper Kaghan) and continue westward as a thin but fairly continuous sequence towards the Allai area (Kohistan). Here, they expand in the form of a kidney-shaped outcrop and develop a much greater thickness. Other outcrops also appear to the west of the Thakot Fault. According to Chaudhry et al. (1992), these Tethyan Himalaya sediments not only occur only north of the Higher Himalaya but also directly lying on top of the Higher Himalaya and as discontinuous exposures in the form of distinct and separate synclinal occurrences. At places they have been noted to be intimately imbricated with the Higher Himalaya sequence below (Coward et al., 1988). Most importantly both of these occurrences, whether directly beneath the Indus Suture or overlying and folded with the Higher Himalaya, are recognised to be of low metamorphic grade (Martin et al., 1962; Chaudhry and Ghazanfar, 1993). The lithologic nature of these rocks has been summarised for different areas below:

Kaghan Valley:- An attenuated and tectonised sequence of low grade sedimentary rocks occurs in the upper Kaghan Valley. Starting near Babusar Pass, the sequence trends southwest through Lohya Lul Nar, Ledi, Dila along Nili Nadi, through Kohistan towards Chor Ka Maidan and eventually to Banna. To the west of Kaghan Valley the sequence expands at Banna (see below). In the Lohya Lul Nar, the off-white Bachh limestone unit is thinly bedded and slightly argillaceous. The associated calc-pelites show chlorite flakes. The graphitic pelite unit is better seen in the Ledi Nala near Richpar. It is a pyritous dull black phyllite with some quartz veins. In the Nili Nadi (Bhimbal Valley), northwest of Naran, the low grade sequence occurs between Chhalayyan and Dila. In this area graphitic schists with intercalations of calc-pelites and locally oolitic grey marble overlie meta-turbidites which have small intrusive bodies of granite.

Banna:- An over one kilometre thick sedimentary sequence is exposed in a kidney shaped outcrop beneath the Indus Suture in the Banna area. The sequence (Table 11) dominantly comprises of limestone above and carbonaceous argillites below both now metamorphosed to lower greenschist facies. The limestone is medium grained and light grey with white streaks. It is, generally medium to thin bedded with subordinate thick beds. The middle part of the sequence comprises thick bands of graphitic phyllites alternating with thick bands of thin bedded limestone. This is well exhibited on the slopes above Palang, where a new

Table 11.
Lithological sequence of low grade sediments at Banna, Allai.

Lithologies	Approx. Thickness
Sooty black graphitic schist	50m
Mainly marble with subordinate calc-schist and graphitic schist	>500m
Calc-schist and marble with alternations of graphitic schist	400m
Graphitic schist with subordinate calc-schist and marble	300m

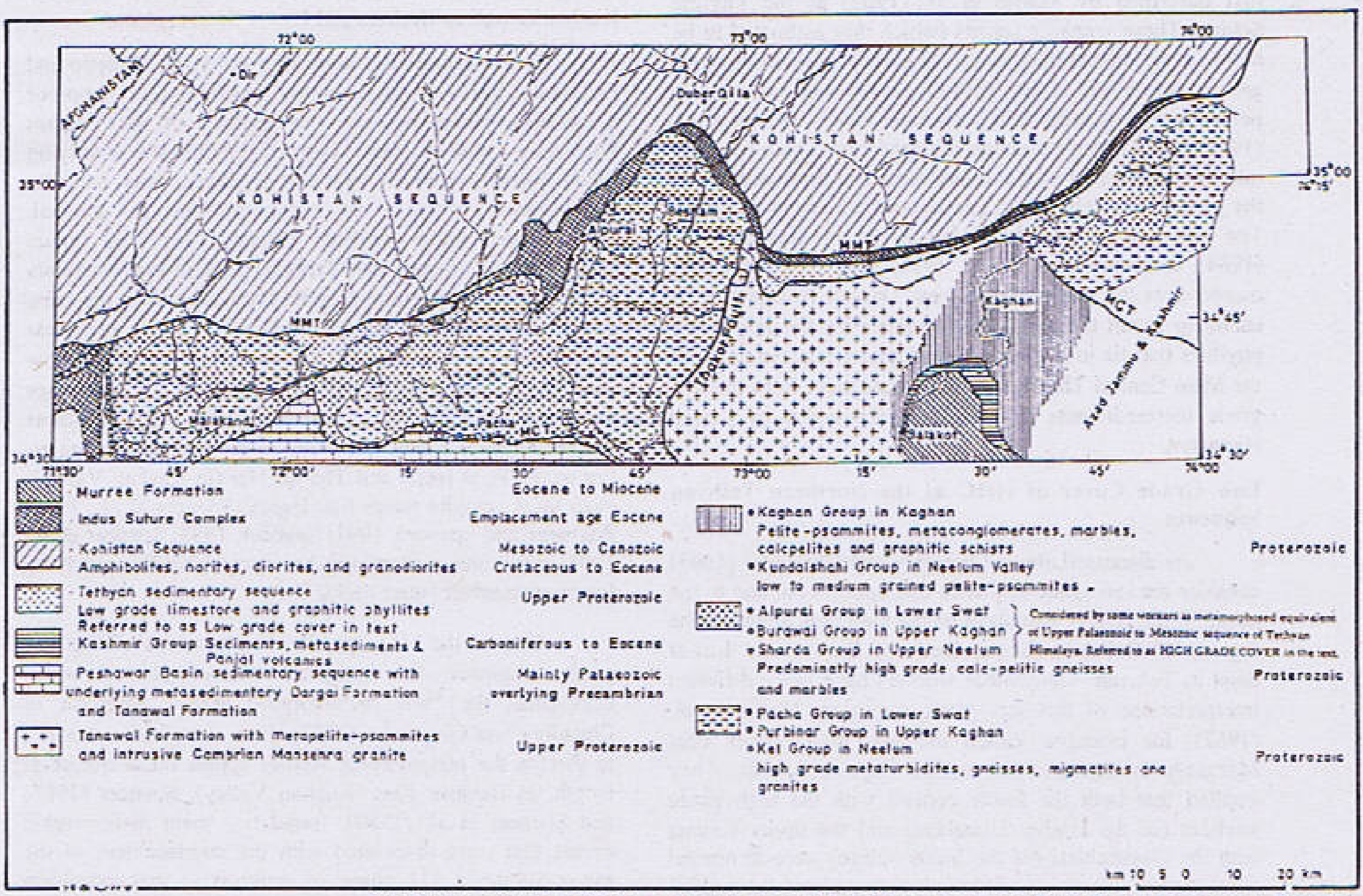

Fig.3. Geologic map of Kaghan and Besham and Lower Swat showing Higher Himalaya with the distribution of high grade cover rocks and of low grade sediments.

dam is proposed. The Banna sediments are lying with a faulted contact at the base in a synclinal trough with a north northeast-south southwest axis plunging northwards at low angle. The sequence is resting on sheared and mylonitised porphyritic Mansehra Granite. The graphitic phyllites and included limestone intercalations show fault related folding in the lower part of the sequence.

Karora/Besham:- Another occurrence of low grade sediments lying directly on top of the high grade Higher Himalaya is found near Karora (Ashraf et al., 1980) on the Besham Swat road. Here, the unconformable contact with the granite-gneiss basement is marked by a conglomerate that contains clasts of pegmatite, foliated granite gneiss, psammites and pelites. The conglomerate is overlain by psammites, then graphitic pelites which become increasingly calcareous towards the top of the sequence, eventually being replaced by marbles (Coward et al., 1988).

Saidu/Lower Swat:- The low grade sequence overlying the high grade rocks in the region of Lower Swat (Fig.3) was first described by Martin et al. (1962) as the Phyllite Schists. These graphitic schists (which they estimated to be 600 to 1200 meters thick) were described as generally dark grey in colour and almost entirely pelitic, with some semi-pelites and occasional thin psammitic layers. Martin et al. (1962) imply that the contacts are gradational both upwards into the greenschist of the suture zone and downwards into the garnet mica-schist with garnet upto 2.5 cm in diameter. The unit was named the Saidu Schist by Kazmi et al. (1984). Chaudhry et al. (1974, 1976, 1992) had previously named it as the Dargai schist near Dargai. However, it is useful to retain the name Saidu schists for the low grade phyllites that lie in the terrane of Higher Himalaya north of the Main Central Thrust, to differentiate them from the low grade metasediments at Dargai in the realm of Lesser Himalaya.

Low Grade Cover of HHC as the Northern Tethyan Sequence

As discussed above Chaudhry and Ghazanfar (1993) consider the low grade sequence that appears on, and to the north of, the Higher Himalaya below the Indus Suture in the regions of Babusar, Banna, Besham, Karora and Lower Swat as Tethyan. Many other workers have made different interpretations of this low grade sequence. Martin et al. (1962), for example, called the low grade rocks near Manglaur in Lower Swat as the Phyllite Schists. They implied that both the lower contact with the high grade gneisses (of the Higher Himalaya) and the upper contact with the greenschists (of the Indus Suture) were in normal stratigraphic succession. Although they realised the sudden appearance of large sized (2.5 cm) garnet in the underlying rocks, they did not place a fault between the two sequences. Kazmi et al. (1984) correlated the low grade sequence of Lower Swat, with the Indus Flysch and considered it Palaeozoic to Mesozoic. The Indus Flysch (or the Lamayuru Formation) has been assigned a Triassic to Upper Cretaceous age in Ladakh and, further east, it is overlain by Paleocene-Lower Eocene nummulitic limestone. In Lower Swat the lower flyschoid part is overlain by shelf carbonates.

Coward et al. (1988) have interpreted the over one kilometre thick Banna sequence of the Allai area as a thrusted wedge. They interpret that this sedimentary sequence of southern Hazara has been transported from the south as a backthrust sheet and is now placed further north between the Hazara nappe and the Indus Suture. However, the sedimentary sequence of south Hazara is at least 70 Km south of this location. Moreover, it is difficult to correlate the unfossiliferous thin bedded grey calcareous sequence of Banna and its underlying graphitic schist with any sedimentary sequence of Hazara. Finally, it is not only the Banna sequence but also the numerous other occurrences of low grade sediments that need to be explained in Upper Kaghan as well as Besham and Lower Swat regions.

Working more recently in Lower Swat, Dipietro and Lawrence (1991) do not recognise a metamorphic jump nor a tectonic contact between the gneisses of the Tilgram Formation (their Kashala Formation) and the overlying Saidu Formation which they call phyllites. They consider the upward decrease of metamorphism as gradual. Furthermore, these workers consider the low grade sediments as younger than Triassic because they correlate the underlying high grade Tilgram Formation to be the same as the Upper Triassic Kashala Formation of the Peshawar Basin to the south. Even if the lower contact of the low grade sediments is explained as gradual at any one place there are numerous in Lower Swat and Kaghan places where kyanite is frequently found in the contact lithologies. For example, at Besal and Thanda Nar (in Kaghan Valley), even local eclogite facies lithologies (Spencer et al., 1990; Pognante and Spencer, 1991; Spencer, 1993; Spencer et al., 1995) are found a short distance away from the overlying lower greenschist facies rocks.

One of the more popular explanations of the low grade sequence is retrograde metamorphism, which contradicts the "low metamorphic grade" assertion of Chaudhry and Ghazanfar (1993). It is, therefore, necessary to discuss the metamorphic studies across Indus Suture at length. In Babusar Pass (Kaghan Valley), Spencer (1988) and Spencer et al. (1989). found two main metamorphic events that were associated with the emplacement of the Indus Suture: a M1 phase of progressive metamorphism followed by a M2 phase of retrogressive metamorphism. The M1 phase of progressive metamorphism reaches kyanite grade, upper amphibolite facies metamorphism and is interpreted as being associated with the initial subduction of the Indian Plate, probably during the Late Cretaceous. The M2 phase of retrogressive metamorphism is a Barrovian-type of overprinted retrogressive metamorphism interpreted as being associated with the rejuvenation of movement along the Indus Suture during the terminal collision and obduction of the Kohistan Island Arc and Asian Plate. The M2 metamorphism is interpreted to have occurred during the Late Eocene to early Oligocene. The effect of the M1 and M2 phases of metamorphism were found to vary on the lithological units within the Indus Suture at Babusar Pass. For example, the metamorphism in the Babusar Ultramafic Mélange is indicated by the general mineral assemblage of talc + carbonate ± quartz. This assemblage is stable over a narrow temperature range of 300-360°C but unrestricted over a wide pressure range. Presence of syntectonic zeolites also suggest that the pressures were lower than 3 Kbar. Thus, the M2 retrogressive metamorphism is the most dominant in this mélange. The abundance of talc in the matrix and clasts suggests that the fluid phase during retrogression was near X_{CO_2} > 10 Mole percent (Trommsdorff et al., 1969; Winkler, 1979). The mineral paragenesis of the Tatabai Metavolcanic mélange suggest physical conditions that are of greenschist facies. This is estimated to occur at temperatures of 360°C and 4.5-5 Kbar (Laird and Albee, 1981) in the M2 phase of retrogressive metamorphism. Therefore, Spencer (1988) argues that the Indus Suture at Babusar Pass marks a significant break in pressure and temperature conditions from upper amphibolite facies in the Indian Plate to lower greenschist facies in the Kohistan Island Arc with no occurrence of low grade (or unmetamorphosed) lithologies in between. Furthermore, the mélanges are transitional between these facies and a post-kinematic M2 retrogressive metamorphism is seen by mineral replacement and low grade minerals such as chlorite and epidote. It is suggested that the mélanges show a lower temperature metamorphism and pressure than the adjacent high grade Indian Plate lithologies and medium grade Kohistan Amphibolites, a retrogressive characteristic of sutures that is common to subduction zones. The lower than average geothermal gradients within the subduction zone causes a local depression of the metamorphic isograds (Ernst, 1973). The absence of high-pressure blueschist mineral phases at Babusar Pass does, however, makes it possible that this area represents a fairly shallow structural level within the subduction zone which developed during Arc- continent convergence and collision. It is argued that, in places along the Indus Suture, the Kohistan Arc contained blueschists that predate the collision (Maluski et al., 1984) in the Indus Suture mélange Group (Desio, 1977; Shams, 1980; Shams et al, 1980; Kazmi et al., 1984). This would, therefore, indicate that the Kohistan Arc immediately above the Indus Suture must have been cold, which would rule out the possibility of significant downward heat transfer across the Indus Suture. Therefore, the Kohistan Amphibolites were colder than the high grade metamorphic rocks of the Indian Plate. Rather than the normal prograde inversion of blueschist to greenschist in the Indus Suture mélange group, there is the possibility of an upward heat transfer across the Indus Suture. This sharp thermal discordance across the Indus Suture has been recorded by fission track data by Zeitler (1985).

Chamberlain et al. (1991) also calculated some pressure and temperature conditions for lithologies in the Indus Suture Zone, and adjacent Indian Plate lithologies to the south at Babusar Pass. They were obtained by mineral assemblages, textural relationships and thermo-barometric techniques, especially by using inclusion minerals in garnet. They suggest that the differences between the pressure-temperature conditions calculated between the Indian Plate and the Indian Plate mélange are real, where the Indian plate may have reached higher maximum temperatures (upto 580°C) than the maximum in the mélange (~520°C). The garnets in the volcanic mélange record a different thermal history where cores equilibrated at temperatures ~ 580°C compared to the rim which was ~520°C. Their data show that the mélange lithologies associated with the Indus Suture were metamorphosed at similar conditions of low temperature Barrovian metamorphism. The Indian plate mélange, for example, contained garnet + chlorite ± chloritoid ± biotite ± calcite + phengite + paragonite + plagioclase + quartz. The amphibolites in both the Indian and Kohistan plate mélanges contained garnet + amphibole + chlorite + plagioclase + albite ± epidote ± muscovite ± biotite + calcite + quartz (although it is here noted that Ca/Na plagioclase and albite cannot be in equilibrium and hence in the same paragenesis; B. Lombardo, pers. comm.). They also note on a sample of a calc-schist (PK-22-88) a rare assemblage containing garnet + hornblende + chloritoid + zoisite + phengite + calcite + quartz + plagioclase, which is suggested to be found in only a few places in the world (Thompson and LeClair, 1987). Geobarometric and geothermometric calculations were also made using the garnet-chlorite (Dickenson and Hewitt, 1986), garnet-biotite (Ferry and Spear, 1978) and garnet-hornblende (Graham and Powell, 1984) geothermometers and the garnet-muscovite-biotite-plagioclase-quartz and garnet-hornblende-plagioclase-quartz (Kohn and Spear, 1990) geobarometers. Temperatures range from 352°C-585°C and pressures from 6.7-9.4 Kbar. Chamberlain et al. (1991) interpret these results as showing that the Suture zone has metamorphic discontinuities which occur at major thrust faults and that the rocks of the Indian plate equilibrated at somewhat higher pressures (~ 8.5 Kbar) and temperatures (~550°C) than the rocks in the calc-schist mélange (pressure ~ 7 Kbar and temperatures ~ 400°C). In the Kohistan volcanic mélange, one pressure-temperature estimate of 585°C at ~9 Kbar was obtained. They also calculated pressure-temperature paths for lithologies in the Indus Suture Zone at Babusar Pass, within the sediments that are considered by Ghazanfar et al. (1991) as 'low grade'. These calculations were made using inclusion minerals in garnet and they showed that the Indian Plate mélange had a different history from that of the Kohistan Arc mélange (Volcanic mélange). Garnets from both the Indian plate and calc-schist mélange (Indian plate mélange) showed an initial increase in temperature of 50° to 100°C which was followed by a decrease in temperature of ~50°C from the temperature maximum to the temperatures of final equilibrium (Chamberlain et al., 1991). The barometer history of the mélange units was not well constrained, but one sample (PK-24-88) from the calc-schist mélange shows that pressure decreased by ~2.5 kbars during garnet growth. Chamberlain et al. (1991) suggest that the differences between the pressure-temperature conditions calculated between the Indian plate and the Indian plate mélange is that the Indian plate may have reached higher maximum temperatures (upto 580°C) than the maximum in the mélange (~520°C). The garnets in the volcanic mélange record a different thermal history where cores equilibrated at temperatures ~ 580°C where the rim was ~520°C. This work on the Indus suture lithologies at Babusar Pass by Chamberlain et al. (1991) provides information on the pressure-temperature history of the Suture Zone. The data records significantly lower pressure and temperature estimates than that of the Upper Kaghan Nappe (and the Kohistan Island Arc) suggesting that the Indus Suture itself is a 'lower' grade discontinuity separating two higher grade units (the Indian Plate and the Kohistan Island Arc).

Finally, Smith et al. (1994) calculated pressures and temperatures in lithologies of the Indian Plate (Higher Himalaya) and the Main Mantle Thrust Zone in the Naran area (Middle Kaghan). Specifically, he analysed the 'Graphitic Schists' which occur directly below the suture which is the same unit that Ghazanfar et al. (1991) considers 'low grade'. Two samples (KK-23, KK-26) contained the assemblage quartz + muscovite + garnet + staurolite + biotite which can be used to determine temperatures using the garnet-biotite exchange equilibria. However, this assemblage (as noted by Smith et al., 1994) does not lend itself to a determination of pressure using mineral equilibria and reasonable values were assumed. The results gave *minimum* temperatures of 480-520°C with pressures in the range of 4-8 Kbar. Therefore, this unit occurs mainly in the chlorite-epidote zone of the lower amphibolite facies (in the suture zone). The structurally lower Higher Himalaya is shown also to be at staurolite-garnet grade. Therefore, the metamorphism is clearly considered retrograde by Smith et al. (1994) with no evidence at all for unmetamorphosed or low grade lithologies between the Indian Plate and the Suture.

In summary, the work of Spencer (1988), Spencer et al. (1989), Chamberlain et al. (1991) and Smith et al. (1994) indicate that none of the rocks analysed could be considered as 'low' grade and all of them prefer the interpretation of these unit directly below the suture zones and retrogressed. Nevertheless, according to four of the authors of this present paper (MG, MNC, SSH, HD), the retrogressive relationship of the low grade sequence in Kaghan (Spencer, 1988; Spencer et al., 1989; Chamberlain et al., 1991; Smith et al., 1994) with the underlying high grade rocks is regarded as questionable. The metamorphic jump from the high grade Higher Himalaya to the overlying low grade lithologies (Saidu Formation) is from upper amphibolite facies to greenschist facies. They consider it difficult to explain the metamorphic jump simply as one of retrogression. According to them, such a uniform retrogression as appears near Saidu (and elsewhere in Lower Swat), as well as for the Banna sequence (in Allai) is highly improbable. They argue that in the Saidu, Karora and Banna Allai regions, no relics of high grade metamorphics or migmatites, nor evidence of extensive shearing are found in these regions. This therefore makes the retrogressive interpretation of Spencer (1988), Spencer et al. (1989), Chamberlain et al. (1991) and Smith et al. (1994) implausible for these regions. They consider that there is a more or less lateral continuation between the over one kilometer thick, Banna sequence and the Upper Kaghan low grade slivers. Therefore, because the Banna sequence is thought to be be 'low grade', by assumption, the Babusar slivers have to be considered the same and not a sequence that has undergone retrogression.

A final possibility that needs to be considered is that the lithologies between the Higher Himalaya and the Indus Suture, undoubtedly of 'Tethyan affinity', are simply the sediments of the passive margin of the Indian continent. They can therefore be considered as part of the Suture Zone itself. As such, these flysch sediments were preserved in the suture zone, due to the lower than average geothermal gradients within the subduction zone causes a local depression of the metamorphic isograds (Ernst, 1973).

In general the preserved low grade sediments are pelitic below, calc-pelitic in the middle and calcareous above. The base is nearly everywhere tectonised. Only at one locality (Sassoi near Karora in the Lower Swat/Besham area), a boulder bed mainly of local derivation underlies the graphitic phyllites and rests directly on the high grade gneisses of the Higher Himalaya. In the Lower Swat area the lower pelitic part is well developed and several hundred meters thick. Chaudhry et al., 1994b) also suggest presence of the Trans-Himadri Fault at their base and interpreted this sequence as the northern Tethyan sequence or the Tethyan Himalaya in Pakistan. No fossils have so far been reported from the low grade sedimentary sequence lying below the Indus Suture. However, no serious efforts have so far been made to find these and may be found at a later date. Absence of fossils, if real, strengthens the possibility of a Precambrian age for its lower part. Similarly, the Tethyan sequence in Kumaun, Spiti, Kashmir and Hazara is unfossiliferous in the Lower Cambrian and the upper Proterozoic. However, the Tethyan sequence is fairly richly fossiliferous from Cambrian upwards. Likewise, the low grade metamorphism of the northern Tethyan sequence in Pakistan indicates that these relict slices may belong to the lowermost likely Upper Proterozoic part of the Tethyan pile, which is metamorphosed in the low grade in the Tethyan of Central and Eastern Himalaya.

High Grade Metasedimentary cover as the Tethyan Himalaya in Pakistan

In the Higher Himalaya of Kaghan Valley (and in the areas further to the west), a basement-cover sequence is recognised (Greco et al., 1989) that is clearly different from the last known occurrence of the basement-only lithologies to the east in Zanskar. The basement consists of the Higher Himalayan Crystalline *(sensu stricto)* with granitoids and metagranites. This is overlain by a cover unit of metagraywackes of suggested Lower Palaeozoic age (Greco et.al. 1989) with a clear sedimentary origin. This is then diachronously and unconformably overlain by a distinctively mappable unit consisting of some 30-40 extensive amphibolite layers at the base of the cover. It is associated with syn-volcanic marine deposits (marbles). This sequence then develops into an extensive dolomite-rich shelf sequence with minor mica-schist horizons.

Two main ideas exist on the age of these high grade cover units overlying the basement described above: (1) the metasedimentary units were thought to be part of the Precambrian Salkhala Formation proposed by Wadia (1931). This Precambrian interpretation has been incorporated into numerous works since (e.g., Chaudhry and Ghazanfar, 1987; Chaudhry et al., 1992), (2) Greco et al. (1989) and Papritz and Rey (1989) first made the suggestion that the cover sequence was not Precambrian, but suggested a correlation and comparison with adjacent regions. To the east, for example, the Permian Panjal Traps and overlying Triassic series were noted to have a distinct similarity to the Cover units found in Upper Kaghan. Subsequently, numerous lines of evidence were suggested to link the metamorphosed (eclogite/amphibolite facies) cover to the unmetamorphosed (with up to greenschist facies transition) equivalent (Greco et al., 1989; Papritz and Rey, 1989; Spencer et al., 1991; Spencer, 1993) based on field, petrographic, geochemical, stratigraphic, structural, fossil, stable isotope and regional correlations. In order to solve the problem of the protolith age of the cover, an attempt was made to make an accurate determination of the eclogite protolith. Previous protolith ages on the Upper Kaghan eclogites by Sm-Nd whole-rock data (Spencer, 1993, Spencer et al., 1995) yielded an unpublished errorchron 'age' of 337±434 Ma. New work incorporating SHRIMP-dating, especially when combined with cathodoluminescence information of the zircon to be dated, is however a new technique that can now obtain this required information (e.g., Gebauer et al., 1988; Gebauer, in press; Vavra et al., in press). Thus, zircons from the eclogites of Upper Kaghan (Sample 90/180 used in Tonarini et al., 1993) were analysed to help solve the problem of the disputed and geochronologically poorly constrained protolith ages of the Higher Himalayan Cover. Within the oscillatory zoned zircon domains that were formed during precipitation of zircon in the mafic protolith, a Permian protolith age of about 269 Ma was found. It is important to note that, based on the size of the magmatic zircons, the protolith was not effusive (basaltic) but intrusive (e.g. gabbroic). This is in accordance with the outcrop locality - a basement feeder (Tonarini et al., 1993; Spencer, 1993). This data, according to Spencer and Gebauer (1996) confirms a Tethyan affinity and, therefore, the stratigraphic correlations that were first suggested by Greco et al. (1989). Moreover, according to Spencer and Gebauer (1996), these results provide for a modified extension of the Tethyan Himalaya into Pakistan. The new SHRIMP evidence is suggested to show that the Higher Himalaya and Tethyan Himalaya can also be clearly distinguished in the NW Himalayan region. However, the Tethyan Himalaya is clearly modified (metamorphosed) in this region and, for the sake of consistency and conformity, they suggest that the term "Higher Himalaya" be kept in the Pakistan Region, even though it is now shown that this Higher Himalayan units only act as a basement to its cover of the "Tethyan Himalaya".

Similar observations of a 'Tethyan' metamorphic cover over the Higher Himalayan have also been made in the in Ladakh (India). As reported by Gansser (1964), Hayden (1904, 1908) was the first person who recognized some relation of the Spiti sediments (Tethyan Himalaya) with the Rupshu metamorphics (Higher Himalaya). He was able to trace Carboniferous-Triassic sediments into the slaty and phyllitic rocks on the border of Tso Morari of southern Rupshu. Also, Honegger et al. (1982) reported that in the High Himalayas, the Himalayan-aged tectonic activity was accompanied and outlasted by a Barrovian-type metamorphism that affected Triassic sediments of the Kashmir-Nun Kun Synclinorium upto kyanite/staurolite grade and the deeper seated units upto sillimanite grade.

Finally, the possibility of a thrust relationship between the Mesozoic (Tethyan Himalaya) and the underlying Vaikrita Group (Higher Himalaya was invoked by Valdiya (1980). He noted that the upper part of the doubly plunging Tso Morari anticline in southeastern Ladakh constitutes metamorphosed cover strata, but the cores are made up of basement rocks (Vaikrita) intruded by anatectic granites and involved in imbricate thrusting. The More Thrust is suggested to have brought Mesozoic strata from the south upon the tectonised Tso Morari dome. Valdiya (1980) pointed out again that a regional fault extending more than 1,600 Km, from north of Nun Kun (Zanskar) to east of Sagarmatha (Everest), also marked the boundary between the Himadri (Higher Himalaya) metamorphic terrane and the Tethyan Himalaya sedimentary rocks.

Discussion of Metasedimentary Cover as the Northern Tethyan Sequence North of the MCT

As noted above, there are two main cover sequences: a low grade sedimentary and a high grade metasedimentary overlying the Higher Himalaya basement in Pakistan (Fig. 3). These have both been individually suggested to represent the Tethyan Himalaya north of the Main central thrust in Pakistan. The arguments that suggest that the high grade cover sequences of the Higher Himalaya to be the modified equivalent of the Tethyan Himalaya have been noted. Four of us (MG, MNC, SSH, HD) however, consider the age of the high grade cover rocks of the Higher Himalaya in Pakistan as a less than settled question. The protolith age of the eclogite (269 Ma; Spencer and Gebauer, 1996) and the correlation of these metabasites with the Panjal volcanics of Ladakh would indicate an Upper Carboniferous to Mesozoic age for the high grade metamorphic cover of Higher Himalaya in Pakistan. However, Chaudhry and Ghazanfar (1992), prefer the suggested Precambrian age for this cover unit. In general, the following evidence can be cited for an older than Upper Palaeozoic age for the high grade cover overlying the granitic basement. First, it has been suggested that the low grade Saidu Formation of Lower Swat (which is flyschoid in part and correlates with the Eo-Cambrian Hazara slates) continues as the basement Dargai Formation under the Lesser Himalaya of Peshawar Basin where they are overlain by the younger Palaeozoic sequence. This idea is strengthened by the fact that Baig (1990) dated with the Argon-Argon method a pegmatite vein cutting the low grade Karora sequence near Besham at 493 ± 1 Ma. However, it is unclear how this age survived the subsequent reheating of the Himalayan metamorphism, and so this age needs to be considered questionable.

Secondly, an intrusive granitic body is found at Malakand, within the domain of the Higher Himalaya, just to the north of the major tectonic scar suggested to be the Main Central Thrust. It is a roughly oval shaped intrusion (8 Km by 5.5 Km) of generally non-porphyritic fine to medium granite cut by small pegmatite and aplite veins. Detailed description of the Malakand Granite is given in Chaudhry et al. (1976) and Hamidullah et al. (1986). Maluski and Matte (1984) have attributed an age of 23 ± 2 Ma to the Malakand granite on the basis of $^{39}Ar/^{40}Ar$ technique using biotite separates. More recently, Zeitler and Chamberlain (1991) and Smith et al. (1994) have analyzed cores and rims of zircons with U/Pb SHRIMP analysis. They found Carboniferous ages of 275 ± 11 Ma in the cores and 47 ± 3 on the overgrowth rims. They interpret the cores to represent the magmatic age of this intrusion and the ages on the rims to correspond with the Himalayan metamorphism. Therefore, the age (23 ± 2 Ma) given by Maluski and Matte (1984) must be interpreted as a biotite cooling age. At Malakand, the Malakand Granite has been mapped by Chaudhry et al. (1974) as intruding the high grade cover rocks of Alpurai Group forming a thermal aureole. If the protolith age represents its intrusion age, then the minimum age of the cover must be Pre-Carboniferous. Alternatively, if the Malakand Granite was remobilised during the Himalayan metamorphism (and incorporated the protolith zircons), then the cover would be Pre-Tertiary.

Thus to find the correlatives of Tethyan Himalaya in Pakistan it is important to decide whether the high grade cover of the Higher Himalaya is Upper Palaeozoic-Mesozoic and, therefore, 'Tethyan'. This is now considered as established, based on radiometric dating (Spencer and Gebauer, 1996) to one of the authors of this paper (DAS). The other four authors of this paper (MG, MNC, SSH, HD) however, consider the evidence contradictory and insufficient.

CONCLUSIONS

The overall tectonic picture differs between Kashmir and Western Himalaya of Pakistan in as much as there is a well developed Main Central Thrust followed by Higher Himalaya to the north of the Peshawar Basin and to the north of Naran in Upper Kaghan. The Higher Himalaya in Kashmir region does not show a well developed slab, but rather as anticlinal/domal structures (e.g., the Tso Morari) and as windows in the Zanskar region. In Pakistan, it has now become possible to demarcate the terranes of Lesser- and Higher Himalaya due to the delineation of the Main Central Thrust in Neelum, Kaghan and Lower Swat. The zone between Main Central Thrust and Main Boundary Thrust in Pakistan, with the low grade basement rocks of Hazara slates and Tanawal Formation and overlain by a Phanerozoic sedimentary cover has been called the Lesser Himalaya. In Pakistan, the Phanerozoic Tethyan cover sequence has developed not only to the north between the

Higher Himalaya and the Indus Suture but also to the south of Main Central Thrust in the domain of Lesser Himalaya. The Autochthonous Fold belt of Pir Panjal represents a lateral continuation of the Kumaun Lesser Himalaya with the additional development of post Upper Carboniferous sequence. This belt can be traced still further west over the Hazara-Kashmir Syntaxis into the sedimentary belt of Hazara and Attock -Cherat where cover sequences of somewhat different facies are met. The Peshawar Basin developed to the north of this sedimentary belt is analogous to the Kashmir basin and represents not only a similarly well developed Palaeozoic stratigraphy but also an alkaline rift related magmatism of Carboniferous to Permian age.

One of the main questions in Pakistan regarding the Tethyan Himalaya is whether or not it has developed at all north of the Higher Himalaya. This is the typical domain for the development of Tethyan Himalaya in India and Nepal. Here the granitic Higher Himalayan basement in Pakistan is overlain by a high grade cover sequence called the Burawai and Alpurai groups in Kaghan and Swat respectively. Subsequently, this is suggested to be overlain by a less well developed low grade cover sequence of carbonaceous shales, schists, limestones and marbles. Many geological workers (e.g., Greco, et al., 1989; Spencer, 1993) tend to regard the high grade cover as Permo-Triassic and therefore, the entire sequence overlying the granitic basement as younger than Permian. As such, they imply that the Tethyan Himalaya can also be clearly distinguished in the NW Himalayan region although note that the Tethyan Himalaya is clearly modified in this region. One of the authors of this paper (DAS) suggests that for the sake of consistency and conformity, the term "Higher Himalaya" only be kept in the Pakistan region, even though it is now shown that this Higher Himalayan unit acts as a basement to its cover of the "Tethyan Himalaya".

By contrast, suggestions have been made by other workers (Ghazanfar et al., 1991), a viewpoint that is followed by four authors of this paper (MG, MNC, SSH, HD), that the overlying low grade cover that occur in the form of synclinal inliers and patches which generally occur to the north of the Higher Himalaya, should not be considered as part of this unit. These low grade pelite psammites and limestones are, according to these workers, possibly representative of the lower part of the Phanerozoic Tethyan sequence which eastwards in Kashmir is generally low grade and unfossiliferous. Moreover, they have a similarly extensional tectonised lower contact with the underlying Higher Himalaya (inclusive of the high grade cover) and may be regarded at the Tethyan Himalaya.

MG and MNC thank the University of the Punjab (Lahore) for a special research grant which supported their fieldwork in the Pakistani Himalaya. DAS was financially supported by an ETH-Imperial College Scholarship (Nr. 0.330.028.02/8), a Swiss Federal Institute of Technology Grant (Nr. 0.20.367.89) and a Swiss National Science Foundation Research Fellowship (Nr. 2100-039080.93/1). SSH and HD thank the Pakistan Museum of Natural History and the Pakistan Science Foundation for logistical and financial support.

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STRUCTURAL GEOLOGY OF THE WESTERN EXTREMITY OF THE KOHISTAN ISLAND ARC IN DIR AREA, NWFP.

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Abstract:-*Structural studies show that the rock of Kohistan Island Arc exposed in the area are folded into northwards dipping southwards verging tight folds in the south (near MMT) which opens up northwards. The amphibolite have undergone at least two phases of isoclinal folding. In the first phase recumbent or isoclinal folding S_1. axial planner faliation 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 rocks of Kohistan Island Arc has undergone a third phase of deformation which produced the shear zones resulting into retrograde metamorphic chlorite grade rocks. That is related most probably to the collision of India plate with Kohistan complex.*

The southern part of the Dir amphibolite near MMT mostly trend EW and dips 65° to 80° northwards which is almost parallel to the trend of MMT. In the central portion of the mapped area the plutonic rocks trend NE to SW and their dips varies from 40° to 70° NW and SE. Most of the fold axes in the plutonic sequences are parallel to each other which mostly trend NE to SW and plunges from 12° to 50°. The northern part of the Dir amphibolites mostly NE and dips 15° to 60° SE.

INTRODUCTION

The area is located on the south western extremity of Kohistan Island Arc where it is sutured to the Precambrian basement of Indian plate in the form of Main Mantle Thrust (M.M.T). The structures of the area are strongly effected by this regional feature and mostly trends parallel to it.

The southern portion of Kohistan complex in Timargara area, comprises mainly of amphibolites which are tightly folded into southwards upright and northwards dipping folds, which slightly opens up northwards.

The plutonic sequence comprising norites, gabbronorites, diorites, tonalites, trondhjemites and granites intruded below the amphibolites has also undergone folding producing as a result of crustal shortening in response to collision and under thrusting of Indian basement under Kohistan block.

The description of the structural data and its structural interpretation will be discussed in this paper. The structural studies carried out on the Timargara, Lal-Qila and Wari areas district Dir are compiled as a structural map of the area (Fig.1). Three structural crossections are presented along the lines AA', BB' and CC' which shows the profile view of structures in the area (Fig.2).

GEOLOGICAL SETTING

The Timargara area in Dir district is a part of the Kohistan complex which is lying in the westren most extremity of the complex. The rocks of Indian plate and Kohistan are very well exposed along the Panjkora river along which is Malakand-Chitral trunk road. The eastren and central portion of the Kohistan complex which is lying in the westren most extremity of the complex. The rocks of Indian plate and Kohistan are very well exposed along the Panjkora river along which is Malakand-Chitral trunk road. The eastren and central portion of the Kohistan complex has been deciphered from the models of Dewey and Bird (1970), Crawford (1974), Powell and Conaghan (1973), Gansser (1974) and subsequently applied to area of Kohistan and interpreted by Tahirkheli et al. (1979), Powell (1979), Chaudhry et al. (1974a, b, 1983 and 1984), Butt et al. (1980), Jan & Howie (1981), Kazmi et al. (1984), Coward et al. (1986), Baig (1989), Ashraf and Loucks unpublished (199o), Miller et al. (1991), Loucks (1996), Khan et al. (1997), Asharf and Hamood (1997).

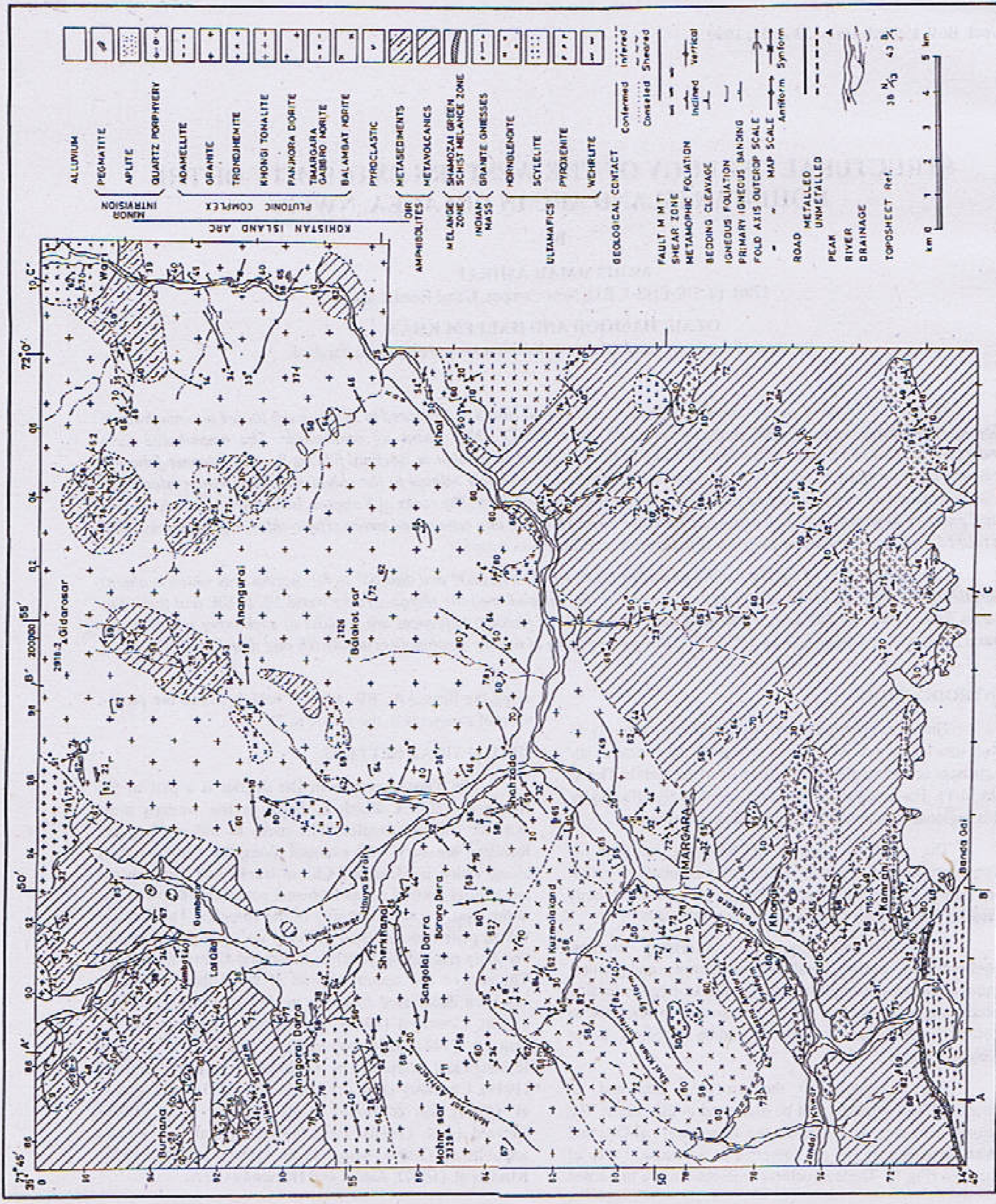

Fig. 1 Structural geological map of Timargara Area, District Dir, N.W.F.P.

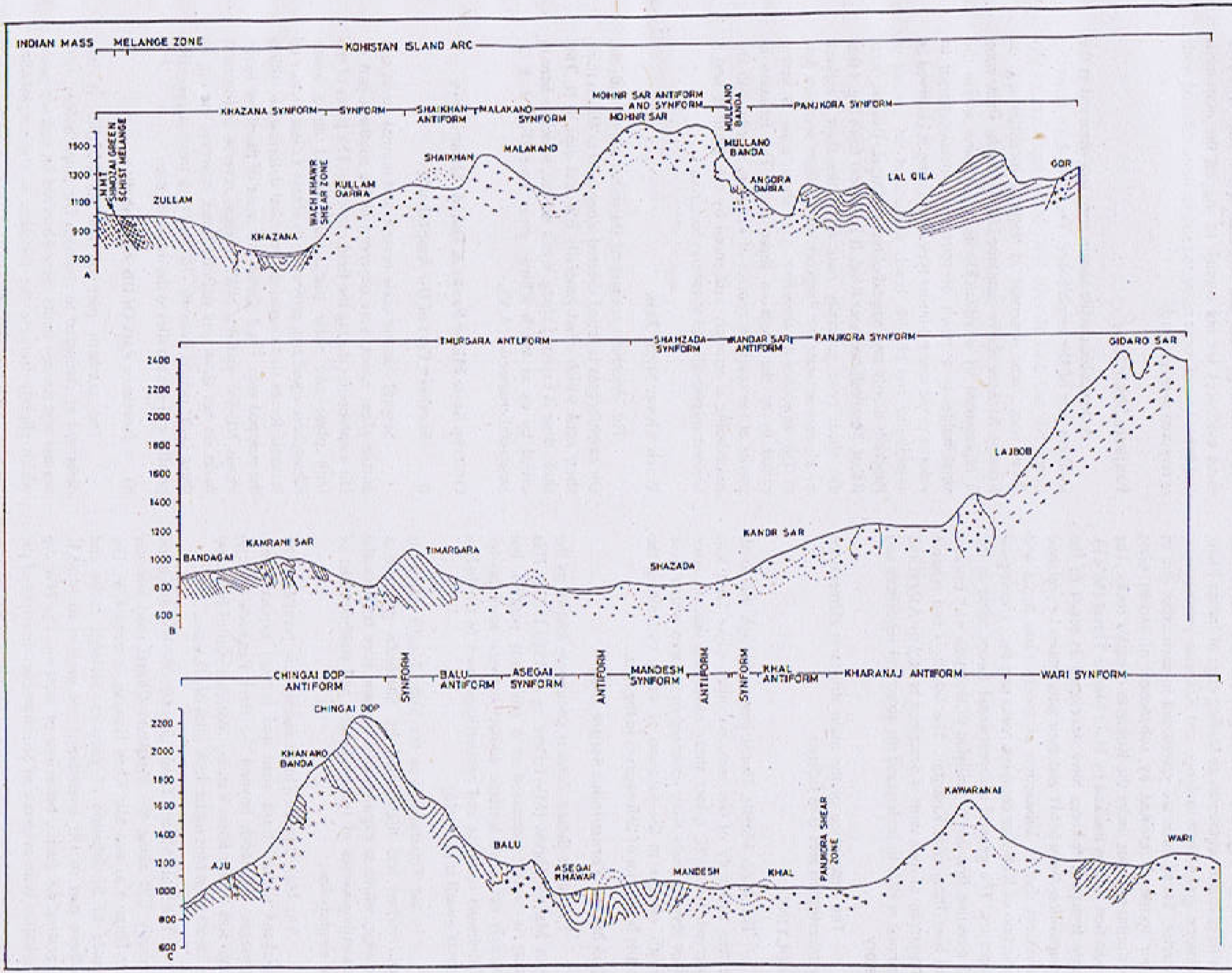

Fig. 2 Structural cross section of Timargara Lal-Qila Area, District Dir, N.W.F.P.

The geology of the Timargara ares can be divided into three major sequiences as leading edge of Indian Plate, Shamozai greenschist melange and Kohistan petrotectonic province. These three are juxtaposed to each other due to majer tectonism created by subduction of Indian plate para/ortho gneisses under the Kohistan complex rocks. The subduction zone is marked by Main Mantle Thrust (MMT). Many structural features have developed as result of the juxtaposition along MMT and their interactions i.e., relative movement due to subduction of Indian plate rocks and obduction of Kohistan complex rocks and their rheological properties. The general compressional forces acted in the NS direction first due to collision of Kohistan with Eurasia and later India with Kohistan. The lithology and relative stratigraphy of rock units is described briefly by Ashraf and Hamood (1997) to understand the structural sequences and history.

The description of the main structural elements of the investigated area is as follows.

FAULTING

The Main Mantle Thrust passes through the south western extremity of the area, no other major fault was observed. However, minor shear zones and outcrop scale minor reverse faults were observed in the area which were slightly oblique to the foliation of strata, evidencing the ductile behaviour of deformation in the area.

Main Mantle Thrust/Indus Suture Zone

The Indus Suture Zone is commonly known as the Main Mantle Thrust (MMT,Bard et al.,1980,1983). This suture is mostly expressed as a schistosity parallel, but intensely deformed tectonic contact between amphibolites of Kohistan complex and para/orthogneisses of the Indian plate (Coward et al., 1986).

In the Timargara area the Main Mantle Thrust is well marked and highlighted by Shamozai greenschist melange, which is exposed as a tectonic slice between the para/orthogneisses of Indian domain and southern part of Dir amphibolite.

The Main Mantle Thrust mainly runs parallel to the Malakand Chitral trunk road and is well exposed near Bandagai. It extends beyond the river Panjkora through Shigo Kas to Mir Khan Kandao. Whereas east of Bandagai the suture zone runs under thick piles of alluvium.

The Main Mantle Thrust dips 60°-75° NW and trend generally EW along the Malakand Chitral road whereas near Shigo Kas and Mir Khan Kandao, it trend EW. The attitude of S_1 foliation of gneisses, melange rocks and southern part of Dir amphibolite are parallel to M.M.T, suggesting the ductile behaviour of suturing. The NW dip of foliation is an evidence of SSE transport direction of the rock of melange zone and Kohistan Island Arc. However these evidences are not enough to suggest the movement and behaviour of rocks along the suture, more detailed work is required in this regard.

Panjkora Shear Zone

A mappable ductile shears zone was observed in the southern part of Dir amphibolite. The shear zone generally trends NE and dips 30°-70° NW. Many exposures of this shear zone were observed at various localities e.g. at Khongi. At these above mentioned localities the shear zone is represented by phyllite/chlorite schist band within the amphibolite as a result of retrograde metamorphism to chlorite grade rocks. Similar type of shearing is observed as amphibolite and phyllite bands exposed at the contact of Panjkora diorite and amphibolites, at Dogai, Bahrun, near Rabat, Mandesh and near Khal. It is evident from Fig. I that this shear zone generally runs along the river Panjkora which also separate the Panjkora diorite from southern part of Dir amphibolite, therefore, this shear zone is herein called by us the Panjkora shear zone. The foliation in diorite at the southern contact of Panjkora diorite with Dir amphibolite is strongly influenced by the shearing and it seemed amphibolitized at various localities.

Wach Khwar Shear Zone

The shouthern contact of Balambat norite with the Dir amphibolites is found sheared along a 30 to 60 cm thick shear zone which trend generally EW and dips to N. This shear zone is exposed along Wach Khwar, which is here in called by us as Wach Khwar shear zone (Fig. 1 & 2, Structural crossection AA').

Outcrop Scale Minor Faults & Ductile Shear Zones

i) Southern Part of Dir Amphibolites

Several outcrop scale reverse and normal faults and ductile shear zones were observed in the southern part of Dir amphibolites during the field mapping. The poles of the fault plane and shear planes are plotted on a lower hemisphere equal area projection to obtain a clear picture of tectonic forces that caused the regional deformation within the mapped area. Fig.3 shows that most of the shear zones trends NE-SW and dip NW, whereas reverse and normal faults do not show any definite trend, however the dip of these faults ranges from 40°-70° and their trend is generally parallel and sub parallel to the main foliation.

ii) Northern Part Of Dir Amphibolite

The northern part of Dir amphibolite is less deformed as compared to southern Dir amphibolites, both normal and reverse faults were observed on outcrop scale, which slightly truncate the foliation in the amphibolite.

These features are seemed to be more pronounced where huge acidic pegmatites or ultramafic plutonics are intruded.

At some outcrops minor pegmatites and quartz veins are truncated by faults which make these features more pronounced. These faults are oblique or perpendicular to the regional foliation.

The poles of outcrop scale normal and reverse fault planes are plotted on a lower hemisphere equal area projection (Fig.4) which shows a scattered figure of the orientation. These faults which evident that these features has no relation to the regional deformational trends and are perhaps produced due to local intrusive activity of acid minor bodies present in the area.

iii) Balambat Norite

In Balambat norite the shear zone is mostly oblique to foliation and shows similar behaviour as in diorite. The lower hemisphere equal area projection to the poles of reverse fault and shear zone shows that the shear zone generally dips NW and trend generally NE (Fig.5)

iv) Panjkora Diorite

In Panjkora diorite shear zones were observed at a number of stations, among which one is observed near Mian Banda along the road, At this station shearing has produced a shear fabric in a 30cm to 60cm thick zone, it trends NS and dips W. The shearing is nearly oblique to the foliation of the roe. At the next station shearing deforms the primary cross laminar structures. The primary composition of bands of plagioclase were stretched to augen shape structure. The shearing trends EW and dips 62° and is nearly sub parallel to the foliation of diorite. A 45 cm thick epidotized vein is present along it shear zone in which stretched grains of chlorite could be easily identified. Similar type of situation was observed at Kuz Malakand in Balambat norite. At this station the epidotized vein is about 60 cm to 1m thick and crenulation folds are developed in it which trend SW and plunges about 40° suggesting some strike slip motion along the shear zone, chlorite is also developed in the epidotized vein.

The eastern contact of Panjkora diorite and amphibolite exposed near Dogai 2 km east of Timargara bazar is also found sheared trending NNE and diping NW. This shear zone is the continuation of the Panjkora shear zone which passes through Khazana and Khongi.

The lower hemisphere equal area projection to the poles of these shear zones along with normal and reverse faults are shown in (Fig.6) which shows that most of the shear zones and reverse faults trend NE-SW and dip NW.

The outcrop scale shear zones mostly occur in the southern part of the mapped area both in amphibolites and in plutonic rocks (i.e. Balambat norite & Panjkora diorite). These shear zones seemed to be absent in the northern part of the mapped area.

The lower hemisphere equal area plots of these outcrop scale structures (Figs. 3, 4.5,6) show that most of the shear zones trend EW and NE and dip W & W NNW that is why most of the data of shear zones concentrate in the south eastern quadrants of the equal area net. The trend of these shear zones shows that the trend of deformational force is mostly northwards which has produced these structures.

It shows that these structures were produced due to the continued collision of India with Kohistan complex sequences followed by under thrusting of Indian basement rocks which is the major deformational agency in the area.

In addition to these a shear fabric is observed in a zone of about 5 to 10 cm at the contact of nearly all the quartz porphyries in the southern part of amphibolites and in some porphyries in Balambat norite and Panjkora diorite. It may have been produced due to difference in the response to the deformational forces.

FOLDING

The folding in the area is highly influenced by MMT especially in the southern portion of the mapped area. The folding is tight in the southern part of Dir amphibolite, exhibiting an anticlinorium structure with southwards upright and northwards verging asymmetric to upright folds. The over turning is evident by the presence of locally preserved pillow structures which shows top bottom relationship. The folding in the most of the southern part of Dir amphibolite is tight and overturned that is why no major mapable fold axes was drawn after the syntheses of structural data. These tight folds slightly open up towards north as we go away from the MMT in amphibolites and in the plutonic sequence.

The folds observed in the plutonic sequences are slightly open and upright. The trend and plunge of fold axis are documented on a structural map (Fig.1). Following is the description of some mapable folds present in the project area.

Khazana Synform

Khazana synform is a plunging synformal structure produced due to the folding of southern part of Dir amphibolite. The fold axis of this fold trends NE and plunges 20°-30° NE. The Panjkora shear zone has deformed its southern limb. A body of tonalite is also exposed on the southern limb along the river Panjkora. The long axis of this tonalite body is parallel to the fold axis (AA' Fig.2), evidencing the presence of tonalite body beneath the amphibolites.

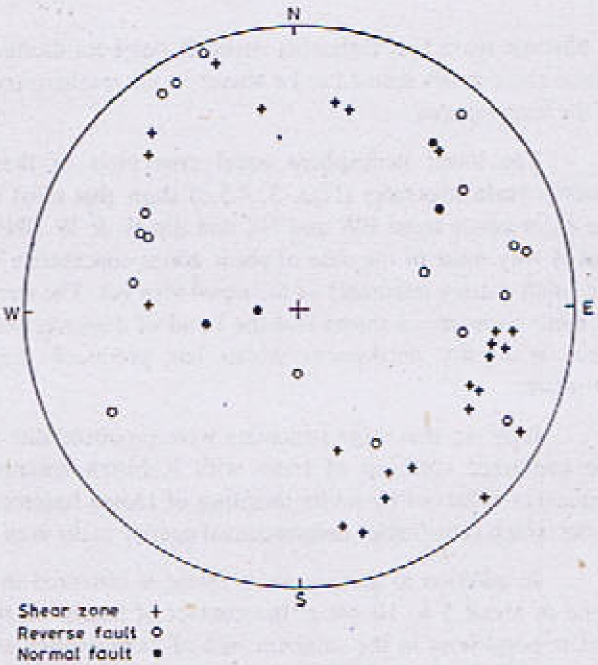

Fig. 3 Lower Hemisphere equal area projection to the poles of outcrop scale shear zones, reverse and normal faults within southern part of Dir amphibolites, showing that most of shear zones trends NE-SW and dip NW, while reverse faults and normal faults shows scattered trends.

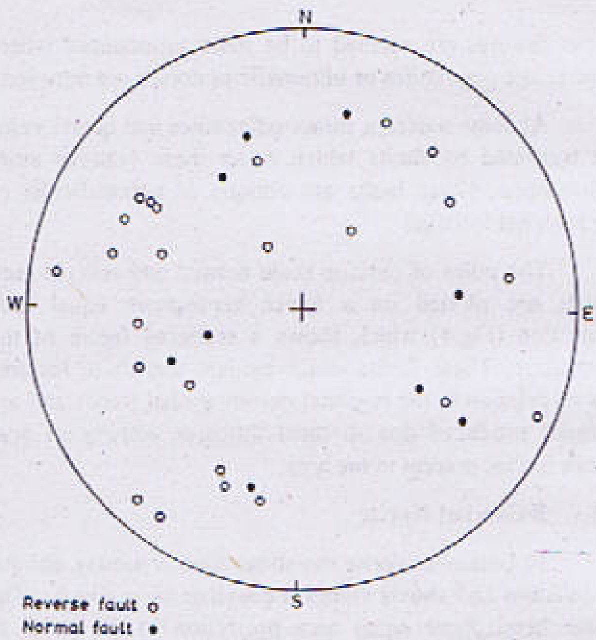

Fig. 4 Lower Hemishphere equal area projection to the poles of outcrop scale reverse and normal faults within northern Dir amphibolites, showing that most of the reverse fault are scattered and are not oriented in any specific direction.

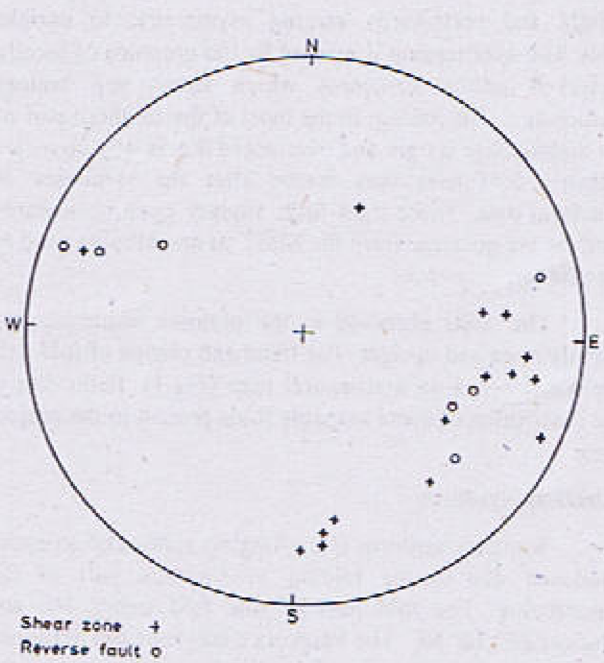

Fig. 5 Lower Hemishphere equal area projection to the poles of outcrop scale shear zones and reverse faults within Balambat norite. The shear zone mostly dips NW and trends NE to EW.

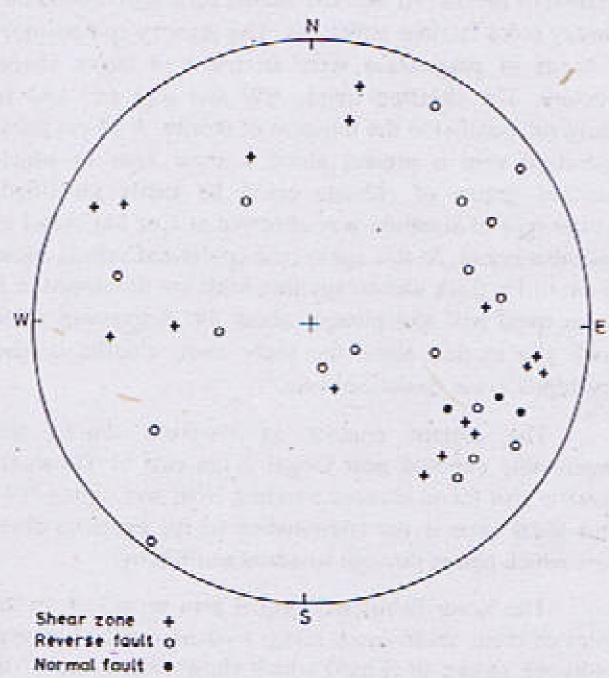

Fig. 6 Lower Hemisphere equal area projection to the poles of outcrop scale shear zones and reverse faults within Panjkora diorite. The reverse faults shows scattered figure but the shear zones mostly dip NW and trends NE.

Khazana Antiform

Khazana antiform is doubly plunging anticline plunging at 40° to 60° on both eastern and western sides. The fold axis of Khazana antiform is parallel to Khazana synform. At the northern limb of Khazana antiform Balambat norite is exposed which has an intrusive contact with the Dir amphibolites, but this contact is found sheared at various places along Wach Khwar (AA' Fig.2).

Shaikhan Synform

Shaikhan synform is an open plunging fold. Its folds axis trend's NE-SW and plunges at 30° to 60° on both northern and southern sides. Balambat norite is generally exposed in the area around the fold however two patches like elongated bodies of hornblendite are found intruded in the norite on the southern limb of this fold (Fig. 1). Generally it is an upright fold as appears (Fig.1, AA' Fig.2).

Shaikhan Antiform

Shaikhan antiform appears as a ridge of mountains around Kulam Darra and Ghulam Darra. Balambat norite occurrs in the core and on both limbs. It is also a doubly plunging fold which plunges 12° to 30° NE and south west. Its fold axis is parallel to fold axis of Shaikhan synform, and Khazana antiform and synform (AA' Fig. 2).

Malakand Synform

Malakand synform trends SW and plunges 18° to 40° on both SW and NE. Panjkora diorite is exposed on the north western limb of this fold while Balambat norite is exposed on the south eastern limb, tow ultramafic bodies of scyelite and hornblendites are exposed in its core. The long axis of these ultramafic bodies are also parallel to the fold axis as in the case of other bodies (Fig. 1 AA' Fig. 2).

Mohnr Sar Antiform

Panjkora diorite is folded into an antiformal structure which forms the high peaks of Mohnr Sar. The fold axis of this fold trends NE and plunges 20°-50° NE. (Fig. 1).

Mullano Banda Antiform

A huge roof pendant or part of the roof is found exposed at the northern contact of Panjkora diorite and northern part of Dir amphibolite which is bounded on the north by a body of adamellite which is probably the differentiate of diorite (Fig.1, AA' Fig. 2).

The fold axis of this antiform trends east west and plunges about 28° westwards. The amphibolites exposed near Takatak are also folded in a similar manner and the antiformal axis show similar behaviour (Fig. 1).

Lal Qila Synform

Lal Qila synform is a EW to SE trending complex synformal structure which can more preferably be called as a synformal synclinorium. Many parasitic folds were observed on both the limbs.

The vast planes of Kumbat and Haya Serai are present in the core of this synform in which Panjkora diorite is exposed. Amphibolites are exposed on the northern limb of this synform along with some patches and dykes of granites and acid minor bodies i.e. pegmatites (Fig. 1).

Lajbok Darra Antiform

Panjkora diorite is exposed in the core of this antiform which is eroded by stream passing through the Lajbok Darra. The antiform trends NS to NE. It is a doubly plunging antiform which plunges 25°-40° both in northern and southern directions. A roof pendant of amphibolite is exposed along the south eastern limb. Four bodies of hornblendites are intruded on the limbs of this fold, among which one is exposed on the south eastern limb and three are exposed along the north western limbs. The long axis of these elongated bodies to the fold axis (Fig. 1).

Other Map Scale Folds

Many other map scale folds were inferred after plotting and interpretation of structural data collected in the field. These includes Udegram synform, Manjai antiform, Gurgia synform, Kharanai antiform, Khwada synform, Qalagai antiform and Shahzada synform. Panjkora diorite is folded in all these above mentioned folds.

The southern portion of the Dir amphibolites is tightly folded into southwards verging and northward dipping inclined folds. As this area is very near to Main Mantle Thrust (M.M.T) which has great influence on the structures of this area. The overturning of strata is recognised at few localities on the basis of deformed upside down pillow structures. The fold axis of some of the folds are plotted on the structural maps (Figs.1 & 2) which support the views presented above.

Outcrop Scale Minor Folds

Many outcrop scale minor folds were observed during the field mapping program in southern and northern part of Dir amphibolites as well as in Panjkora diorite. Generally these folds are associated with the regional deformation of the area and therefore given a special status during the mapping.

Most of the outcrop scale folds in the southern part of Dir amphibolite trends EW to NE and plunges 20°-60° N-NW which evident that most of the deformation in these rocks are produced due to the collision of Indian continental mass with the Kohistan Complex. Which is followed by the under thrusting of Indian basement under the metamorphosed ocean floor of Kohistan complex. These outcrop scale folds also shows that the deformation in amphibolites is mostly ductile in nature. Kink bending is also observed in amphibolite which evident the layered parallel shortening due to deformation.

FOLIATION

About half of the mapped area consist of amphibolites, the other half is covered by the plutonic rocks such as norite, gabbronorite, diorites, trondhjemite, adamellites and granites. For convenience we discuss the metamorphic and igneous foliations separately.

Matamorphic Foliations

i) S_1 Foliation

S_1 is the main fabric within the southern and northern amphibolites. S_1 foliation is defined by banded by banded gneisses composed of leucocratic and melanocratic layers and bands on laminae scale.

ii) S_0/S_1 Bedding Cleavage

S_0/S_1 bedding cleavage is observed in the metasediments present as inter-layers along with metavolcanic stuff and pillow structures in the amphibolite. This fabric may be the axial planner cleavage of recumbent or isoclinal folds. S_0/S_1 bedding cleavage is also the main fabric in metabasite type amphibolites containing deformed pillows.

Therefore, the S_1 foliation could be recognised as banded gneiss and S_0/S_1 bedding cleavage, it is the most pronounced fabric which has transposed over S_0 primary foliation in pillow lava and S_0 bedding in metasediments.

In southern extremes, of mapped area the foliation in southern Dir amphibolites occurs to be strongly effected by M.M.T. In this portion the foliation trends NE-E to SW with moderate angle dip ranging 20°-70° NW in southern extremes to SE to NE in the central and northern portion. The lower hemisphere equal area projection to the poles of the S_1 and S_0/S_1 foliation and its frequency distribution on contour diagram shows the regional trend of foliations within southern part of Dir amphibolites (Fig.2) which shows that most of the southern part of Dir amphibolites trend EW and dips northwards especially along M.M.T.

Primary Igneous Foliation in Plutonic Rocks

In the plutonic rocks of the project area (i.e. norite, gabbronorite, diorite, tonalites, trondhjemite, and granites), a variety of primary igneous foliations were observed. Although nearly almost all the plutonic rocks contacts with amphibolites are agmatitic, yet some sort of fabric is seen to be developed which may be the result of post emplacement deformational activities going on in the area due to the Himalayan orogeny. But these primary features are nearly undisturbed in the core or in the central portion of major plutons near Malalkand, Shaikhan and Balambat in norite, whereas in Khal, Udegram, Sar Banda, Damamo Banda and Sangolai Darra in Panjkora diorite.

i) Flow Foliation

Flow foliation is a variety of primary igneous foliation that is due to parallelism of platy minerals. In our field area flow foliation is marked by the parallelism of pyroxenes and plagioclase. The parallel arrangement shows planner structure. The roof pendants of amphibolite in diorite are also aligned parallel to flow foliation especially in Panjkora diorite.

ii) Primary Igneous Banding

Primary compositional bands of mafic and felsic rich minerals are also observed at some stations both in Balambat norite and Panjkora diorite. The structures are also mapped as primary igneous foliation. Primary banding is observed well developed near Kuz Malakand and Kulam Darra in Balambat norite, Malai and Kuz Banda in Timargara gabbronorite, Khal, Damamo Banda and Qalagai in Panjkora diorite. Whereas cross bedding is observed in Panjkora diorite near Khal and Qalagai.

MAGMATIC UNDERPLATING

In the Timargara area the amphibolites are the oldest rocks which are intruded by norites, gabbronorite, diorites, tonalites, trondhjemite and granites. Nearly all plutonic bodies show underplating behaviour with the roof rocks i.e. amphibolites, forming agmatitic structures. The agmatitic structurs were observed at many places.

Most of the agmatitic zones at the contact of amphibolites and plutonic rocks are several meters thick. Two phases of rock are developed in these agmatites, one is extremely acidic forming aplites/pegmatites and the second one is that of ultrabasics forming hornblendites. These are well developed and non penetrating type rocks through the amphibolite roof. These phenomena can happen when the two rest magmatic solutions become immisible after the crystallization of main basic rocks like norite, gabbronorite and diorite etc. The hornblende crystals developed in the agmatite zones are < 2-10cm length. The undeformed nature of the aplites/pegmatites and in some cases of hornblendites evidently show the agmatitic nature of the lower part of the Dir amphibolite.

ROOF PENDANTS

Roof pendants of amphibolites were found in the diorite, tonalite, granite and in norite at several places.

Their maximmum concentration is found near the contact zones.

Different internal structures of roof pendant are evident, these include, disc shape, rod shape, rounded, lens shaped and pillow shaped. The metamorphic foliation of amphibolites are found preserved in most of pendants, which is sometimes more or less parallel to flow foliation of the host rock. Roof pendants of metavolcanics, carbonate and phyllitic rocks are several meters in length, but their thickness is not more than two to three meters or some tens of meters. In the roof pendants which are quartzitic in composition, garnet is seen to be well developed, those pendents are disc shaped, rounded and pseudo-pillow shaped. The primary bedding features are preserved in some of the quartzitic roof pendants as well.

The roof pendants of metavolcanic amphibolites are usually lens shaped and rod shaped whose edges are seen to be dissolved in the host magma.

PRESERVED PRIMARY STRUCTURE

In the amphibolites some of the primary igneous/volcanic and primary sedimentary structures were found preserved. However these primary features are superimposed by the metamorphic fabric. These includes bedding foliation in metasediments, pillow structure and vesicular structure in metavolcanics.

Pillow Structure

Deformed pillow structures were observed at various places in northern and southern part of Dir amphibolites, indicating that these amphibolites, are produced due to the metamorphism of pillow lavas. The top and bottom relationship could be easily identified in some of the less deformed pillows.

Pseudo pillows were also observed which are actually boudin structures formed due to the deformation of metasediments mostly quartzites, which are interlayered in amphibolites, and were deposited with the volcanic flows and pillow lavas.

The pillow structures are found well preserved in the southern part of Dir amphibolites at several localities. In the northern part of Dir amphibolites pillow structures are present but are not abundant perhaps due to the relative thinner lava flows as compared to southern part of Dir amphibolites.

Vesicles

Vesicles are swarms of tiny holes in volcanic rocks. They are the frozen records of gas bubbles in lava. The vesicular structures are abundantly found in the metavolcanic stuff of northern part of Dir amphibolite although they are deformed, but their primary nature could be identified easily.

DISCUSSION

In the area under investigations three petrotectonic units are juxtaposed along the MMT after the collision. The timing of collision in the western Himalayas is poorly constrained. Paleocene age is recommended by Baig et al. (1984) which is evident by the presence of Paleocene unconformity (Ashraf et al., 1972) in the north western Himalayas on the leading edge of Indopak plate. Eocene timing is suggested by Coward et al. (1986). Timing of 40 Ma (Priabonian i.e., Late Eocene) for collision of India and Asia is suggested by Molnar & Tapponier (1975) and Klootwijk & Radhakrishnamurty (1981). The last movement along MMT is 15 Ma as recorded and interpretted by Zeitler (1982) from fission track data.

The ortho and para gneisses exposed on the leading edge of Indopak plate just south of MMT represent the basement rocks of Indian mass and are exposed due to high uplift produced as a result of collision. The Indian basement rocks have recorded several episodes of orogeny yet the effect of Indian-Asian collision occurred during Himalayan orogeny had transposed over the previous orogenic deformational records evident from the prominent gneissic foliation in the rocks unit which is nearly parallel to the MMT.

The Shamozai greenschist melange along the MMT is being reported for the first time which consist of blocks of metasediments and blocks of ultramafic metamorphosed to greenschist facies (chloride grade) evident by the petrographical studies of various rocks units. The structural and metamorphic history of this petrotectonic unit is very complex. This unit is in the form of lenses and blocks that have caught up in between Indian basement rocks and amphibolites of Kohistan Island Arc. The presence of tension gashes in carbonate blocks which were filled by quartz, evident some shearng effects and strike slip movement along the MMT which might have occurred along the suture zone. The presence of minor scale drag folds in phyllites also support the strike slip sense of movement.

The MMT dips 60°-75° NNW and trends generally EW along the Malakand Chitral roads, near Shigo Kas and Mir Khan Kandao. The attitude of S_1 foliation of gneisses, melange rocks and southern part of Dir amphibolite are parallel to MMT, which suggests the ductile behaviour of suturing. The NNW dip of foliation is an evidence of SSE transport direction of the rocks of melange zone and Kohistan Island Arc. However these evidences are not enough to suggest the movement and behaviour of rocks along the suture, more detailed work is required in this regard.

The amphibolites of Kohistan Island Arc were basically metamorphosed ocean floor material under which the arc was built. These rocks were deformed by at least two phases of folding. The first phase of isoclinal or recumbent folding has developed S_1 foliation in metavolcanics and S_o/S_1 bedding cleavage in pillow lavas and metasedimentary layers within metabasites and metasediments respectively. This S_1 foliation is basically the axial planner cleavage of earlier formed isoclinal or recumbent fold. The isoclinal phase of folding in amphibolites were also suggested by Coward et al. (1982). In the second phase the amphibolites were again folded into northwards dipping southwards verging structures which are tight in the southern Part of Dir amphibolites and generally opens northwards. The earlier phase of isoclinal or recumbent folding was probably subduction related (i.e. subduction of Kohistan under Asian continent). The metamorphism of these rocks might have probably happened in this phase of deformation. The second phase of folding seems to be collision related of Indopak plate with Kohistan, it might have occurred in two stages. In the first stage the rocks were folded in response to crustal shortening which happened due to collision of Kohistan block with Eurasian continent. In the second stage when the Indopak continent collided with Kohistan blocks these folds became tight into northward dipping southward verging isoclinal folds.

The influence of deformation produced in the southern extremity of southern part of Dir amphibolites can be easily judged by the regional trend of these rocks along the MMT. The frequency distribution of the poles of S_1 and S_o/S_1 foliation in southern Dir amphibolites (Figs.3 & 4) shows that most of the data lie in the SE quadrant showing that the dip of rocks is mostly NW.

The rocks of Kohistan Island Arc have been subjected to a third phase of deformation which might has been produced due to the crustal adjustments (i.e. crustal shortening due to continuous northward drag of Indian plate which still moves 4 cm/year) after collision (Powell, 1979). This phase is evident by the presence of shear zone (i.e. Panjkora shear zone and Wach Khwar shear zone) in both amphibolites and plutonic rocks. Most of the shear zones in amphibolites were observed as phyllite bands which often serves as best ductile material during such sort of deformation activities. The retrograde metamorphism to chlorite grade was observed along these shear zones (i.e. Panjkora shear zone and Wach Khwar shear zone) both in the field and in the petrographic study. The retrograde metamorphic overprint is also evident in amphibolites near M.M.T. The plutonic rocks of Kohistan Island Arc are also effected by the strong straining in quartz which show the post emplacement deformation. The fold axis in Balambat norite and Panjkora diorite are also parallel to each other and appear to be influenced by the collision.

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BIOTITE-ANNITE-SIDEROPHYLLITE SERIES IN FELDSPATHOIDAL SYENITE OF THE KOGA ALKALINE IGNEOUS COMPLEX, SWAT, NW PAKISTAN

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Abstract:- *The mineral chemistry of biotites has been investigated by the electron microprobe analysis performed on various rock units from the Koga feldspathoidal syenite complex. Four distinct groups - biotite-annite-siderophyllite series have been recognized; (1)* $An_{70}\,Sd_{30}$ *to* $An_{60}\,Sd_{40}$ *with 0 to 5% phlogopite (2)* $An_{80}\,Sd_{20}$ *to* $An_{65}\,Sd_{35}$ *with 5 to 15% phlogopite (3)* $An_{95}\,Sd_{5}$ *to* $An_{73}\,Sd_{27}$ *with 15 to 30% phlogopite (4)* $An_{90}\,Sd_{10}$ *to* $An_{73}\,Sd_{27}$ *with 30 to 50% phlogopite.*

INTRODUCTION

Trioctahedral micas (biotites) occur along the phlogopite-annite join as an important mafic mineral phase over a wide range of petrogenetic environment. The final product of igneous Mg/Fe fractionation is represented by extreme Fe- enrichment in biotite towards ideal end - member annite composition. This trend is particularly well exhibited within the differentiated products of SiO_2-undersaturated,-saturated and -oversaturated syenites and alkali granites from anorogenic alkaline igneous complexes.

Numerous investigations on the mineral chemistry of biotites from the calc-alkaline complexes were carried out in the past (Speer 1984). But the data on the biotite variation in the nepheline syenites are sparse (Duke and Edgar 1977, Parsons 1979, Parsons et al. 1991, Mitchell and Platt 1982, Platt and Woolley 1986, Flohr and Ross 1989, Worley et al. 1995). Biotite coexisting with pyroxene, magnetite or garnet and alkali feldspars in the alkaline complexes may provide quantitative assessment of controlling parameters such as temperature, pressure and oxygen fugacity that governs fractional crystallization trends of the alkaline magmas (Parsons et al. 1991)

In this paper the microprobe investigations of biotite-annite-siderophyllite series in the feldspathoidal syenite suites from the Koga alkaline igneous-carbonatite complex, Swat, NW Pakistan are presented. Biotite is invariably found in the nepheline syenites and syenites in association with pyroxene, magnetite and garnet if present. It occurs as dark brown or brownish green, medium to coarse subhedral flakes.

GEOLOGICAL SETTING

The Koga feldspathoidal syenite-carbonatite complex is the most interesting for the petrogenetic study of the alkaline igneous province of NW Pakistan. It occurs in the middle part of the Paleozoic Ambela granitic complex and forms horseshoe shaped outcrop. The feldspathoidal syenites are well exposed near the type locality of Koga village (34.23 N, 72.28 E) in the Chamla valley of Buner in Swat at a distance of about 55 km north west of Mardan district Pakistan (Fig. 1).

The Koga plutonic complex is one of the several intrusions of the alkaline igneous province which extends over 200km from the Loe-Shilman (Khyber Agency) in the west near Afghan border to Tarbela Dam in the east. The alkaline province is tectonically emplaced within the metamorphosed thrust blocks of NW Himalaya along the continental margin of the Indo - Pakistan Plate.

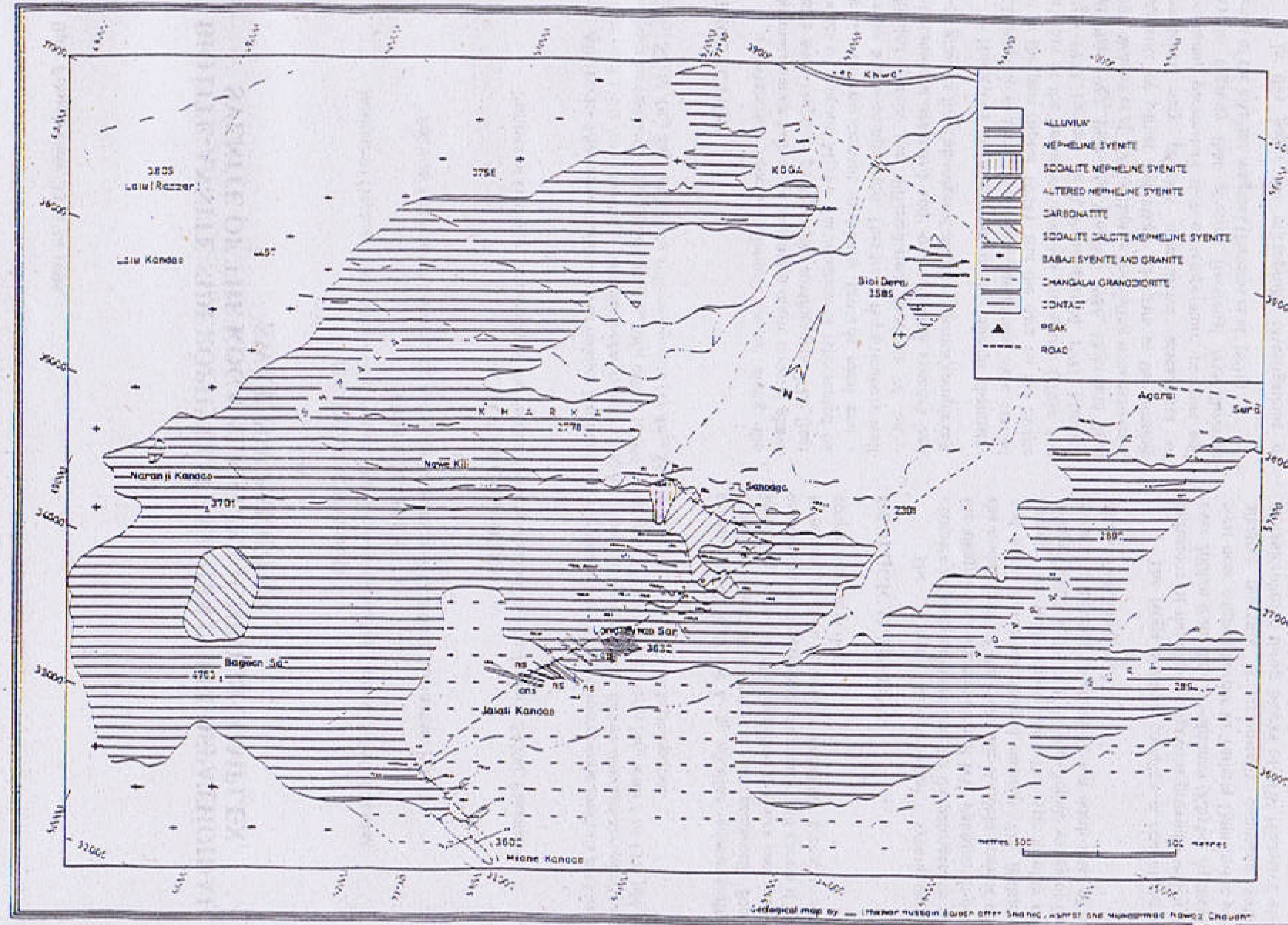

FIG. 1. GEOLOGICAL MAP OF THE KOGA FELDSPATHOIDAL SYENITE COMPLEX

The detailed account of the geology and petrology of the Koga alkaline complex is given elsewhere (Siddiqui et al. 1968, Chaudhry et al. 1981, Baloch, 1994 and Baloch et al. 1994). The complex comprises of predominantly feldspathoidal syenites associated with dikes, sills and minor intrusions of ijolites, microgabbros and carbonatites. Well developed fenite zones occur around the carbonatite bodies.

The rocks are essentially pyroxene-biotite feldspathoidal syenites. Various units comprise small intrusions of foyaites, sodalite-cancrinite bearing foyaitic pegmatites, garnet-bearing feldspathoidal syenites, pulaskites and nordmarkites.

The feldspathoidal syenite is generally medium to coarse grained often showing flow foliation roughly trending NS. Foyaites form irregular intrusions of later generation which are fine to coarse grained and even pegmatitic. The feldspathoidal syenites contain numerous aplitic and pegmatitic veins of variable composition and texture. Pegmatites are both zoned and unzoned. They are either intrusive or replacement bodies.

The mineralogy of feldspathoidal syenite comprises of nepheline (5-35%), microcline (20-70%), albite (2-10%) cancrinite and sodalite (up to 12-15%), aegirine (2-3%), biotite (1-4%), magnetite (up to 3%) and sphene and garnet (up to 1% and 4 % respectively). Apatite and zircon are accessory minerals.

The mafic minerals occur as aggregates and clots as well as subhedral to euhadral grains. Pyroxene and biotite are generally fresh and primary crystallizing phases which coexist in most of the rocks. The amphiboles are absent or rare, garnet when present is invariably associated with pyroxenes.

MINERALOGY OF BIOTITE

Representative samples of feldspathoidal syenites were prepared for electron-probe microanalysis (EPMA). Biotites were analyzed on a Jeol Superprobe JXA 8600 at the Department of Geology, University of Leicester, UK. The equipment was fitted with an on-line computer for ZAF correction and was calibrated against appropriate natural and synthetic standards. Quantitative results were obtained on the wavelength dispersive system using the operating conditions of 15 kV acceleration voltage and 0.03 microampere current.

Representative chemical compositions of biotites are given in Table 1, calculated on the basis of 22 oxygens, with total iron as FeO. A major problem in the microprobe analyses of biotite lies in the difficulty of assessing the relative contribution of FeO and Fe_2O_3 and water contents. All Fe has been assumed to be in divalent state. This assumption gives a minimum estimate for the amount of vacancies in tetrahedral Al. According to the calculations suggested by Deer et al. (1992), biotite formulae were calculated on the basis of total cation charge of +22 balanced by total oxygen=10 and (OH, Cl, F)=2. Biotites are plotted (Fig. 2) in the field outlined by Deer et al. (1992, p 298) to evaluate the composition, which gave four distinct groups as follows:

$An_{70}\ Sd_{30}$ to $An_{60}\ Sd_{40}$ with 0 to 5% phlogopite

$An_{80}\ Sd_{20}$ to $An_{65}\ Sd_{35}$ with 5 to 15% phlogopite

$An_{95}\ Sd_{5}$ to $An_{73}\ Sd_{27}$ with 15 to 30% phlogopite

$An_{90}\ Sd_{10}$ to $An_{73}\ Sd_{27}$ with 30 to 50% phlogopite

Trioctahedral biotite-annite-siderophyllite series is recognized in all the rock samples studied from the Koga feldspathoidal syenite. Biotite is present in association with pyroxenes. These biotites are relatively rich in alumina (Al_2O_3=14.22 to 19.20 wt. %, mostly in the range of 14-15 wt. %). TiO_2 is between 1 and 2 wt. % however, one sample showed high value up to 3.2 wt. %, calcium and barium occur in trace amounts. It is interesting to note that TiO_2 has a significant negative correlation with MgO. Compositions of biotites plotted on the triangular MgO-(total Fe as) FeO-Al_2O_3 after Nockolds (1947) from the igneous rocks (Fig. 3) gave more or less the same trend of biotites associated with other mafic minerals.

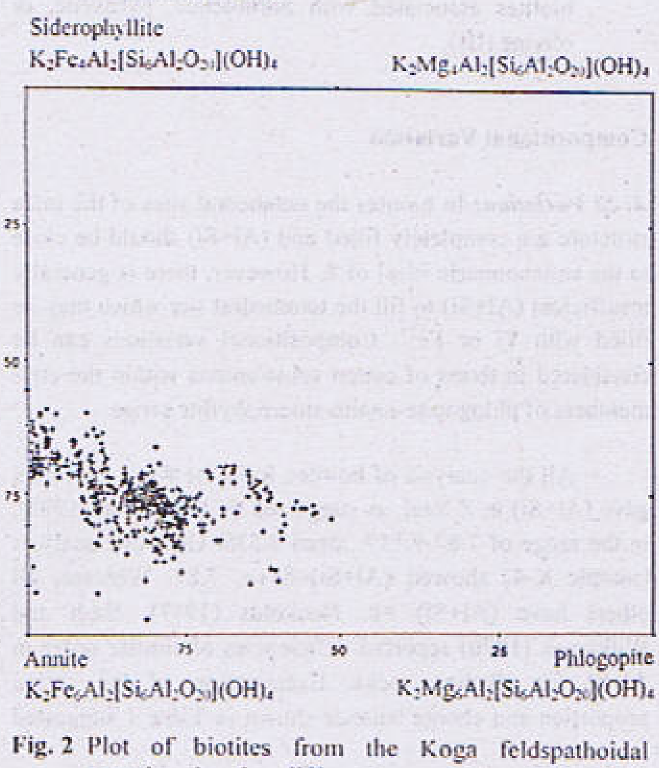

Fig. 2 Plot of biotites from the Koga feldspathoidal complex showing different compositions (after Deer et al. 1992).

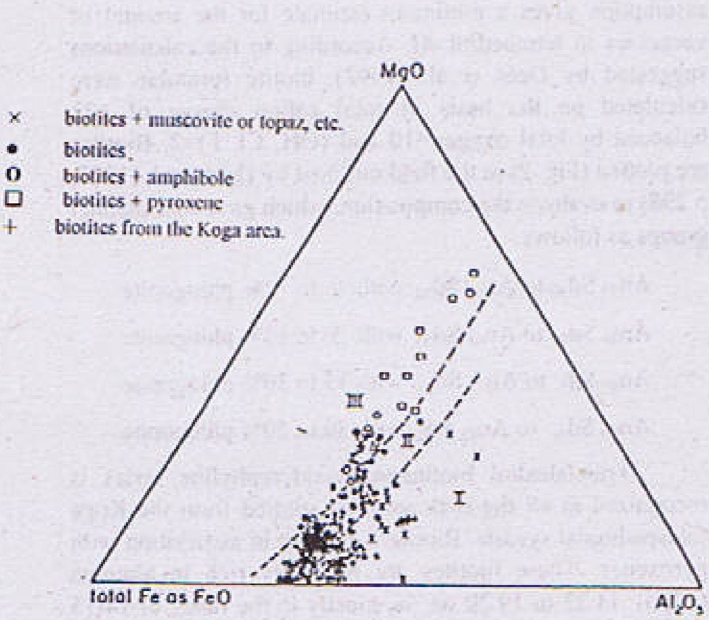

Fig. 3 Biotites from the Koga feldspathoidal syenite plotted on the triangle MgO(total Fe as) FeO-Al_2O_3 with biotite compositions from igneous rocks after Nockolds (1947). Roman numerals refer to the fields of biotites associated with muscovite or topaz (I), unaccompanied by other mafic minerals (II), and biotites associated with hornblende, pyroxene, or olivine (III).

Compositional Variation

Al-Si Variation: In biotites the octahedral sites of the mica structure are completely filled and (Al+Si) should be close to the stoichometric ideal of 8. However, there is generally insufficient (Al+Si) to fill the tetrahedral site which may be filled with Ti or Fe^{3+}. Compositional variations can be considered in terms of cation substitutions within the end-members of phlogopite-annite-siderophyllite series.

All the analysis of boitites from the Koga Complex gave (Al+Si) in Z total, as suggested by Deer et al. (1992), in the range of 7.87-9.117, mean 8.538. Only one analysis (sample K-4) showed (Al+Si)<8 i.e. 7.87. Whereas, all others have (Al+Si) >8. Nockolds (1947), Nash and Wilkinson (1970) reported deficiencies of similar order in Al+Si for alkaline rocks. Examination of the cation proportion and charge balance shown in Table 1 suggested that most of the iron is present as Fe^{2+}. These biotites differ from those given by Heinrich (1946), quoted by Speer (1984).

The higher atomic (Al+Si) in the biotite of Koga feldspathoidal syenites is similar to the biotites characteristic of granites (de Albuquerque 1973). Biotites in the igneous rocks are commonly the host of the excess aluminum, and follow the compositional equilibria among coexisting ferromagnesian minerals. The Al-Si ratio increases with magmatic evolution. The coexisting pyroxenes in the Koga feldspathoidal syenites are highly alkaline aluminous having jadeitic component (Baloch et al. This Journal).

The ratio atomic Al/(Al+Si) is plotted against Fe/(Fe+Mg) in Fig. 4 to compare the variations with those in Klokken biotites (Parsons et al. 1991). The Koga biotites are relatively aluminous and show the trend towards annite-siderophyllite join.

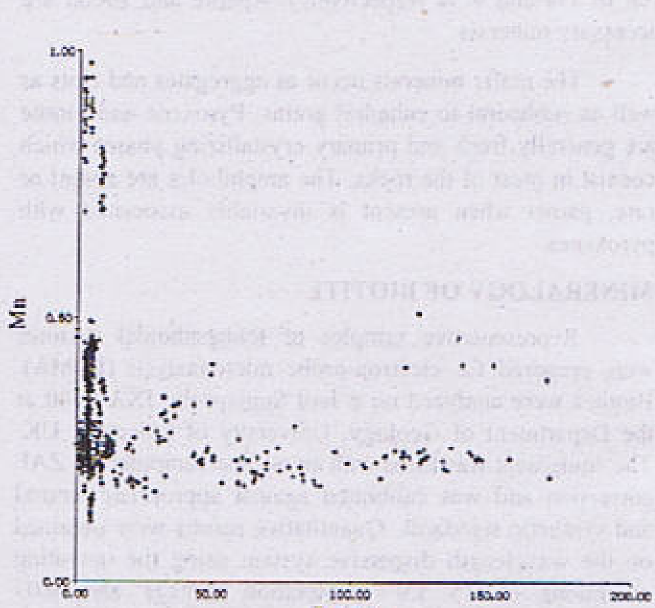

Fig. 4 Biotites from the Koga feldspathoidal syenite plotted on Fe / Mg versus Mn.

Table I

Microprobe analyses of biotites from the Koga Complex

Sample No.	K-2		K-3		K-4		K-5		K-6		K-8		K-9	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
SiO_2	35.95	0.25	33.80	0.75	33.90	0.60	33.37	0.79	32.96	0.87	33.59	0.42	32.82	0.97
TiO_2	2.21	0.19	2.19	0.13	1.48	0.12	1.53	0.05	1.64	0.24	1.39	0.07	1.64	0.68
Al_2O_3	18.59	0.42	14.87	0.59	14.64	0.47	15.52	0.39	15.11	0.47	14.97	0.25	19.20	0.82
FeO	22.94	0.98	27.91	0.93	29.46	0.83	28.91	0.43	28.86	1.30	27.73	0.35	28.50	1.27
MnO	2.73	0.18	2.45	0.11	2.03	0.43	2.29	0.08	2.34	0.38	2.74	0.08	2.33	0.53
MgO	2.39	0.10	3.85	0.36	4.27	0.29	3.70	0.17	2.76	0.78	4.07	0.34	1.16	0.91
Na_2O	0.34	0.20	0.26	0.19	0.00	0.00	0.26	0.17	0.13	0.08	0.23	0.12	0.19	0.12
K_2O	9.63	0.15	9.44	0.27	9.43	0.32	9.30	0.24	9.16	0.17	9.55	0.13	9.57	0.15
Total No.	10		9		36		7		43		21		27	

No. of cations on the basis of 22 oxygens

	K-2	K-3	K-4	K-5	K-6	K-8	K-9
Si	5.664	5.524	5.215	5.466	5.522	5.530	5.314
Ti	0.262	0.269	0.171	0.188	0.207	0.172	0.200
Al	3.453	2.865	2.655	2.997	2.985	2.905	3.665
Fe	3.023	3.815	5.077	3.961	4.044	3.818	3.859
Mn	0.364	0.339	0.265	0.318	0.332	0.382	0.320
Mg	0.561	0.938	0.979	0.903	0.689	0.999	0.280
Na	0.104	0.082	0.000	0.083	0.042	0.073	0.060
K	1.936	1.968	1.851	1.944	1.958	2.006	1.977

Sample No.	MK-1		MK-2		MK-5		MK-6		MK-10		MK-14		MK-16	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
SiO_2	32.78	1.12	32.61	0.54	33.79	0.28	32.96	0.87	32.94	0.35	33.16	0.25	32.73	0.74
TiO_2	1.55	0.17	2.11	0.34	2.73	0.08	1.64	0.28	1.66	0.09	3.19	0.15	3.06	0.37
Al_2O_3	19.02	0.45	16.06	0.32	15.05	0.18	15.11	0.47	15.31	0.26	14.74	0.51	15.42	0.33
FeO	27.71	1.05	24.07	0.52	27.47	0.51	28.86	1.30	29.88	0.63	28.42	0.54	33.52	0.85
MnO	1.91	0.28	5.30	0.30	1.86	0.06	2.34	0.38	1.91	0.14	1.02	0.10	1.65	0.11
MgO	1.27	0.79	1.60	0.07	3.80	0.05	2.76	0.78	2.86	0.61	2.99	0.11	0.20	0.10
Na_2O	0.51	0.13	0.13	0.02	0.16	0.09	0.13	0.08	0.09	0.03	0.14	0.14	0.15	0.23
K_2O	9.53	0.16	9.08	0.14	9.44	0.15	9.16	0.17	9.28	0.12	9.15	0.12	9.22	0.15
Total No.	41		19		18		43		11		16		48	

No. of cations on the basis of 22 oxygens

	MK-1	MK-2	MK-5	MK-6	MK-10	MK-14	MK-16
Si	5.364	5.531	5.519	5.522	5.480	5.516	5.410
Ti	0.191	0.269	0.335	0.207	0.208	0.399	0.380
Al	3.669	3.211	2.898	2.985	3.003	2.891	3.005
Fe	3.792	3.414	3.753	4.044	4.157	3.954	4.634
Mn	0.265	0.761	0.257	0.332	0.269	0.144	0.231
Mg	0.310	0.404	0.925	0.689	0.709	0.741	0.049
Na	0.048	0.043	0.051	0.042	0.000	0.045	0.048
K	1.990	1.965	1.967	1.958	1.970	1.942	1.944

Table 1 Continued

Sample No.	MK-18		MK-20		MK-21		MK-24		MK-25		SB-1		SB-5	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
SiO_2	33.58	0.85	33.44	0.58	34.69	0.28	33.01	0.33	33.50	0.37	33.67	1.29	34.66	1.09
TiO_2	2.26	0.61	1.55	0.07	1.40	0.05	1.51	0.09	1.41	0.11	2.11	0.90	1.31	0.14
Al_2O_3	14.96	0.63	14.90	0.46	15.37	0.29	14.76	0.20	14.22	0.23	15.54	1.12	14.61	0.82
FeO	30.31	2.39	29.71	0.49	24.81	0.19	28.78	0.54	26.96	0.70	29.59	2.73	27.14	1.93
MnO	1.91	0.23	1.58	0.09	3.14	0.09	3.14	0.10	2.80	0.13	1.60	0.47	1.86	0.53
MgO	2.76	1.84	3.62	0.25	5.29	0.14	3.14	0.17	4.44	0.27	3.39	2.78	6.03	1.59
Na_2O	0.23	0.56	0.16	0.11	0.12	0.04	0.10	0.06	0.11	0.11	0.17	0.20	0.21	0.27
K_2O	9.48	0.40	9.03	0.33	9.55	0.07	9.38	0.11	9.32	0.10	9.31	0.25	9.44	0.25
Total No.	58		28		5		34		45		35		18	
No. of cations on the basis of 22 oxygens														
Si	5.500		5.529		5.605		5.507		5.749		5.477		5.582	
Ti	0.278		0.193		0.170		0.189		0.172		0.258		0.159	
Al	2.883		2.904		2.928		2.903		2.715		2.980		2.774	
Fe	4.152		4.108		3.352		4.015		3.651		4.025		3.655	
Mn	0.265		0.221		0.430		0.444		0.384		0.220		0.254	
Mg	0.674		0.892		1.274		0.781		1.072		0.822		1.447	
Na	0.073		0.051		0.038		0.032		0.035		0.054		0.066	
K	1.981		1.905		1.968		1.996		1.925		1.932		1.939	

Sample No.	SB-11		SB-15		S-1		S-3		S-6		BD-3	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
SiO_2	32.76	0.38	35.08	0.70	34.93	0.67	33.39	0.54	34.02	0.89	34.90	0.80
TiO_2	3.24	0.53	1.43	0.09	1.20	0.28	1.40	0.11	1.43	0.13	1.13	0.26
Al_2O_3	15.92	0.27	17.36	0.45	16.37	0.83	14.79	0.32	16.67	0.39	14.64	0.50
FeO	32.18	1.24	16.27	0.54	23.64	1.20	25.51	0.65	26.11	1.03	27.00	1.16
MnO	1.50	0.14	6.32	0.52	1.92	0.15	2.91	0.13	2.74	0.16	1.70	0.10
MgO	0.84	0.74	4.77	0.27	7.59	1.77	4.32	0.14	3.51	0.34	6.92	1.63
Na_2O	0.13	0.10	0.26	0.10	0.21	0.11	0.14	0.10	0.17	0.16	0.16	0.17
K_2O	9.36	0.12	9.25	0.17	9.82	0.16	9.25	0.17	9.94	0.15	9.42	0.13
Total No.	34		19		44		28		28		8	
No. of cations on the basis of 22 oxygens												
Si	5.375		5.700		5.497		5.594		5.521		5.568	
Ti	0.400		0.174		0.142		0.176		0.175		0.136	
Al	3.080		3.323		3.037		2.921		3.189		2.754	
Fe	4.416		2.211		3.111		3.574		3.544		3.603	
Mn	0.208		0.870		0.256		0.413		0.377		0.230	
Mg	0.205		1.156		1.780		1.079		0.849		1.645	
Na	0.041		0.082		0.064		0.045		0.053		0.049	
K	1.959		1.973		1.972		1.977		2.058		1.917	

Fe-Mg-Mn-Ti Variation: Biotites of the Koga feldspathoidal syenites show variation in the ratio $(Fe^T+Mn)/(Fe^T+Mn+Mg)$ from 0.65 to 0.99, mostly having higher ratios (0.80 to 0.99) lying in the domain of annite siderophyllite series. Similar trend of progressive increase of the ratio due to Fe-enrichment was observed in the biotites of nepheline syenite from most of the known alkaline provinces (Nash and Wilkinson 1970, Duke and Edgar 1977, Mitchell and Platt 1982, Woolley and Platt 1986, 1988, Parsons 1991, Worley and Cooper 1995).

The compositional variation in the biotites are plotted in terms of Mg - (Fe^T+Mn)-Al in Figure 5. The biotites are distinctly aluminous exhibiting compositional evolution from biotite - annite towards siderophyllite with the increasing Al contents. They are comparable with the micas reported in the nepheline syenites from Blue Mountain and Bigwood complex (Duke and Edgar 1977), Serra de Monchinque (Rock 1978) and Coldwell complex (Mitchell and Platt 1982). Biotites from the Koga complex are neither Mg - rich nor Al-contents are constant (Al varies from 2.655 to 3.699) when compared with biotites from the alkaline complexes of Malawi (Woolley and Platt 1986), Shonkin Sag (Nash and Wilkinson 1970), Kungnat Field (Stephenson and Upton 1982) and Klokken Intrusion (Parson 1991).

The biotites do not show an increase in Mn with an increasing Fe/Mg ratio with no wider scatter (Fig. 4 as in case of the most evolved biotite compositions reported Upton et al. 1985, Flohr and Ross 1989). Similarly the biotites are low in Ti contents (Ti varies from 0.136 to 0.4, generally within the comparable range of values in the biotites from most of the alkaline complexes.

The observed compositional variation trends of biotites towards the aluminum-rich annite and siderophyllite may be due to the significant increase in both tetrahedrally and octahedrally coordinated Al with Fe through the extensive Tschermak's substitutions. Fe^{3+}, Al^{3+} and Ti^{4+} exhibit preferential partitioning in the M2 sites (Cruciani and Zanazzi 1994).

Na-K Variation: The atomic cation contents of K (1.85 to 2.006) in biotite are quite comparable to those observed from most of the alkaline complexes. The biotites are generally fresh and are not chloritized. However, Na contents in the biotite are relatively low (0 - 0.104) compared to the values recorded from the nepheline syenites of Greenville and Malawi provinces (Duke and Edgar 1977, Woolley and Platt 1986, 1988).

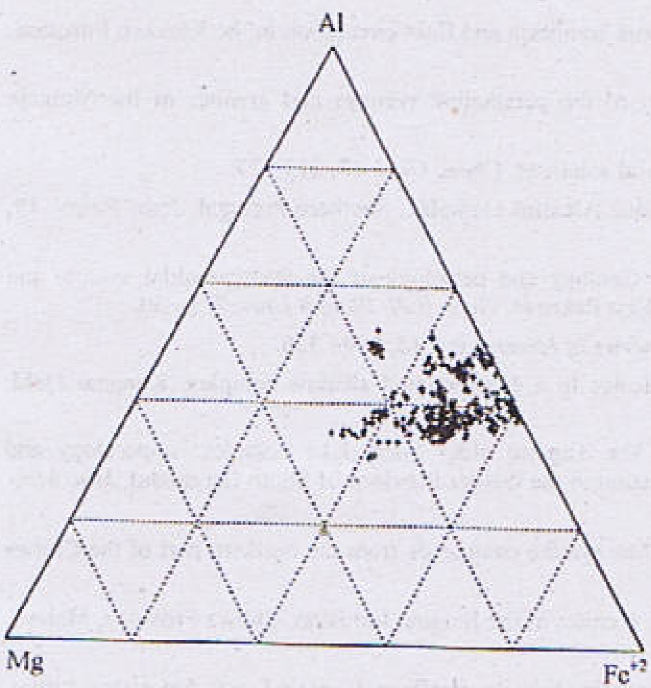

Fig. 5 Microprobe analyses of biotites from Koga, plotted in terms of Mg - Al - Fe^{+2}.

DISCUSSION

The Koga feldspathoidal syenite - carbonatite complex is predominantly felsic plutonic association believed to have been emplaced within the continental rifting structure of the northern continental margin of Indo-Pakistan plate. The feldspathoidal syenite rocks intrude the older Chingalai granodiorite gneiss. To the north west and south west the rocks of the complex appear to be intruded into the Babaji syenites but the contact at places particularly on the west is gradually diffused and the two types appear comagmatic. A number of small carbonatite bodies are exposed within the feldspathoidal syenites close to Naranji Kandao, Shapala and near Nawe Killi (Siddique 1967, Siddiqui et al. 1968). The feldspathoidal syenite intrusions are interpreted to have been emplaced at relatively shallow depth and low pressures >1 and < 5kb (Baloch 1994).

Biotite compositions of the Koga feldspathoidal syenites show considerable variations in terms of changing $(Fe^T+Mn)/(Fe^T+Mn+Mg)$ and Al/(Al+Si) ratios. The biotites are distinctly aluminous showing trends of compositional evolution from biotite - annite towards siderophyllite with the increase in Al contents and Fe - enrichment (Fig. 5). Ti and Mg values are low, particularly Ti contents are even lower than plutonic values given by Robert (1976). The low Ti and high Al contents in biotite can be correlated with low temperature crystallization (Robert 1976) in the felsic magmas. The phlogopite component decreases with magmatic evolution, having the lowest values for foyaites and foyaitic feldspathoidal syenites. These are the most evolved rocks (phlogopite component 0 - 15 %, and low Ti and Mg), compositionally related to phonolitic trends.

The coexistance of alkali feldspar, pyroxene, biotite (annite-siderophyllite) and magnetite in the Koga feldspathoidal syenites allow some indication of the relative volatile fugacities in the magmas, if fO_2 T& P of the equilibrium of the assemblage can be estimated (Nash and Wilkinson 1970). The increasing annite - siderophyllite component in the biotite is related to a decrease in fO_2 with falling temperature (Woolley and Platt 1986).

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Geol. Bull. Punjab Univ. 33 & 34, 1999.

EVALUATION OF THE INDUSTRIAL USES OF THE PALEOCENE DUNGAN LIMESTONE OF THE THALANG PHUSHT AREA, D.G. KHAN, PAKISTAN.

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Abstract:- *Limestone is one of the major rock types in the stratigraphic column of Pakistan. Dungan limestone of Palaeocene age from the Thalang Phusht quarry is categorised as fine grained micritic limestone. Based on carbonate contents this limestone is of medium purity. Material from the two of the seven benches meets the specifications for its use as whiting in paint, rubber, polish and chemical industries. Limestone from the other benches can be used as an extender certain paints in plastic floor-tiles; and as filler in baking-foam in carpets. Good quality lime having high reactivity and surface area can be produced with controlled calcination conditions at 1050 C. Production of fines during calcination is very low which suggests that lime is reasonably strong.*

INTRODUCTION

Limestone is very important raw material used by industrialised nations. For example, more than 120 million tonnes is extracted annually from quarries and mines in the United Kingdom (British Geological Survey, 1992). A major amount is used as cheap aggregate for construction purposes, because it is readily available and is cheaper to extract and crush than harder igneous rocks or gritstones and greywackes. Limestone is also the major ingredient in cement manufacture. In addition it is an essential raw material for chemical, steel, plastics and other industries. Specifications for these uses are generally much stricter than for aggregates or cement manufacturer, and stone is required to be of high purity and/or to have other desirable physical properties. In the United Kingdom around 12 million tonnes per annum are used for non-aggregate and non-cement purposes. In tonnage terms this is a minor proportion compared with the overall extraction, but in terms of value it is much more important. Some limestone and lime products are several £10's per tonnes and occasionally >£100 per tonne is received for specially processed material. Limestone aggregates are typically around £5 per tonne, ex quarry.

Limestone is found at various stratigraphic levels in Pakistan. Several are exploited for use in construction industry (e.g. Margala Hill Limestone) and some are used for cement manufacture (e.g. Dungan Limestone). In addition, there are recrystallised limestones and marbles in mountainous northern areas, which are pale grey and white in colour. These are cut and used for tiles and other decorative stone products (e.g. pale green onyx-type). The use of limestone for other industrial uses is underdeveloped in Pakistan, although there is some lime manufacture (e.g. for steel and sugar industry).

The purpose of this paper is to provide a brief review of the uses and specifications of limestone for non-aggregate and non-cement purposes and to discuss methods for the evaluation of limestone resources. Data from a study of the Palaeocene Dungan limestone in the Eastern Sulaiman Range from Thalang Pusht near D.G. Khan (Saleemi 1991) are used for an example and the results are discussed in the context of evaluating this limestone resource. This limestone is currently used only for cement manufacture.

USES AND SPECIFICATIONS OF LIMESTONE

Limestone is used by a large number of different industries for many different purpose either because of its chemical composition, its high strength, or because it can be made into a non-toxic relatively cheaper powder. Occasionally other properties are relevant for some uses, such as its mild abrasiveness, or its attractiveness as a dimension or building stone, but in general, for a limestone to be useful for a range of industrial applications, other than as an aggregate or for cement, it must be of high purity, have acceptable strength and produce a white powder. Table. 1 gives a summary of the uses of limestone in relation to the product size, and includes details of the typical specifications required of the rock for these uses in the United Kingdom. Stone for aggregate and other construction uses are included because in the United Kingdom, material for these uses is taken at virtually every site of extraction. The extraction and crushing process for a limestone often needs to be set up to produce the maximum amount of stone of particular size for a major market. However, other sizes are produced as well during crushing, and for maximum utilisation of the raw material and for maximum return on extraction and crushing costs, all of the stone needs to be sold. Thus, presentation of the uses of limestone in a form showing products in relation to particle size is appropriate.

Unless careful selection of stone is made before or during the crushing process, the impurities in a limestone, such as clays, usually become concentrated in the finer grained fractions (Thanoon, 1984). These sizes can than only be used for low specification purposes, such as in agriculture and as an asphalt filler. To produce high purity powder products, stone needs to be selected from the coarser fractions after removal of fines, before further crushing. Ultrafine grinding of limestone or marble to give particle size $< 10\mu m$ is used to produce very high value products for use in paper coating and some other filler applications (e.g. paint).

Limestones which have superior properties to those given in Table 1 can command higher prices or may be used in preference to poorer quality products. Limestone with >98.5% $CaCO_3$ is generally considered to be of very high purity (Harris 1982). Other categories of purity are; 97.0-98.5%, high purity; 93.5-97%, medium purity; 85.0-93.5%, low purity and <85%, impure. A white colour for powdered limestone used as a filler or extender in rubbers, plastics and paints is preferred, even if it is to be used in a non-white products, unless there is a distinct price advantage in the non-powder. The reason for this is that whiteness is equated with purity, and the customer is more likely to receive a consistent product if whiteness is specified. For many filler and extender applications, limestone powders (including marble) compete with other minerals including kaolin, talc, dolomite, barytes and nepheline syenite. In general the finer the particle size distribution of the limestone powder and the whiter it is, the greater the price of product. Powders with various particle size distributions can be produced by a combination of crushing in a ball mill or other micronising process along with screening and air classification.

Lime, made by calcining lumps or pebble-sized pieces of limestone in a suitable kiln has a wide range of uses. It is the major flux in steel making, and some is used in iron ore agglomeration processes and in the beneficiation of non-ferrous metals (Harrison, 1992).

It is used in soda ash manufacture, in the bayer process for alumina purification, in the paper pulp industry, in sugar refining and in the process for extraction of magnesium oxide from sea water. It is an important chemical for water treatment, in removal of hardness, bacteria removal, coagulation of suspended solids and neutralisation of acid effluents. It finds uses in the construction industry in making sand-lime bricks, in light weight building blocks, in mortars, plasters and coatings. In USA there is a major use in soil stabilisation prior to highway construction. At present in Europe, markets for lime are increasing due to its usefulness in treatment of industrial effluents and increasingly strong environmental legislation.

The principal consideration in choosing a kiln for making lime, is fuel efficiency, as about 80% of the cost of lime is in the energy consumption, removing the carbon dioxide from the limestone. There are many types of kilns, most being either vertical shaft or inclined rotary types. Shaft kilns, especially modern ones in which the stone moves in the same direction as the fuel combustion products, are the most efficient, and give a uniform lime product (Phelps, 1983). As well as having a high or very high chemical purity, limestone for lime manufacture should have sufficient strength to withstand loading and abrasion, and should not decrepitate during calcination. The choice of fuel for burning can also be important as impurities, such as sulphur from oil, or ash from coal can become incorporated into the lime product affecting its composition. Generally a higher purity of limestone is required for lime manufacture than for other uses, as the proportion of impurities almost doubles in the lime due to the loss of 44% CO_2.

The properties of lime depend on the type of kiln, the temperature of calcination and the burning characteristics of the stone. The latter are evaluated by determining the porosity, bulk density, surface area, loss on ignition and reactivity of the lime by laboratory work, pilot plant and full-scale trials at different temperature and times of calcination. For most purposes, lime should be made at temperatures just above the decomposition temperature of limestone (950 $^{\circ}C$ at atmospheric pressure), and for sufficient time so that all of CO_2 is lost. Lime made in this way is readily reactive with water, has a high porosity (approx. 50%), high surface area (approx. $2.6m^2/g$), and low bulk density (approx. $1.6g/cm^3$). Different petrographic types of limestone have different burning characteristics

(Scott et al. 1983). In general, compact limestone, which is microcrystalline or has a variable but overall small crystal size can be made into a suitable lime without difficulty. Coarsely crystalline material, such as calcite, as well limestone with a lot of coarse sparry calcite cement, and marble, readily decrepitates in a normal kiln and requires special techniques for burning, such as a fluidised bed calciner (see Boynton, 1980).

Table 1
Uses and specifications of limestone products

Approx. size	Use and specification
>1m	Cut and polished stone Large blocks with no plane of weakness Consistent white or attractive pattern of colouration Frost resistant and non porous for external use
>30cm	Building stone Acceptable compressive strength Available in beds of suitable size and extent Consistent appearance Frost resistant and non-porous for external use
>30cm	Rip-rap or armour stone Acceptable compressive and impact strength Bulk density >2.65 Available in blocks of specified size Frost resistant and non-porous
1-20cm	Aggregate, including concrete, roadstone and rail ballast Aggregate impact value, 24 Aggregate crushing value, 24 Aggregate abrasion value, 14 Polished stone value, 40 10% fines value, 190 KN No soluble salts Frost resistant and non porous Forms equidimensional shaped particles
1-5cm	Aggregates, including roofing granules, terrazzo and stucco Adequate strength Suitable colour or appearance No soluble salt Frost resistant and non porous for external use
3-30cm	Lime manufacture (size dependent on type of kiln) High or very high chemical purity. Individual specifications depend on use of lime, eg. sulphur must be <0.05% in lime for the steel industry No decrepitation during calcination Suitable burning characteristics
3-8cm	Filter bed stone Adequate compressive strength and does not form dust during handling and use Moderate to high chemical purity Low moisture absorption Frost resistant

0.2-5cm	Chemicals >97% $CaCO_3$, depending on use Limits on MgO, Fe_2O_3, SiO_2, Al_2O_3 and organic matter, depending on use Adequate strength and does not form dust when handled
3-8mm	Poultry grit Moderate to high chemical purity Adequate compressive strength Equidimensional grains
1-5mm	Glass >98.5% $CaCO_3$, <0.035% Fe_2O_3 Other colouring elements in glass not present <1%, hydrochloric acid insoluble residue <1% organic matter
<4mm	Agriculture Acceptable neutralising value (around 53%) (i.e. moderate or high chemical purity) No element or compound toxic to soils
<3mm	Iron ore sinter, foundry fluxstone and non-ferrous metal fluxstone >85% $CaCo_3$, <3% SiO_2, <1.5% Fe_2O_3 Negligible sulphur
<0.25	Mine dust Moderate chemical purity <3% SiO_2 Uniform light colour Free from any tendency to cake
<0.2mm	Filler and extender in plastics, rubber, paint, paper, adhesives and putty High chemical purity, usually >96% $CaCo_3$ No toxic elements White colour and high brightness Low oil absorption
<0.2mm	Asphalt filler Originating from a calcareous rock
<0.2mm	Mild abrasive, fungicide and insecticide carrier Moderate to high chemical purity No free quartz Near white colour
<0.2mm	Glazes and enamels Moderate to high chemical purity No free quartz impurity
<0.15mm	Flour, food and other pharmaceutical uses >97% $CaCo_3$, Arsenic <4ppm, Lead <20ppm Acid insoluble residue, <2%
<0.1mm	Flue gas desulphurisation >85% $CaCo_3$ and <5% MgO, but usually higher purity is specified Microporosity is beneficial

Data modified from Scott and Dunham (1984), with additions and other data taken from Harris (1982) and Power (1985). Where actual values are given, they are based on specifications for use in the United Kingdom.

Types of Calcium Carbonate

Calcium carbonate occurs in many forms in nature. It is most common in many parts of the world as limestone made up of calcite, or occasionally aragonite. Limestones with wide ranging textures, including dense micrites, porous microcrystalline chalks, bioclastics, algal, reefal and intraclastic allochemical limestones with micritic or sparry cements, and recrystallised limestones, are all used for the applications discussed above. Marble is a substitute for many uses of limestone, and in some cases, marble can have enhanced properties over limestone, such as in making high whiteness and high brightness powders for paint and paper use.

Other forms of calcium carbonate in nature include carbonatite, vein calcite, cave deposits (onyx) travertine and tufa, some modern beach deposits, caliche soils, and oyster shells. All of these find some use, sometimes specialised, such as onyx decorative cut, turned and carved stone products. Carbonatites are the only available form of calcium carbonate in some countries in Africa, and have been used for cement manufacture. Travertine and tufa can make attractive cut and polished stone. Oyster shells have been used for lime manufacture, particularly in the USA Gulf Coast states. Vein calcite as a by-product from the extraction and processing of other minerals, such as fluorite, barytes and galena, can find several uses as granular white pebbles (e.g. as exposed aggregate in concrete products), and as a source for white calcium carbonate powders.

Precipitated calcium carbonate, which is made from carbonating hydrated lime, can be made in many different forms, with different specifications. Although a chemical, its ultimate source is limestone. It is used for some of the same applications as limestone, particularly where a high purity, very fine particle size and very white powder is needed.

DUNGAN LIMESTONE
(Thalang Phusht Limestone Deposit)

(a) Geology

The project area lies between co-ordinates 70° 27' 40" E to 70° 29' 30" E and 30° 18' 30" N to 30° 21' 30" N in toposheet 39 J/7 of Survey of Pakistan. Only Tertiary Formations from Palaeocene to Pliocene / Pleistocene are exposed in the project area. The oldest rock formation is Dungan limestone and the youngest formation is Chaudhwan Formation, which is subsequently overlain by Sub Recent to Recent deposits. In the quarry area (Fig.1) the Dungan Limestone is dominantly composed of limestone with subordinate shale, silty shale and arenaceous limestone. Limestone is brown, grey and brownish on weathered surface and if observed from a distance has typical brown look in contrast to surrounding Ghazij Shale. The Dungan Limestone forms an anticlinal shape and at the top it is brecciated showing local reworking before the deposition of the Ghazij Shale. At this level at a number of places chert nodules and dendrites have been found. The cherty material have size from 10-150 mm and occasionally coarser upto 300mm. The underlying zone is mostly well exposed in the area delineated and is 0.3-5 metres thick containing cherty microfossils and calcareous mega and microfossils. The percentage of cherty fossils varies from 2-7 at a number of places and decreases down to less than 0.5%. Further below, the limestone beds are moderately to highly fossiliferous and are free from cherty fossils. In general limestone is mostly thick to medium bedded, massive compact and hard to break. Jointing pattern is of two to three sets. Veins and veinlets of recrystallised calcite are hardly present in whole mass of limestone, however numerous veinlets can be seen on both sides of major fault plane as thin streaks of distinctly white colour. At places Dungan limestone is ovrlain by Ghazij shale formation which is mainly composed of limestone and occasionally intercalated with shale or marly shale. The core drilling results (Ashraf et. al., 1981) show that the thickness of the Dungan Limestone is 65-68 metres.

Structurally the Dungan limestone forms anticlinal shape, the crest of which has been faulted showing a displacement of 50 metres. Due to anticlinal folding a number of minor folds and faults have formed. The faults are developed due to perhaps tension release on the upper part of the fold as the compressional forces are more or less east-west and faults mostly north-south. The faulted blocks show very minor throw from 5-50 metres showing step faulting and horse and graben structures. The faulted plains show typical granulation and breccia, which is very minor as thick as 2 metres. The anticline is nowhere is thoroughly dissected as its stratigraphic variations and full thickness is not known. The maximum exposure seen is only 50 metres near Thalang Phusht.

(b) Mineralogy

Chip channel sampling was carried out from the each bench of the Thalang Phusht limestone quarry (location of samples shown on Fig. 1). Seven samples were collected, each weighing about two Kg. For thin section study samples showing different textures on visual inspection were also selected.

Thin sections were stained with Alizarin Red-S (Dickson, 1965) to facilitate distinction between calcite and dolomite minerals, and with Potassium Ferricyanide to determine the ferroan nature of the calcite and dolomite

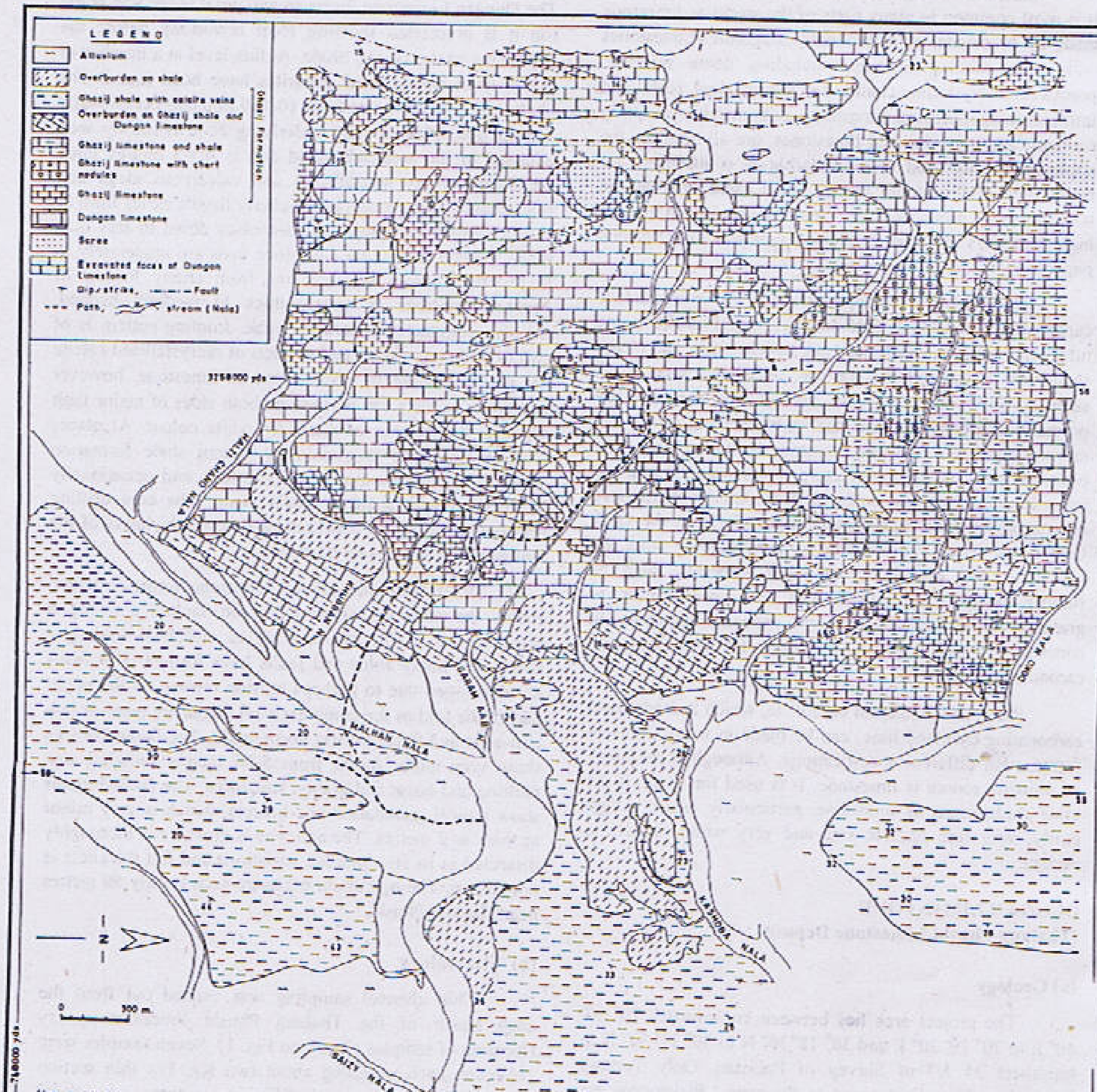


Fig. 1 Geological Map of the Dungan Limestone and Ghazij Formation, D.G. Khan, Pakistan.

(Dickson 1965). The classification used to define petrographical parameters of limestone is that of Dunham (1962).

Texturally the rocks are generally fine grained ranging from skeltal mudstone to wackstone and sub equigranular to microcrystalline, while recrystallised are predominantly euhedral to subhedral. Thin section studies of samples from various benches of the quarry revealed that calcite occurs as microcrystalline, cryptocrystalline and crystallised mineral forming the main mass of the rock in which mostly calcareous fossils are embedded. The recrystallised calcite occurs as veinlets, patches and in fossils. The amount of calcite varies in rock from 95% to 98.5%. Dolomite occurs as coarse grained, euhedral to subhedral rhombs. It is generally in traces but exceptionaly is found up to 3%. Quartz is present as extremely fine authogenic grains. It occurs as admixed aggregate in fossils and in groundmass. Its amount varies from 0.5 to 1%. Chert occurs mostly as small aggregate, as discrete cryptocrystalline grains and as admixed aggregate in fossils and groundmass. Its concentration reaches from traces to 0.5% in the studied samples. Clays occur as extremely fine grained dispersed phase and reach up to 1%. Hematite /limonite occur in the form of small grains as amorphous looking aggregate, streaks, stains and partial replacement of some fossils. It varies from 0.1 to 0.5%.

The staining revealed that some samples have dolomite rhombs of matrix selected dolomitization. Normally dolomite crystals are encircled by ferroan calcite, this type of dolomitization is restricted to void filling cement. The ferroan calcite shows an earlier selective dissolutioning and incorporating Fe^{++} ions in the reducing environments. In some samples the fractures are filled with sparry calcite (Fig. 2.1) and major part of this sparite is ferroan calcite. In many samples the fossils are partially recrystallised and in some cases shells or chambers of fossils are recrystallised to sparry ferroan calcite (Fig. 2.2). Occasionally it has been noticed that whole fossil has converted into sparry calcite with a thin layer of micrite enveloping the fossil (Fig. 2.3). At places micrite matrix has recrystallised into sparry calcite in the form of patches. These patches have sharp boundaries with the adjoining micritic matrix and appear to be closely related to pore fillings. In these patches two generations of cement are quite obvious, inner core of this sparry calcite is ferroan calcite encircled by Ca-calcite (Fig. 2.4). In some thin sections the effect of physical compaction due to diagenesis is prominent. This compaction has caused distortion and micro fracturing in the fossils and these micro fractures are latterly filled by sparry calcite. In general porosity which originally was present has been occluded due to precipitation of sparry calcite with drusy mosaic. The allochems in limestone are fossils and fossil fragments, which include large population of Foraminifers, Moluscs, Echinoids and Algeas.

For X-ray diffraction analysis samples were ground in pastle mortar and were further reduced between 5-10 microns by micronising. Cavity mounts were prepared and run on Philips PW 1729 diffractometer for whole rock mineralogy.

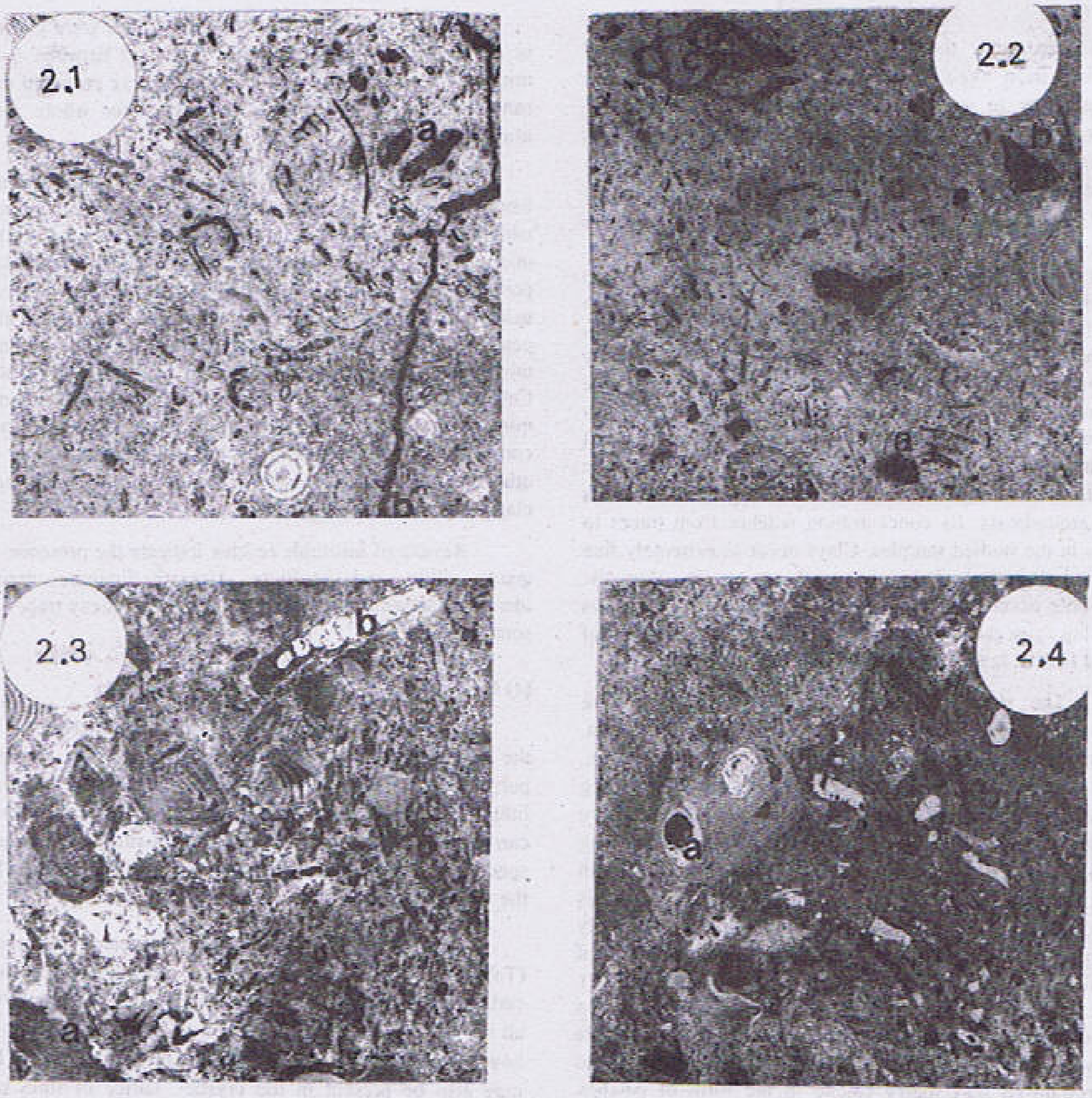
Microcellulose filters were used to trap the residue from a sample of powdered limestone of known weight which has been dissolved in N/10 hydrochloric acid. Initial mineralogical determination of the insoluble residue was performed by optical microscopy, followed by analysis using X-ray diffractometer. Almost all the traces show the peaks of same minerals indicating the consistency in the mineralogy of limestone throughout its exposed depth. Calcite is present as major phase, while dolomite show minor concentration. The dolomite peaks intensities are comparatively high in samples B5 and B6 than those of other samples. Phases present in traces include quartz and clay minerals like illite and kaolinite.

Results of insoluble residue indicate the presence of quartz, illite and kaolinite. Hematite/limonite grains identified optically were also confirmed by X-ray traces of some samples.

(c) Chemistry

A total of seven samples from different benches of the quarry face were analysed for major elements. For this purpose fusion discs of samples were prepared by using lithium tetra borates as fluxing agent and the analysis was carried out using Phillips 1400 X-ray fluorescence spectrometer. The loss on ignition was also determined for the same samples.

The chemical analysis are represented as oxides (Table 2). Ca and Mg oxides are converted into their carbonates by using their molecular weights assuming that all the Ca, Mg and Mn are present in calcite and dolomite, however a small amount of these elements particularly Mg may also be present in the crystal lattice of illite clay mineral. The analysis reveal that with the exception of samples B5 and B6 all other show weight percentages of calcium carbonate ranging between 94.30 to 96.84 and the dolomite content normally fluctuate between 2.4 to 3.5 percent, however samples B5 and B6 show almost double concentration of dolomite. The silica may be present as free quartz as well as associated in the crystal structure of the clays. All the alumina is considered to be incorporated in clays. Fe is considered to be present in hematite and limonite as well as in illite and ferroan-calcite. The presence of sodium is attributed to illite.



Scale of all microphotgrphs is = 1mm

Fig. 2 Different textures present in Dungan Limestone.

2.1 Bioclastic wackstone. (a) Dolomite crystal surrounded by sparry calcite, (b) Microfracture filled with sparray calcite.

2.2 Skeltal wackstone/packstone. (a) Non fabric porosity occluded by ferroan sparry calcite. (b) Occlusion of porosity by sparray calcite with drusy mosaic. (c) verticle section of gastropod replaced by ferroan calcite.

2.3 Foraminiferal wackstone. (a) effects of physical compaction on the foraminifers. (b) Complete recrystallisation of gastropod shell into sparry calcite.

2.4 Bioclastic packstone. (a) Two types of cement generation, inner core is ferroan sparry calcite and outer zone is Ca-calcite.

Table 2
Chemical composition of Dungan Limestone with loss on ignition values.

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	L.O.I	$CaCO_3$%	$MgCO_3$%	$CaCO_3$% by diff.
B1	0.50	0.02	0.17	0.27	0.01	1.67	53.42	0.27	0.02	0.05	56.40	43.84	95.34	3.49	95.18
B2	0.62	0.01	0.21	0.25	0.01	1.24	54.01	0.40	0.01	0.03	56.79	43.88	96.39	2.59	96.77
B3	0.33	0.01	0.11	0.39	0.01	1.15	54.26	0.26	0.01	0.03	56.56	43.90	96.84	2.40	96.78
B4	0.82	0.02	0.28	0.23	0.01	1.25	53.89	0.64	0.04	0.05	57.23	43.67	96.18	2.61	95.34
B5	0.13	0.01	0.09	0.15	0.02	2.77	52.86	0.14	0.03	0.06	56.26	44.04	94.34	5.79	92.67
B6	0.18	0.01	0.10	0.19	0.03	3.10	51.36	0.16	0.01	0.07	55.21	44.00	91.66	6.48	92.41
B7	0.41	0.02	0.15	0.18	0.01	1.29	53.06	0.30	0.04	0.04	56.07	43.87	94.67	2.70	95.57

PHYSICAL METHODS OF EVALUATION

Less than 125µm material was used for carrying out all the tests performed on powders of limestone with the exception of oil absorption test in which -53µm material was used.

(a) Colour measurement

The colour measurements were made on pressed pellets by using the Diffusion System Ltd. (formally known as EEL) Abridge Reflectance Spectrometer Model 99 was used for this purpose and measurements were taken following the CIE system of colour measurement. Tristimulate values of x, y and z filters were measured and a white ceramic tile used as working reference was calibrated against $MgCO_3$ standard. The values of L^*, a^*, b^* and E^* were also calculated. The results are presented in Table 3.

Table 3
Colour measurement, X, Y and Z, along with the derived L^*, a^*, b^* and E^* values.

Sample No.	X	Y	Z	L^*	a^*	b^*	E^*
B1	72.6	71.3	83.3	89.1	-0.6	3.1	1.34
B2	69.4	71.2	73.4	87.6	0.8	4.9	3.42
B3	75.5	76.6	69.0	94.2	-2.2	6.3	2.72
B4	71.4	73.3	81.0	88.6	-1.0	3.9	2.50
B5	83.5	85.4	95.2	96.0	-0.4	3.6	2.10
B6	83.9	85.5	95.8	94.1	0.2	3.3	2.42
B7	74.4	73.8	70.1	93.7	0.6	4.2	1.53

(b) Oil Absorption

The method used follows BS 3483: part B7 British Standard method for testing pigments for paints. Refined linseed oil having an acid value of 5.0 mg as KOH/gm was used as regent. Seven measurements were made on duplicate samples collected from each bench of the quarry and the results are shown in the Table 4.

Table 4
Oil absorption values of Dungan limestone. Oil absorption value ml/100gm.

Sample No.	1st Reading	2nd Reading	Average
B1	15.0	15.0	15.0
B2	15.0	15.0	15.0
B3	16.0	15.0	15.5
B4	15.0	15.5	15.5
B5	15.0	15.0	15.0
B6	15.0	15.0	15.0
B7	15.0	15.0	15.0

(c) pH Measurements

The Proceedure is adopted from BS 3483: part C4. A 10% (Mass/mass) suspension of the limestone powder in distilled water (i.e., 5 gram of powder dispersed in 50 ml of water) was prepared. The pH value was measured at room temperature using a glass electrode. Before measurement was started the pH meter was calibrated against the buffer solution with a pH value 7. The results are presented in Table 5.

Table 5
pH values of Dungan limestone

Sample No.	pH
B1	9.1
B2	9.3
B3	9.1
B4	9.1
B5	9.1
B6	9.1
B7	9.3

(d) Acid Insoluble Residue

Impurities in limestone vary considerably in type and amount but are important from an economic point of view only if they effect the usefulness of the rock. Five gram of limestone powder was placed in a large beaker and 10% of HCL was added until no further reaction took place. The liquid and the residue were then placed into the vacuum cup onto a weighed No. 5 filter paper. The acid was filtered through, followed by three washes with distilled water until all the acid was washed out of the filter paper. The filter paper was then dried and weighed to obtain the weight of the remaining. A check on moisture content was also done by using a filter paper which was rinsed with acid and then washed with distilled water and dried followed by being weighed. Duplicate tests carried out on each sample with average values of the results are given in Table 6.

Table 6
Percentage of acid insoluble residue in Dungan limestone.

Sample No.	1st. value	2nd. value	Average value
B1	0.4	0.4	0.4
B2	0.4	0.4	0.4
B3	1.2	0.8	1.0
B4	0.6	0.8	0.7
B5	0.2	0.2	0.2
B6	0.2	0.2	0.2
B7	0.4	0.4	0.4

(e) Calcination and lime properties

Closely sized (12.5-25mm) stones of five samples selected using the petrographical parameters described by Dunham (1962) were calcined. Magnesia crucible was used for calcination and stone were shock calcined in a laboratory muffle furnace for 1.5 hours at temperature ranging from 950 °C to 1150 °C at 50 °C intervals. After calcination samples were drawn from the furnace, cooled for few minutes in the air and then kept in desiccator until they were cooled at room temperature. After cooling, the samples were kept in sealed polythene bags and these bags were kept in a desiccator to prevent any recarbonation or absorption of atmospheric water.

The weight loss, loss on ignition, apparent porosity, bulk density, reactivity, surface area and decrepitation of lime were measured. The apparent porosity and bulk density of the raw stones were also measured. Experimental procedures are similar to those carried out by Lyon (1980) on the evaluation of the burning characteristics of some North American limestones and dolomites. Results of various tests carried out on lime prepared from different samples are almost similar, so the data of a representative sample is given in Table 7. The relationship between these properties and calcining temperature are shown in the

Figure 3. Scanning electron microscope investigations were also carried out on lime prepared at different temperatures. For this purpose a Hitachi S 520 SEM equipped with a back scattered energy disperssive x-ray analyser (EDX) was used. Samples (about 1 cm^3 volume were mounted on aluminium stubs and coated with gold in vacuum evaporator. SEM microphotographs are shown in Fig 4.

Table 7

Properties of lime obtained after shock calcination of Dungan limestone.
Apparent porosity and bulk density of raw stone are 2.4% and 2.57 gm/cm^2 respectively.

Temp ^oC	950	1000	1050	1100	1150
Wt. loss %	32.70	41.70	43.60	43.60	43.60
LOI, %	18.09	1.62	0.76	0.29	0.18
Apperent porosity, %	38.60	49.70	50.70	40.70	31.80
Bulk density	2.10	1.62	1.76	2.19	2.33
Reactivity, (temp. rise ^oC after 2 mins.)	29	41	46	24	10
Surface area, m^2/gm	2.36	2.76	2.25	1.13	0.88
Decrepitation, %	0.36	0.43	0.67	0.59	0.53

SUITABILITY OF THE DUNGAN LIMESTONE

Most of the limestone from the quarry is very similar overall fine-grained micrite. Abundance of allochemical constituents can be found throughout the exposure of limestone. Following the grade assessment (Cox et. al., 1977) of limestone on the basis of carbonate content of limestone, the Dungan limestone can be classified as medium purity limestone. The chemical composition of samples from all benches of the quarry with the exception of samples from bench Nos. B5 and B6 indicates moderate concentration of iron which is present in Ferroan calcite around dolomite crystals and in recrystallised fossils alongwith other iron bearing minerals like hematite and limonite make this limestone unsuitable for filler application where extreme whiteness is required. The iron and silica concentration in samples from benches B5 and B6 are very low and the results of colour measurements of these samples show higher brightness values as compared to the values of other samples. The brightness values (85.5) of these two samples are comparable with the specific requirements of brightness recommended by ECC for paint, paper filler, PVC, polish and chemicals. However, the brightness values of other samples can meet the requirements of brightness for low cost plastics and rubber filler like the latex foam backing for carpets and PVC floor tiles. Oil absorption values of this limestone are smaller than the values of the most of the manufactured $CaCO_3$. This may be due to the reason that the particle size could be coarser than the specific requirements as in our study -53μm material was used and no further size distribution was measured. Fine particle size is required for the most of the applications, which can be achieved by further crushing and classifying. In such case, large oil absorption will result due to the higher surface area, which could be lowered by chemically treating the surface of the particles by fatty or aliphatic acids. The pH of aqueous solution of this limestone is within limits required by most of the applications, however it should not be used with alkali sensitive medium. The acid insoluble concentration results show that samples B5 and B6 have low concentration of impurities even lower than, present in British Cretaceous chalk. The brightness values of these samples which are slightly lower than those of British chalk are due to the different nature of impurities, as Dungan limestone have hematite/limonite and illte which give the colouration causing low brightness. Some colouration is also imparted due the Fe-calcite. On the other hand in the British chalk the main impurity is colourless quartz. Samples from the other benches of the quarry show higher concentration of impurities and are consequently low in brightness.

Lime made from different textural types of the Dungan Limestone have low loss on ignition, high reactivity, high porosity, high surface area and low bulk density when calcined at 1050 °C. The values of porosity, reactivity and surface area increase during progressive calcination from 950 °C to 1050 °C and show declining trends on further elevation of tempreture (Fig. 4). These properties at 1100 °C show signs of hard burning i.e. decrease in porosity, reactivity, and surface area. Bulk density which decreases progressively upto 1050 °C starts increasing at 1100 °C. At further rise of temperature i.e. at

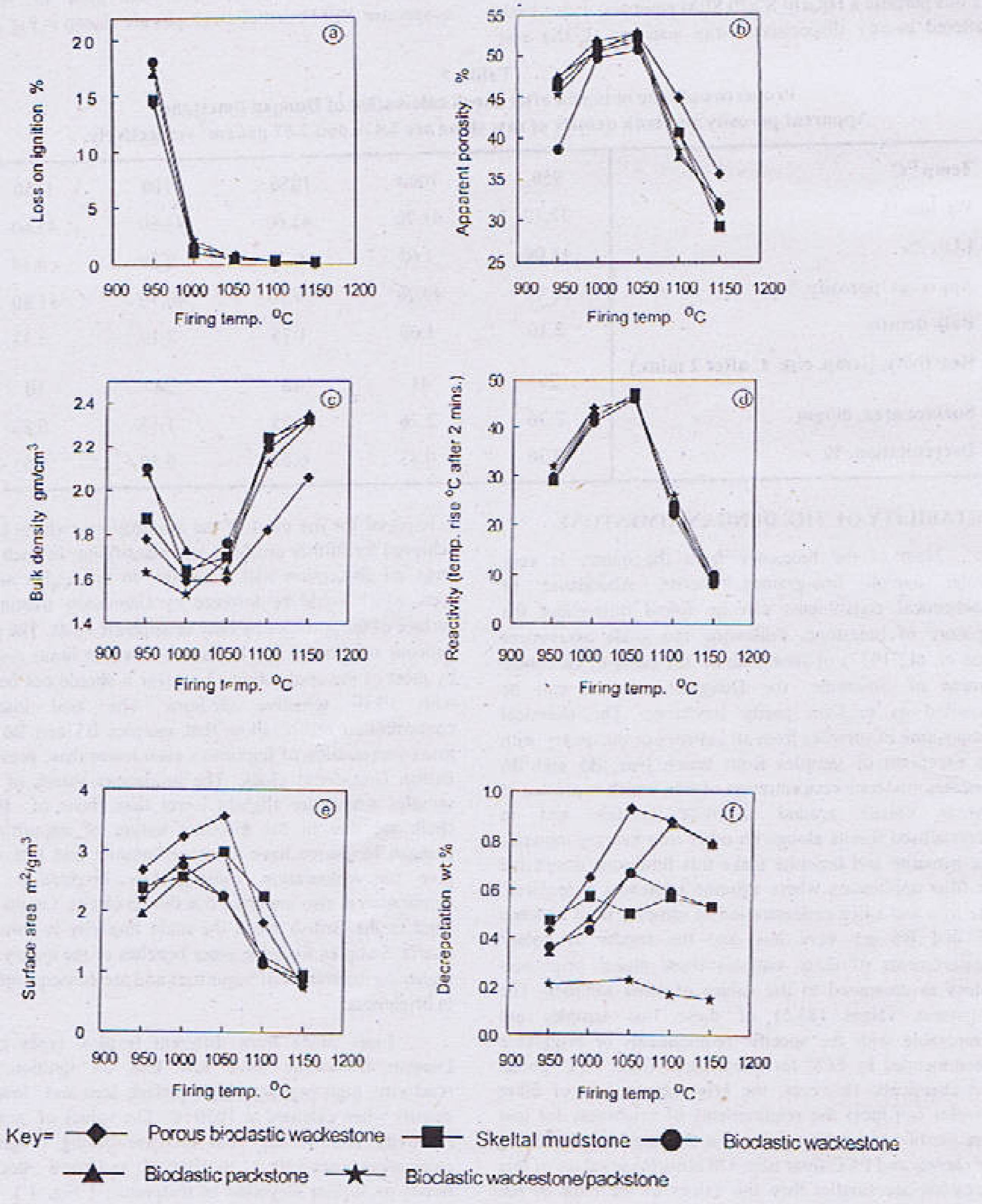


Fig. 3 Plots of different physical properties of lime produced for different types of Dungan limestone at indicated temperatures.

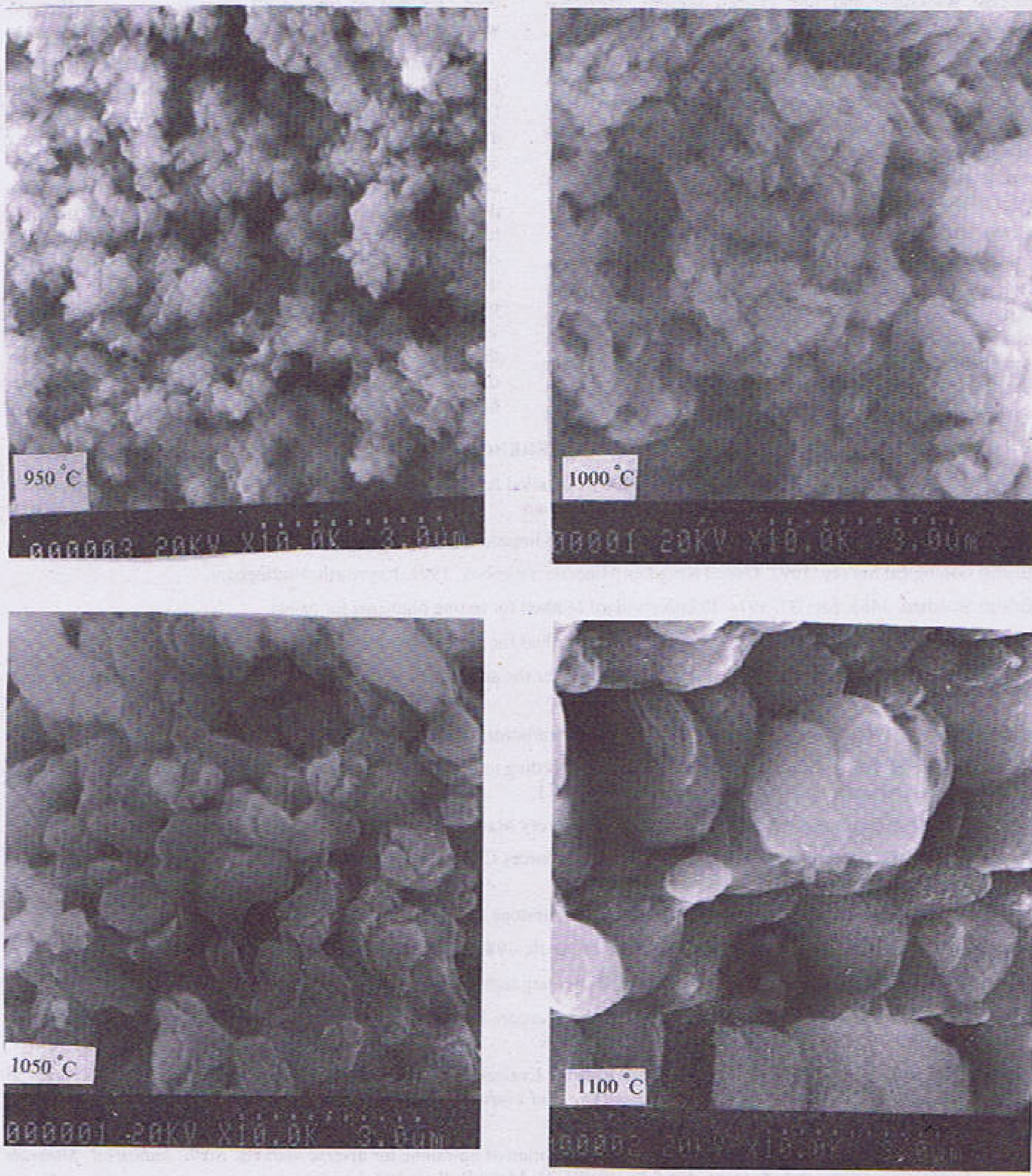


Fig. 4 A set of S.E.M. microphotographs of lime prepared at mentioned temperatures showing reduction in porosity and crystallite size growth at elevated temperatures.

1150 °C there will be further reduction and increase in these properties respectively. Two samples identified as porous bioclast wackstone and fine grained skeletal wackstone show a lower calcining temperature as compared to others, this can be related to higher degree of porosity and fine grained nature of the raw stones. Decrepitation test reveals that this limestone is suitable for lime production with rotary and shaft kilns as the production of fines during calcination is reasonably low and the required lump size can be calcined with the production of low percentage of fines in these kilns.

CONCLUSIONS

Laboratory tests performed on powder of the Dungan limestone from the Thalang Phusht quarry show that only two benches have brightness values (85.5), which make it suitable for use as whiting in paint, rubber, polish and chemical industries. However the limestone from other benches of the quarry can be used as an extender in applications where the colour is of no importance e.g. in some kinds of paints, plastic floor tiles and as filler in baking foam in carpet industry. This limestone can also be used for making linseed oil putty for use as a filler in wooden frames.

Almost all textural varieties of this limestone are fine grained to micritic in nature. The calcination of the Dungan Limestone in a laboratory muffle furnace show that a good quality lime having high reactivity and surface area can be produced with careful control on calcination conditions, as above the 1050 °C the lime stars becoming dead burn rapidly. So a check is necessary to maintain a temperature at which lime with low loss on ignition, high reactivity and surface area, with acceptable porosities and densities could be obtained. The decrepitation results indicate that the production of fines during calcination is very low showing that lime is reasonably strong. However there may be excess percentage of fines during calcination of this limestone in commercial kilns due to mechanical handling and abrasion in the kiln.

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Geol. Bull. Punjab Univ. 33 & 34, 1999.

THERMOTECTONIC HISTORY OF LOE SHILMAN CARBONATITE COMPLEX, N W PAKISTAN, BASED ON FISSION TRACK DATING OF APATITE AND OTHER RADIOMETRIC AGES

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Abstract: *The Peshawar Plain Alkaline Igneous Province (PAIP) consisting of alkaline granites, syenites, gabbros, albitites, carbonatites etc., occurs in the north of Peshwar Plain in an arcuate fashion. It stretches from Loe Shilman near Pakistan-Afghanistan border up to Tarbela through Warsak, Sillai Patti, Shewa-Shabazgarhi, Koga and Ambela. The Loe Shilman Carbonatite Complex comprises of sill like bodies emplaced along thrust plain of an east-west trending and northerly dipping fault zone in Paleozoic to Pre-Cambrian metasedimentary rocks.*

This paper presents the use of fission track age of apatite as paleotemperature indicator and its significance in the recognition of the emplacement time and tectonometamorphic history of the Loe Shilman Carbonatite Complex in combination with other radiometric ages.

The K-Ar date of 31.00±2.00 Ma on biotite and U-Pb date of 30.00 Ma on calcitic indicate that the Loe Shilman rocks were emplaced during the Oligocene times. The fission track age of 18.87±1.33 Ma on apatite from Loe Shilman, estimated by us, represents a time during the post-metamorphic uplift history of the area, when these rocks passed through the 115 °C isotherm, corresponding to a depth of about 3.5 km from their present position, if a paleogeothermal gradient of 30 °C per km is assumed to have prevailed. Based on present work, in combination with other available ages, we support the idea of emplacement of the complex in the Oligocene in contradiction with the earlier view of emplacement of these rocks in the Permo-Carboniferous.

INTRODUCTION

Fission track dating depends upon the ability of minerals to record the radiation damage (as tracks) caused by the spontaneous fission of U^{238} (Fleischer et al., 1975; Durrani & Bull 1987). Fission tracks become stable, well below the temperature of mineral formation; therefore the fission track ages may be quite different from the age of mineral formation (Fleischer et al., 1965 & 1975). The quantitative accumulation of tracks in a mineral begins once the mineral has cooled down below the "closure temperature". For terrain south of the Main Mantle Thrust (MMT) the "closure temperatures" of 270°C, 210°C and 115°C have been chosen for sphene, zircon and apatite (Zeitler et al., 1982). The corresponding "closure depth" for these temperatures is 8.67, 6.67 and 3.5 km respectively, if a paleogeothermal gradient of 30°C / km is assumed to have prevailed. The fission track age of a mineral defines the time at which it passed through its "closure depth" during its uplift history. The closure temperature and track-annealing behavior is different for different minerals. The closure temperature of apatite is lower than the zircon and sphene; that is why a fission track age of apatite is usually a younger age or a point in the thermal history of a rock than the fission track ages of zircon and sphene. The fission track ages of different minerals can therefore, be used not only to interpret the geological ages but also to construct the quantitative models of the thermal and tectonic uplift histories of mountain ranges and sedimentary basins (Gleadow et al., 1983; Wagner 1972).

THE PESHAWAR PLAIN ALKALINE IGNEOUS PROVINCE (PAIP) AND THE ASSOCIATED CARBONATITE COMPLEXES

The Peshawar Plain Alkaline Igneous Province (PAIP) occurs in the north of Peshawer Valley in an arcuate fashion. It consists of alkaline granites, syenites, albitites and carbonatites (Kempe & Jan 1970, 1980). The alkaline rocks are emplaced along fault zones in Paleozoic/Pre-Cambrian metasediments over a 200km long belt extending from Loe Shilman, through Momand Agency, Warsak, Sillai Patti, Shewa-Shahbazgarhi and Koga up to Tarbela. The alkaline province is restricted by the Main Mantle Thrust (MMT) in the north and by the Main Boundary Thrust (MBT) in the south. The carbonatite complexes are found at six places, namely; i) Loe Shilman (Jan et al., 1981), ii). Sillai Patti (Ashraf & Chaudhry 1977; Butt et al., 1989), iii). Khungai (Khattak et al., 1984), iv). Jhambil (But et al., 1986), v). Koga (Siddique et al., 1968) and vi).Tarbela (Kempe 1973) as shown in Fig.1.

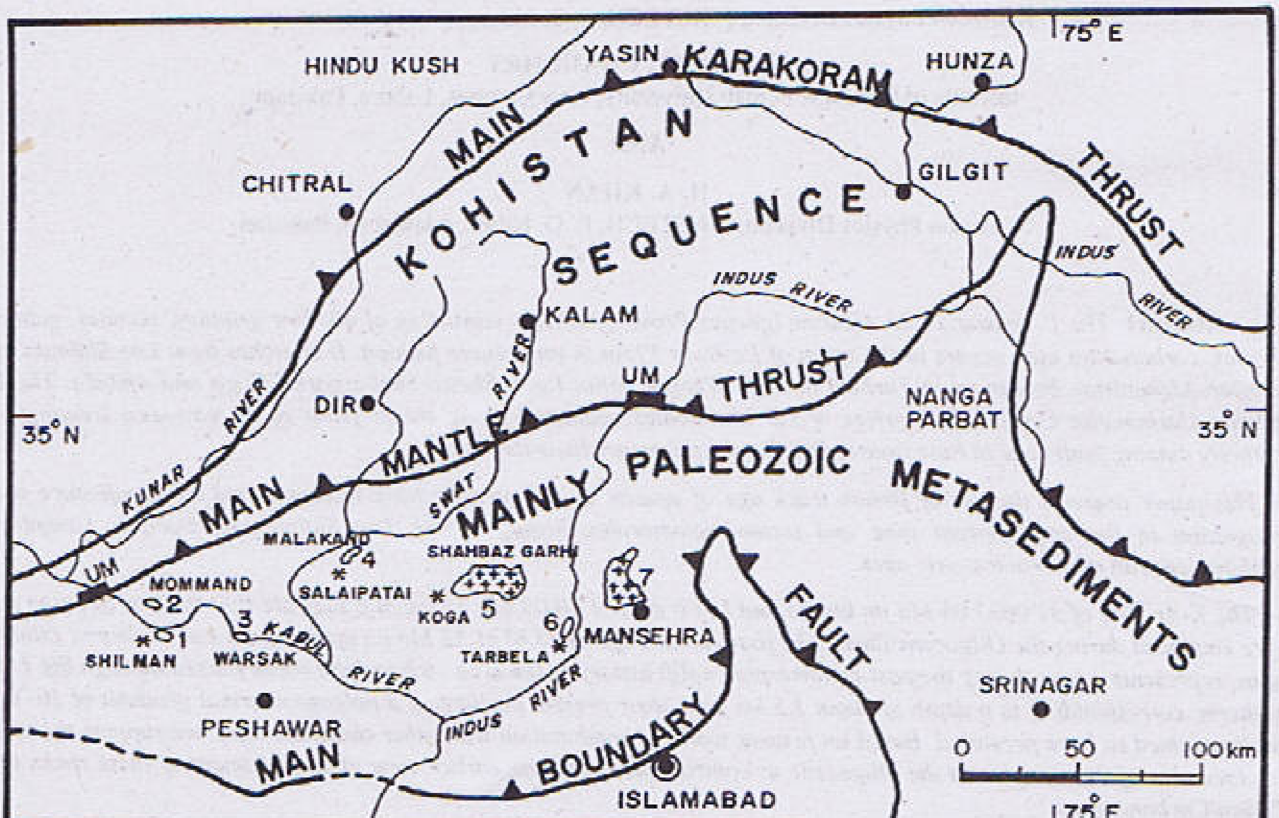

Fig. 1. Geological sketch map of northern Pakistan and adjoining areas (After Tahirkheli, 1979). Kohistan Sequence: mainly composed of garnet granulites, amphibolites, pyroxene granulites with (+++) acidic intrusions, (vvv) volcanics (:::) sediments and (UM) ultramafics at places. Paleozoic Metasediments: mainly composed of pelitic/psamatic shists, graphitic shists marbles, slates, metaconglomerates with granites, granite gneisses and alkaline intrusives. Alkaline rocks are at localities 1-7 and (*) carbonatites are exposed at places where locality name is underlined.

The Loe Shilman Carbonatite Complex, located 60 km north west of Peshawar, consists of a 3km long sheet emplaced in an east-west trending and northerly dipping fault zone. It is underlain by Pre-Cambrian slates and overlain by Paleozoic schists (Fig.2). The calcite carbonatite makes the main mass of the complex whereas the dolomite carbonatite occurs as a band along the southern margin of the complex and as veins and dykes within the calcite carbonatite and country rocks in the south.

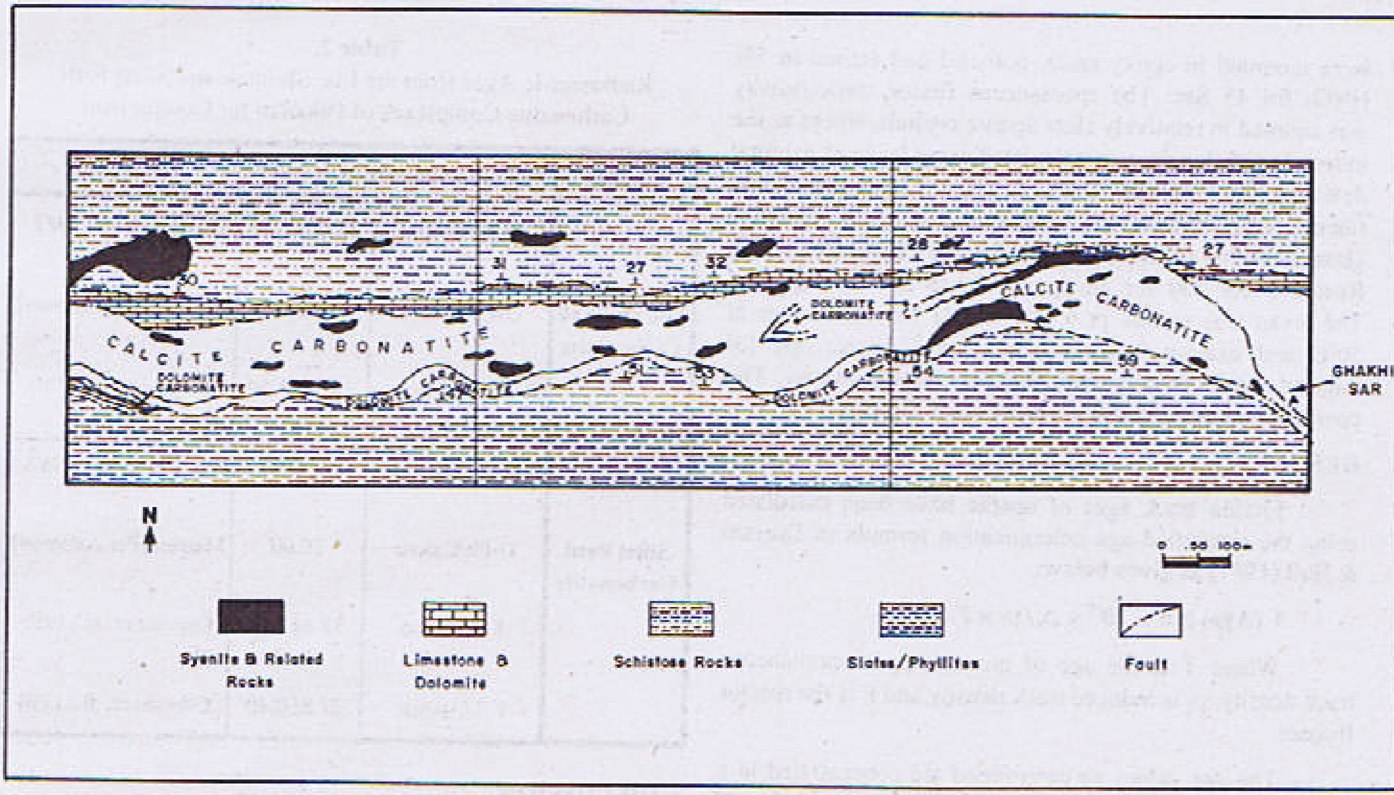

Fig. 2. Geological map of Loe Shilman, Khyber Agency showing a part of carbonatite body. [After Qureshi et al., 1990]. The carbonatite body is bounded by two faults in the north and south. The calcite carbonatite makes the main mass of the complex whereas dolomite carbonatite occurs as a band along the southern margin of calcite carbonatite and as mall bands within the calcite carbonatite.

The Sillai Patti carbonatite complex is located 60-km northeast of Loe Shilman. It consists of an east-west trending and southerly dipping 12 km long and a few meters thick sheet emplaced in the thrust plane of a fault zone (Ashraf & Chaudhry 1977; Butt et al., 1989). The thrust containing the carbonatite may be related to the Main Mantle Thrust, located 20 km north of the complex (Le Bas et al., 1987).

The Koga carbonatite complex is located about 70-km southeast of Sillai Patti. The associated rocks consist of feldspathoidal syenites, granodioritic gneisses and alkaline syenites (Siddique et al., 1968). The carbonatites occurring as small veins are exposed over an about 1-km long and 200 m wide area. Extensive fenitization has been noted in the enclosing nepheline syenites.

About 50 km south-east of Koga at Tarbela, gabbroic rocks, dolerites, albitites, granites, and carbonatites are exposed over a 4 km long and 200 metres wide area (Jan et al., 1981-a). They intrude a major fault, which separates the Pre-Cambrian Salkhala series from Cambrian Tanawal quarzites.

The carbonatite complexes occurring in Pakistan (Fig.1) were formerly considered by Kempe & Jan (1970) to be a part of an alkaline igneous province orignated during the rifting of Peshawar Valley, in the Late Cretaceous or Early Tertiary. Later Le Bas et al. (1987) stated that the rocks of PAIP were emplaced during two episodes of alkaline magmatism, one in the Carboniferous and other in the Oligocene times. Jan et al. (1990) agreed in assigning the PAIP a Carboniferous age but regarded the Oligocene ages to represent theromotectonic events instead of a magmatic episode.

The Loe Shilman carbonatite complex is an important member of PAIP. In order to know about its emplacement time and tectonic uplift history, fission track dating study of the apatite has been carried out. The results have been discussed and compared with other dates available from PAIP. Sphene or zircon was not available from Loe Shilman Carbonatite Complex for fission track dating studies. The data is also compared with that of Sillai Patti carbonatite in order to get information on petrogenetic relationship between the two complexes.

EXPERIMENTAL PROCEDURE

A fresh sample of calcite carbonatite was crushed, ground, sieved and subjected to heavy mineral separation with the help of Wilfley Table and heavy liquids. Clear apatite grains were separated from the heavy mineral concentrate using a binocular microscope. These grains were mounted in epoxy resin, polished and etched in 5% HNO_3 for 45 Sec. The spontaneous fission track density was counted in relatively clear apatite crystals, where as the induced track density was calculated using lexan as external detector. For induced track density determination and fluence measurement, the sample and standard reference glass SRM-963 (a) were irradiated in the Pakistan Research Reactor-1 for 200 sec along with lexan at 5 MW power. The lexan was etched in 6.5 N NaOH for 45 minutes at 50°C and examined under transmission microscope for induced track density and fluence determinations. The counting was done at 400 × overall magnification.

RESULTS

Fission track ages of apatite have been calculated using the simplified age determination formula of Durrani & Bull (1987) as given below:

$$T\ (Age) \cong 6 \times 10^{-8} \times \rho_s/\rho_i \times F\ Years$$

Where T is the age of mineral, ρ_s is spontaneous track density, ρ_i is induced track density and F is the reactor fluence.

The age values so determined are concentrated in a narrow zone of 18.32-20.20 Ma, with an average value of 19.09±0.19 Ma. The results are presented in table-1. The age data of the Loe Shilman and the Sillai Patti carbonatite complexes based on other techniques has been presented in the table-2 for comparison.

Table 1.
Fission Track ages of Apatite from Loe Shilman Carbonatites Complex, NW Pakistan

Grain No	Track Density $(cm^{-2})x10^4$		Fluence $(n.cm^{-2})x10^{15}$	age (my)
	Spontaneous	Induced		
S-115/1	2.72	22.1	2.54	18.76
S-115/2	4.25	35.36	2.54	18.32
S-115/3	2.55	20.40	2.54	19.05
S-116/2	3.71	28.42	2.58	20.20
S-116/3	2.96	24.61	2.58	18.61
S-116/4	3.23	25.29	2.58	19.48
S-117/1	4.61	36.95	2.56	19.16
S-117/3	3.17	24.48	2.56	19.89
S-117/5	2.99	24.52	2.56	18.73
S-117/8	3.12	25.62	2.56	18.70
Mean Age = 19.09 ± 0.19				

Table 2.
Radiometric Ages from the Loe Shilman and Sillai Patti Carbonatite Complexes of Pakistan for Comparison

Locality	Method/Mineral	Age (my)	Reference
Loe Shilman Carbonatite	K-Ar/Biotite	31.00±2.00	Le Bas et. al., 1987
	U-Pb/Calcite	30.00	Mateen [Per.commun]
	F.T/Apatite	19.19±1.30	Qureshi et. al.,[This paper]
Sillai Patti Carbonatite	K-Ar/Biotite	31±2.00	Le Bas et. al., 1987
	U-Pb/Calcite	30.00	Mateen [Per.commun]
	F.T/Zircon	32.3±1.40	Qureshi et. al., 1990
	F.T/Apatite	21.8±0.40	Qureshi et. al., 1990

DISCUSSION

Following views exist about the origin of the carbonatite complexes and their associated alkaline rocks of the Peshawar Plain Alkaline Igneous Province.

Kempe and Jan (1970) considered that the alkaline rocks and associated carbonatite complexes were emplaced during the initial rifting of Peshawar valley in the Late Cretaceous or Early Tertiary.

Later Kempe et al. (1980) and Jan et al., (1981-a) on the basis of K/Ar dates from Koga (50.00 Ma) and Warsak (41.00 Ma), suggested a younger age for these rocks and related their emplacement with Tertiary rifting, initiated by Kohistan and Indian Plate collision.

Le Bas et al. (1987) suggested that the alkaline rocks and associated carbonatites were emplaced in two alkaline magmatic episodes of Carboniferous and Oligocene age. According to them the Koga carbonatite was emplaced during the Carboniferous, while emplacement of the Loe Shilman and Sillai Patti carbonatite complexes took place during the Oligocene magmatic episode. This supposition is based on a Rb-Sr whole rock date (315±15 Ma) on syenite and ijolite from Koga igneous complex (Le Bas et al., 1987) and the K-Ar dates (31.00±2.00 Ma) on biotite from the Loe Shilman and Sillai Patti carbonatites (Le Bas et al., 1987). They suggested that the emplacement of PAIP rocks be not related to the Himalayan collision.

Butt et. al. (1989) and Jan & Karim (1990) suggested that all the rocks of PAIP and associated carbonatites were emplaced during the Permo-Carboniferous tensional rifting and break-up of the Gondwanaland. Butt et. al. (1989) believe that epidote in the Sillai Patti Carbonatite and the associated country rocks is a product of green schist or epidote amphibolite facies of regional metamorphism of older age. Jan & Karim (1989). support their idea on the basis of absence of these rocks from the Post Paleozoic sequence. They correlate the Loe Shilman and Sillai Patti carbonatites with the alkaline rocks of Ambela, Malakand and Shewa-Shahbazgarhi of Late Paleozoic age. Younger ages (fission track etc.) have been interpreted as metamorphic over print of later age.

On the basis of K-Ar date of 31.00±2.00 Ma of Le Bas et al. (1987) and U-Pb age of 30.00 Ma of Mateen (Personal communication), for the Loe Shilman and Sillai Patti Carbonatite Complexes, we support the idea of the emplacement of the two complexes in the Oligocene times. Fission track age of zircon (32.1±1.9 Ma) of Qureshi et al. (1991) also support the episode of magmatic activity in Oligocene Epoch. Presence of epidote in the Sillai Patti carbonatites and associated silicate rocks may be the result of the alteration of the carbonatites or from some very low temperature heating up. The alteration of minerals high in calcium and aluminum such as feldspar, pyroxene, amphibole, biotite etc. can result in epidote formation (Kraus et al., 1959).

The age data so far produced by various workers indicate that some of the rocks in Peshawer Plain Alkaline Igneous Province were emplaced during Oligocene times. The younger apatite age (≈ 19 Ma) represents a time when these rocks crosed an isotherm of 115°C (apatite closure temprature) at a depth of about 3.5 km from their present position, during the uplift of the region on the southern side of MMT (Zeitler et. al., 1982). Our fission track ages of apatite from Loe Shilman carbonatites are concentrated in a narrow zone of 18.32 to 20.20 Ma with a mean value of 19.09±0.19 Ma. This age is similar to the fission track apatite age of the Sillai Patti carbonatite (21.8±0.40 Ma) of Qureshi et al. (1990). The apatite ages of Loe Shilman and Sillia Patti carbonatites are significantly lower than the ages of the emplacement of these two complexes in Oligocene (30-32 Ma). This gape of ≈12 Ma in the Ft zircon and apatite ages may have been due to the residence of the apatite in the region between 6.67-3.5 km depth, corresponding to the closure tempratures of zircon and apatite.

Some workers have certain reservations regarding the "Oligocene" as the age of emplacement of carbonatites because of strong tectonic deformation of these rocks in Oligocene times. However, there is no age data suporting the emplacement of Loe Shilman and Sillai Patti carbonatites in times older than Oligocene. The idea of resetting of ages, during the post collision period, in Loe Shilman and Sillai Patti area because of their proximity to a major thrust and absence of this phenomena from syenites and ijolites of Koga complex because of their occurrence within a thick cover of granites at Chingali and Ambela, can not be accepted.

On the basis of available age data and the similarity in the fission track apatite ages it is clear that the Loe Shilman and Sillai Patti carbonatite complexes underwent a similar thermal/tectonic uplift history after emplacement. The fission track apatite ages indicate a time during the post metamorphic uplift history of the area, when these rocks were uplifted above the 115°C isotherm, corresponding to a depth of about 3.5 km from their present day position. The lower apatite age of the Loe Shilman compared to the Sillai Patti indicates a slightly faster uplift rate of the Loe Shilman as compared to the Sillai Patti carbonatite complex. The age data presented by us may not be very conclusive and the subject is left open for future work and interpretation.

CONCLUSION

The following conclusions have been drawn from the fission track apatite ages and their comparison with the other radiometric ages.

The carbonatitic magmatic activity in the PAIP occurred in two episodes, one in Carboniferous and other in Oligocene times. The Koga carbonatites were emplaced in the Carboniferous, while the Loe Shilman and Sillai Patti carbonatites were emplaced during Oligocene time at the end of the Himalayan metamorphic episode.

The fission track apatite ages of the Loe Shilman and Sillai Patti are uplift related ages when these rocks crossed a closure depth of about 3.5-km at a closure temperature of 115°C.

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Geol. Bull. Punjab Univ. 33 & 34, 1999.

GEOCHEMISTRY OF MAGNESITE-RICH ROCKS FROM THE INDUS SUTURE IN SWAT, NW PAKISTAN

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Abstract:- *A variety of magnesite-rich assemblages (talc + magnesite, magnesite + talc + serpentine, and talc + magnesite + quartz) occur at different places in the Swat valley. These lithologies belong to the ophiolitic member of the Indus suture melange group and appear to have formed by carbonate alteration of previously serpentinized ultramafic rocks in the area. However, unlike the latter, some of the magnesite-rich rocks contain anomalously low concentration of SiO_2 and/ or high amounts of such trace elements as Be, B, Li, K, As, Pb, W, Zr, Y, Ba, Sr and/ or Rb. Detailed geochemical investigation suggests that variable amounts of SiO_2 may have been lost during the process of carbonate alteration. On the other hand, enrichment of these rocks in the above mentioned variably incompatible trace elements seems to be the result of a late-stage hydrothermal activity related to the injection of ubiquitous quartz veins leading to the formation of tourmaline, fuchsite as well as emerald.*

INTRODUCTION

Magnesite-rich rocks are one of the several lithological types which collectively form the ophiolitic member of the melange group along the Indus Suture in the Swat valley. Locally, these rocks host emerald deposits which have been producing one of the world's finest gemstones for the last several decades. Field association, petrographic features and mineralogical composition all suggest that these emerald-hosting lithologies most probably represent carbonate-altered varieties of previously serpentinized ultramafic rocks in the study area (Arif, 1994). However, the validity of this conception in the context of whole-rock geochemical details has not been discussed previously. This is the main objective of the present investigation through which it is intended to highlight possible chemical changes brought about by the process of carbonate-alteration. Furthermore, as the studied rocks are invaded by veins and stockworks of quartz, the nature of geochemical changes, which are likely to result from this evidently late-stage hydrothermal activity, is also discussed.

GEOLOGICAL SETTING

The Indus-Tsangbo Suture between the Indo-Pakistan plate and Kohistan-Ladakh island arc assumes a broad wedge-shaped complex zone in the Swat valley and contains fault-bounded diverse rock assemblages. This assortment of rocks, collectively known as the Indus Suture melange group, is distinguished into three principal types of melanges: the blueschist melange, the greenschist melange, and the ophiolitic melange (Kazmi et al., 1984).

Rocks of the ophiolitic melange occur as small to large lensoidal bodies distributed along the northern edge of the Indo-Pakistan plate. The main localities where such rocks are exposed include the Barkotkai-Lilaunai area, the Gujar Kili village, the Spin Obo-Kuh area and the Mingora town (Fig. 1). The component rocks of the ophiolitic melange possess well-preserved ophiolitic characteristics and consist of the following types: (i) variably altered ultramafics, (ii) gabbroic rocks, (iii) lavas of basic to intermediate composition, and (iv) sedimentary rocks including cherts. Besides, other ophiolitic lithologies such as plagiogranites and albitites are also described from the ophiolitic melange (Barbieri et al., 1994). The ophiolitic rocks are metamorphosed under upper greenschist to lower amphibolite facies conditions. However, typical igneous features, e.g. porphyritic, amygdaloidal, glassy and pillow structures, of the original volcanic rocks are largely preserved.

Locally the serpentinized ultramafic rocks contain small bodies of chromitites and accessory to trace amounts of Ni-rich phases. Mineralogical characteristics of these rocks are discussed in detail elsewhere (Ashraf et al., 1989; Arif & Jan, 1993; Arif & Moon, 1994, 1996a).

In addition to the lithologies, mentioned above, carbonate (i.e. magnesite and, rarely, dolomite)-rich assemblages, form an integral part of the different occurrences of the ophiolitic rocks in the study area. As pointed out earlier, the major economic significance of these carbonate-rich assemblages is because of the enclosed emerald deposits which produce one of the world's finest gemstone quality emeralds (Fig. 1).

The rocks under discussion are fine grained, relatively soft and mostly greyish white to yellowish white in colour. They occur in a number of localities in the study area (Fig. 1). In most of these occurrences, they are spatially associated with variably serpentinized ultramafic rocks. Although also occurring as small patches within the serpentinized rocks in some places, they are mostly distributed at the contact of the serpentinized ultramafic rocks with metasediments. Besides, the carbonate-rich rocks of the Mingora emerald mines area contain small nodules of chromitite (containing more than 50 modal % Cr-rich chromite) as well as relic patches of carbonate-poor to carbonate-free serpentinites. These rocks are also traversed by abundant veins, locally producing stockworks of quartz.

The studied rocks invariably consist of magnesite and accessory to trace amounts of spinel (mostly Cr-magnetite-ferritchromite and in some cases Cr-rich chromite) ± talc ± quartz ± dolomite. On the basis of modal mineralogy, these rocks can be grouped into three principal types: (i) talc-magnesite or magnesite-talc, depending upon whether magnesite or talc is more abundant; (ii) talc-magnesite-dolomite; and (iii) quartz-magnesite.

Some of the investigated rocks also contain fuchsite and tourmaline. Mostly these two minerals coexist in veins and clusters. Fuchsite and tourmaline also occur as fine-grained disseminations in the host rocks as well as within the invading quartz veins. Besides fuchsite forms rims and borders around grains of Cr-rich chromite. The tourmaline is Cr-rich dravite and the fuchsite shows variable but in most analyses anomalously high concentration of Ni. Representative analyses and detailed descriptions of most of these phases are available in the published literature (Arif & Moon, 1996b, c).

GEOCHEMISTRY

Samples and Methods

A total of 60 rock samples were collected. These represent almost all the occurrences of carbonate-containing rocks in the study area. All these samples were studied petrographically, and analysed for As, Li and Be by Inductively Coupled Plasma Emission Spectrometry (ICPES). Many of the samples were also analysed for their major, minor as well as trace element contents using X-ray Fluorescence Spectrometry. Furthermore, the boron concentration of a limited number of samples was determined by Prompt Instrumental Neutron Activation Analysis using the McMaster Nuclear Reactor in Canada.

The major element analyses were performed on fusion beads (glass discs) whereas powder pellets were used to determine the contents of minor and trace elements. The fusion beads were analysed on a Philips 1400 X-ray Spectrometer and ARL 8420' Spectrometer, each equipped with a rhodium anode X-ray tube. The powder pellets were analysed on a Philips PW 1400/10 XRF Spectrometer equipped with either a 3 Kw rhodium anode tube or a tungsten anode tube. A set of international and internal standards was alternately run with each batch of samples to monitor and quantify the precision and accuracy of the instrument. The analytical results demonstrate a high degree of machine accuracy and precision (i.e. greater than 2 % at the 98 % confidence level) for all the major oxides as well as most of the minor and trace elements.

Major, Minor and Trace Element Contents

The major, minor and trace element analyses of representative samples are listed in Table 1. Although all the samples were analysed for their minor and trace element contents, major element compositions of only selected rocks were determined. However, selection in the latter case is broad enough to represent the different mineralogical compositions and cover almost all the individual occurrences of carbonate-rich rocks in the study area.

The compositions of the different types of carbonate-rich rocks are compared with the serpentinized ultramafic rocks from the area with which the former are, in most places associated (Fig.2). Detailed studies show that the serpentinized ultramafic rocks of the ophiolitic melange are mostly peridotites whereas other types such as dunite and pyroxenite are extremely rare (Arif, 1994). The peridotites from the study area can be divided into five groups on the basis of their Al_2O_3 contents (Arif & Moon, in preparation). Shown for comparison in Fig. 2, are the compositions of olivine clinopyroxenite and olivine orthopyroxenite (one sample each) as well as average compositions of the five types of peridotite.

Some of the rocks, especially those from the mining areas, contain high amounts of Sn (up to 4 ppm), As (ranging up to 800 ppm), Sr (six specimens having ~ 100-520 ppm), Pb (four samples with 15-40 ppm), Y (six samples with ~ 5-12 ppm), Zr (four of the samples have 5-15 ppm), K_2O (up to 0.6 wt%), W (several analyses show 5-

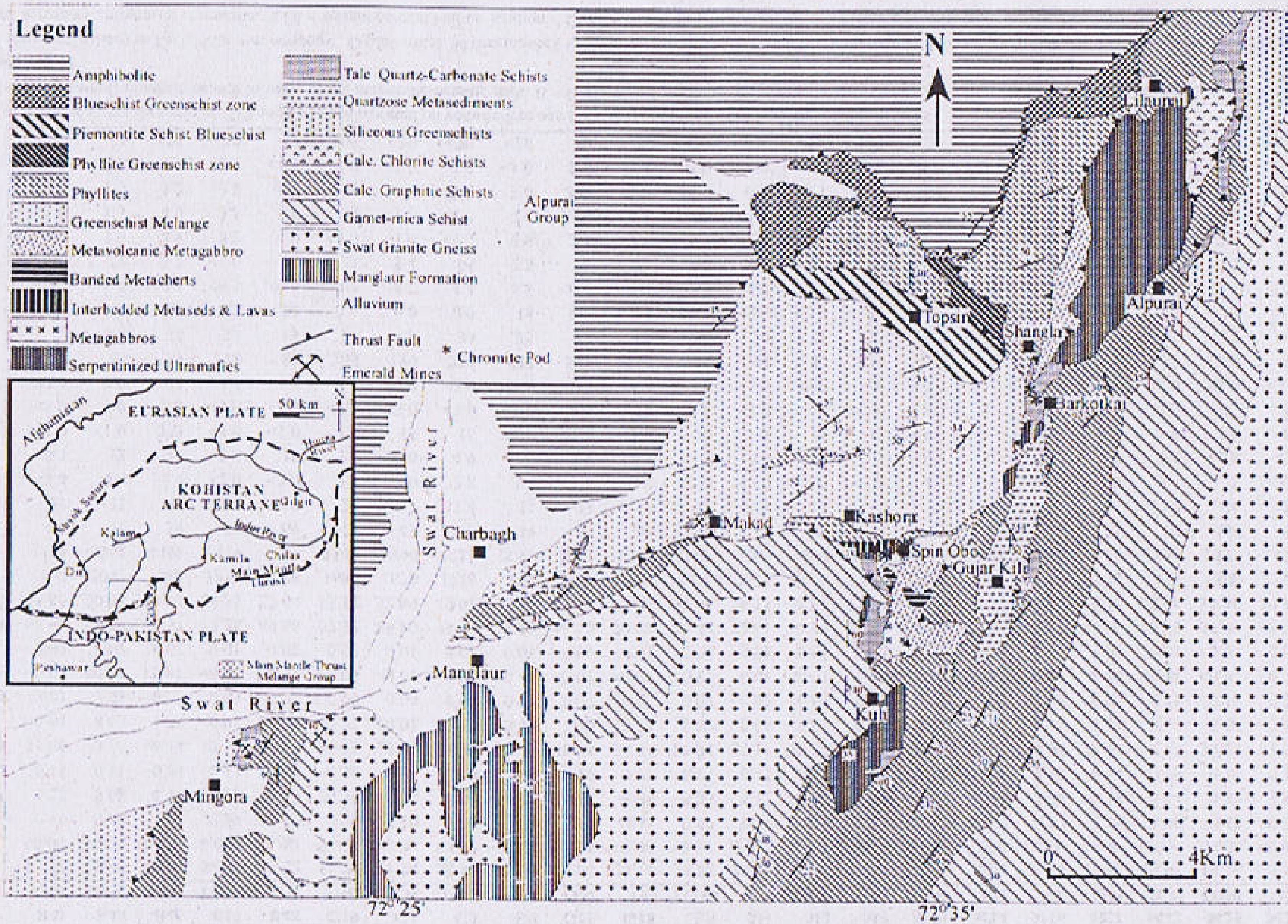

Fig. 1: Geological map of the study area (After Kazmi et al, 1984; Hussain et al., 1984). The inset map shows general location of the study area.

Table 1

Representative major, minor and trace element analyses of the investigated rocks

Sam	B41	B43	B45	B47	B48	C19	G1	G3	G9	G15	G18	L5	M1	M2	M9	M13	M14	M16	M21	M22	M25	M26	Sp14
Min.[1]	QM	TDM	TM	TQM	TD	TSD	TM	QMT	QM	QM	TD	TQM	MT	MT	QM	QTM	TM	MT	QM	TM	TDM	TDM	T
SiO_2	23.35	28.80	16.36	34.93	22.22	51.74	21.74	38.87	32.96	8.04	24.14	33.76	29.71	25.86	11.08	18.45	38.58	26.73	17.58	26.91	18.26	25.49	58.61
TiO_2	<0.00	<0.00	0.074	0.006	<0.00	0.009	<0.00	0.007	<0.00	0.005	<0.00	<0.00	0.007	0.007	0.009	0.018	0.050	0.009	<0.00	0.006	0.006	<0.00	0.034
Al_2O_3	0.19	0.54	1.02	0.29	0.67	0.79	0.19	0.50	0.27	0.69	0.68	0.57	0.21	0.15	1.23	1.35	1.53	0.37	1.45	0.40	0.62	0.34	2.33
FeO*	5.22	5.68	8.70	5.72	5.23	6.54	5.48	3.90	4.71	6.87	6.88	5.86	5.17	4.60	5.85	5.89	4.21	4.70	6.38	5.04	4.87	3.81	9.77
MnO	0.13	0.11	0.20	0.14	0.23	0.10	0.24	0.10	0.08	0.19	0.17	0.13	0.15	0.13	0.13	0.14	0.08	0.18	0.14	0.15	0.18	0.18	0.11
MgO	35.66	25.76	36.19	32.14	20.22	25.13	39.09	34.26	30.23	38.95	26.74	29.74	37.11	38.77	38.37	38.06	25.57	38.04	33.94	37.57	34.24	31.51	28.67
CaO	<0.01	8.65	1.78	<0.01	21.09	12.77	<0.01	0.79	<0.01	1.30	12.22	0.20	0.16	<0.01	0.47	0.48	2.64	1.41	1.44	0.45	6.68	7.40	<0.01
Na_2O	0.03	0.03	0.25	0.03	<0.02	0.09	0.04	0.04	0.03	0.07	0.03	0.07	<0.02	0.05	0.16	0.06	0.02	0.08	0.05	0.05	0.15	0.05	0.08
K_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.12	<0.01	<0.01	0.11	0.08	<0.01	0.47	<0.01	0.13	<0.01	0.56	<0.01	<0.01	<0.01	<0.01
P_2O_5	0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.06	0.02	0.01	0.02	0.01	0.06	0.01	0.01	0.01	0.01	0.01	0.02
Total	64.60	69.59	64.57	73.26	69.66	97.92	66.80	78.48	68.40	56.12	70.88	70.48	72.61	69.59	57.80	64.46	72.84	71.54	61.56	70.59	65.02	68.78	100.7
LOI[2]	35.85	30.02	33.92	25.55	27.64	13.12	32.09	19.91	32.14	43.55	27.03	30.96	26.15	28.29	42.77	34.33	28.90	27.51	38.46	28.06	34.40	30.46	5.78
Ni	2067	2047	980	2213	1088	1680	1620	1718	1467	2254	2084	1676	2637	2639	2363	2688	1290	2302	1970	2417	1808	1211	2836
Cr	1594	2041	3466	1979	1409	2144	1890	1711	2093	2583	1507	2002	1265	3899	3974	2641	1628	1295	3101	1586	2378	1474	3567
Co	65	71	59	73	69	77	43	33	49	67	69	63	63	59	54	72	47	69	73	72	64	54	98
V	21	22	76	31	19	21	17	11.4	21	23	31	32	13	13	43	38	34	16	41	17	36	24	42
Ga	3.4	2.0	2.0	<2.0	<2.0	2.1	<2.0	2.8	3.1	3.6	2.7	<2.0	<2.0	<2.0	3.6	4.5	2.3	2.3	4.9	2.4	2	3.1	3.6
Sc	5.3	12	11	2.6	15	5.5	<2.0	4.9	2.6	3.7	8.2	4.5	3.9	1.7	3.3	6.4	8.3	<2.0	3.4	3.8	5.8	4.2	5.9
Cu	<1.0	<1.0	272	<1.0	<1.0	<1.0	15	16	<1.0	<1.0	<1.0	10	13	14	12	<1.0	<1.0	<1.0	4.4	<1.0	<1.0	15	15
W	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	8.5	18	6.0	<3.0	<3.0	<3.0	5.9	8.7	8.3	8.5	4.3	12	12	<3.0
Pb	<3.0	3.9	<3.0	<3.0	4.5	5.1	<3.0	<3.0	3.6	28	4.8	<3.0	<3.0	<3.0	4.0	<3.0	3.2	<3.0	4.1	<3.0	<3.0	<3.0	<3.0
As[3]	78	78	79	374	83	206	180	223	582	505	798	175	64	84	125	100	72	70	153	87	60	61	191
Zn	12	16	35	28	18	21	26	23	35	37	19	36	20	21	33	41	22	20	42	21	15	11	51
Ba	6.3	13	8.8	8.8	34	2.6	0.0	0.0	18	8.2	35	12	<2.0	<2.0	70	4.9	2.1	5.6	67	5.4	7.2	9.7	50
Rb	<0.5	<0.5	<0.5	<0.5	<0.5	3.4	4.7	4.4	6.8	<0.5	1.4	2.3	4.0	2.7	37	1.1	<0.5	<0.5	27	<0.5	<0.5	<0.5	<0.5
Sr	1.5	29	4.2	<1.0	68	21	5.4	65	2.8	20	71	3.3	6.5	2.7	96	39	102	29	63	8.7	78	74	1.2
Y	3.5	2.0	4.5	3.2	4.0	<1.0	<1.0	<1.0	2.8	2.5	2.6	5.3	<1.0	<1.0	<1.0	1.5	4.1	4.6	12	2.8	2.0	2.1	5.6
Zr	5.0	3.3	4.0	3.5	3.8	<1.0	<1.0	<1.0	2.1	3.8	4.1	3.2	<1.0	<1.0	<1.0	2.7	5.8	4.1	2.7	3.2	3.5	4.2	4.7
B[3]	2.8	1.3	3.2	0.8	n.a.	n.a.	1.6	9.8	3.0	289	1.8	10.9	0.5	5.3	338	94	1.7	4.3	25	4.4	304	106	n.a.
Be[3]	2.1	2.2	2.8	2.3	<1.0	1.0	1.0	<1.0	<1.0	2.6	2.3	2.3	1.8	<1.0	1.8	5.3	2.1	1.9	4.7	2.4	2.9	5.1	2.5
Li[3]	<20	42	<20	<20	37	105	<20	<20	<20	40	28	<20	106	58	149	70	59	<20	73	22	42	<20	<20

Major element analyses for samples C19 and Sp14 are reported on volatile-free basis while those of the others are on volatlie-in basis

Letter(s) in the sample numbers denote location of the magnesite-bearing rock: B = Barkotkai, C = Charbagh emerald mine), G = Gujar Kili, L = Lilaunai, M = Mingora, and Sp = Spin Obo-Kuh (see Fig. 1)

*Total iron recalculated as FeO; [1]Min = mineralogy : D (dolomite), M (magnesite), Q (quartz), S (serpentine), and T (talc) (arranged in the order of increasing abundance), sample Sp14 also contains accessory amounts of magnesite; [2]LOI = weight percent loss on ignition; [3] Determined with ICP-ES; all the other trace elements were analysed by XRF Spectrometry using powder pellets.

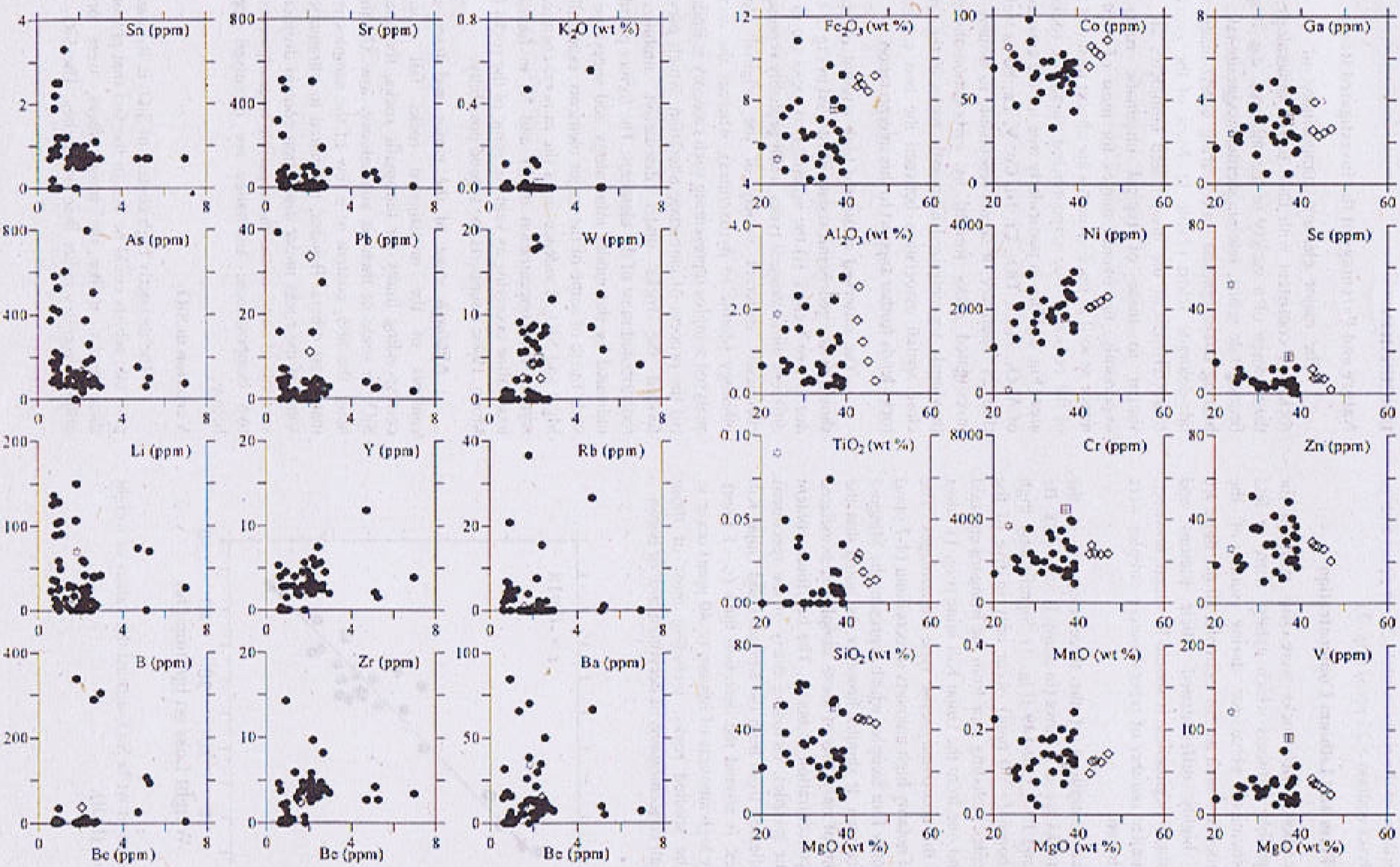

Fig. 2: Geochemical characteristics of the investigated rocks (dots) and their comparison with serpentinized peridotites (diamonds), a sample of olivine orthopyrpxenite (square) and an olivine clinopyroxenite (star) from the study area.

20 ppm), Rb (three of the rocks contain 20-40 ppm) and/ or Ba (four analyses contain > 25 ppm) (Fig. 2).

Boron, Beryllium and Lithium Conlcentration

The carbonate-rich rocks were also analysed for these incompatible elements which exhibit more or less similar geochemical behaviour during some of the geological processes such as, for example, all the three are enriched in highly differentiated silicic plutons and associated aplites/ pegmatites. It should be noted, however, that only a limited number of representative samples were analysed for boron.

The concentrations of the three elements in the investigated rocks are as follows (in ppm): B = 0.5-338; Be = <1.0-7.0; and Li = <20-149 (Fig. 2). Significantly high amounts of boron (> 30 ppm) occur only in five of the analysed samples including four from the Mingora emerald mines area and one from the Gujar Kili mine (Fig. 1). Most of these are the quartz-magnesite type assemblages. The occurrence of notably high amounts of beryllium (4-7 ppm) is limited to only four samples which represent the Mingora emerald mines area. It should, however, be noted that the high beryllium of only two of these samples is associated with a high concentration of boron. The beryllium content of most of the samples, including many of the specimens which are collected from both the Mingora and Gujar Kili emerald mines, is around the detection limit (≤ ~1 ppm). The relatively high amounts of lithium (> 40 ppm) occur in several of the studied rocks, including most of those containing high concentrations of beryllium and/ or boron.

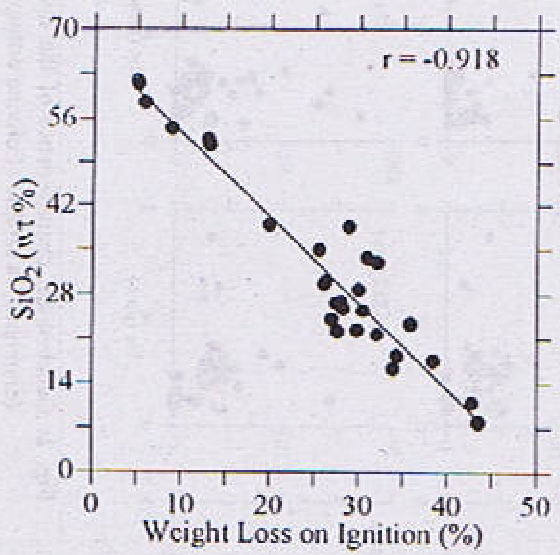

Fig. 3: Variation of wt % SiO_2 against the values of weight loss on ignition (LOI).

DISCUSSION

Nature and Parentage of the Investigated Rocks

The major element compositions of the studied rocks are consistent with their modal mineralogy, that is they consist of a variety of assemblages, e.g. magnesite-bearing talc schist, talc-magnesite, magnesite-talc, quartz-bearing talc-magnesite, talc-bearing quartz-magnesite and talc-dolomite schist (Table 1). Most of the geochemical characteristics of the investigated lithologies are broadly similar to those of typical ultramafic rocks. More importantly, the overall ranges for most of their major, minor as well as trace elements are almost identical to those of the carbonate-free serpentinized ultramafic rocks in the area (Fig. 2). This is particularly true for the concentrations of Al_2O_3, MnO, TiO_2, Cr, Ni, Co, V, Zn, Sc as well as Ga (Fig. 2). Therefore, it seems reasonable to assume that the investigated rocks formed by carbonation-alteration of previously serpentinized ultramafic rocks in the area. The close spatial association between the two categories of rocks lends further support to this interpretation.

The observed relatively high amount of scattering shown by the geochemical data illustrated in Fig. 2 could be due to two factors: (i) the investigated rocks are of several different mineralogical types, each probably representing a chemically different variety of the original ultramafic lithology (dunite to pyroxenites), whereas the number of analysed samples representing each category is limited, and (ii) the process of carbonate alteration, which presumably formed the rocks under discussion, mobilized and redistributed most of the elements. The former possibility is indicated by the modal mineralogy and supported by the wide range of some of the major elements, especially CaO, MgO and SiO_2. Evidence from the mineral-chemical data, namely the concentration of Cr and Ni in fuchsite and tourmaline occurring as veins in some of the rocks (Arif & Moon, 1996c), supports the second possibilty.

Although most of the major and trace element contents of the investigtaed rocks fall within the corresponding limits for ultramafic rocks, the amount of SiO_2 in some of them is anomalously low. On the other hand, the SiO_2 content of a few of the samples is higher than most others. Besides, compared to ultramafic rocks, some of the rocks under discussion contain distinctly high amounts of some of the incompatible trace elements. These two compositional anomalies are discussed separately below.

Variation in SiO_2

The distinctly high content of SiO_2 in the carbonate-poor talc schists could be due to the fact that precursors to these rocks, unlike the most others, were originally orthopyroxenites rather than peridotites. The SiO_2 content of these rocks is comparable to that of the two carbonate-free pyroxenites shown in figure 2 for comparison. On the other hand, the anomalously low amounts of SiO_2 contents in the quartz-magnesite varieties of the studied rocks (less than even 10 wt %) cannot be attributed to original compositional differences because the SiO_2 percentage in known silicate ultramafic igneous rocks rarely falls below 40. The possibility for an alternative explanation that these lithologies were originally impure calcareous sedimentary rocks, i.e. siliceous dolomites, can easily be ruled out because their trace element contents (especially high amounts of Cr, Ni and Co) are similar to typical ultramafic igneous rocks. The point to make here is that some of the chemical changes (e.g. low SiO_2 content) in the studied rocks might have been caused by carbonate alteration. As their SiO_2 contents show a strong negative correlation with the LOI values (Fig. 3), variable amounts of this component were probably removed from the rocks during the process of their formation, i.e. carbonate alteration.

The actual mechanism and factors governing the preferential loss of SiO_2 during the process of carbonate-alteration is not immediately clear and needs a detailed thermodynamic investigation. Nonetheless, the implication is that the process involves the substitution $2CO_3^{-2}$ SiO_4^{-4}. This is opposite to the relatively high temperature contact metasomatic process whereby silicates replace carbonate minerals. A relevant example supporting the current conclusion, i.e. removal of SiO_2 during the carbonate-alteration of serpentinites, is provided by a study of similar rocks from Timmins, Ontario (Schandl & Naldrett, 1992). Schandl & Naldrett (1992) have concluded that substantial MgO was added and SiO_2 removed during the alteration and that the chemical exchange took place at a constant volume. The loss of SiO_2 and gain of MgO during the alteration of rocks studied by Schandl & Naldrett (1992) are also indicated by the negative and positive relationship of these components, respectively, with the values of LOI. Also, the various reaction equations relating the carbonate-alteration of such previously serpentinized rocks (Hess, 1933; Read, 1934) demand that, for the process to take place at constant volume, a significant amount of SiO_2 must leave the system (see Turner & Verhoogen, 1960). However, the addition of MgO may not always accompany carbonate-alteration of serpentinized ultramafic rocks. For example, there is no evidence that the formation of quartz-magnesite and talc-magnesite rocks of the Cobb River district (New Zealand) involved any MgO addition (Wellman, 1943; Turner & Verhoogen, 1960). Similarly, the presently investigated rocks do not show any evidence for MgO addition during their formation. Rather, in contrast to the rocks from Timmins, the relatively low MgO content of the assemblages under investigation suggests that some of the MgO might have been actually lost during the process. This last possibility gets further support from the fact that although many of the carbonate-rich rocks, like the associated carbonate-free ones (serpentinized ultramafics), have high concentrations of such elements as Cr, Ni (and Co), their MgO contents are not comparably high (Fig. 2).

Enrichment in Incompatible Elements

Detailed geochemical investigation of the studied rocks suggests that some, but by no means all, of the samples, especially those from the mining sites of emerald, contain distinctly high concentrations of Be, B, Li, K, As, Pb, Sn, W, Zr, Y, Ba, Rb and/ or Sr (Fig. 2). High concentrations of elements like these do not normally occur in ultramafic rocks. The possibilty that their enrichment is caused by serpentinization and/ or carbonate alteration is precluded because none of them shows any kind of correlation with the values of LOI. Therefore, it is suggested that these elements were added to the studied rocks during a late-stage hydorthermal activity.

Some of the studied rocks contain fuchsite and tourmaline especially where traversed by veins of quartz. Both these phases occur as discrete grains as well as veins traversing the magnesite-rich matrix of the rocks. This mode of occurrence of these two minerals implies that hydrothermal solutions, from which they precipitated, invaded the rocks after their formation by carbonate alteration. As some of the quartz veins also contain emerald, the formation of fuchsite and tourmaline is related to that of emerald and, therefore, to the injection of quartz veins. Thus the observed enrichment of some of the rocks in most of the elements, mentioned above, could be due to the same quartz vein-related hydrothermal activity which resulted in the formation of emerald, fuchsite and tourmaline.

CONCLUSIONS

1) The geochemical characteristics of the studied rocks are compatible with the hypothesis that they are the carbonate-altered equivalents of the spatially associated, previously serpentinized ultramafic rocks.

2) The carbonate-alteration process probably removed variable amounts of SiO_2 from the original rocks and redistributed some of the other elements to a considerable degree.

3) After formation, the rocks were subjected to hydrothermal alteration by solutions that were probably related to the injection of quartz veins. This activity caused enrichment of the studied rocks in Be, B, Li, K, As, Pb, W, Zr, Y and Sr, and led to the formation of emerald, fuchsite and tourmaline.

Geol. Bull. Punjab Univ. 33 & 34 1999.

FLUVIAL CHANNEL DEPOSITS OF THE LOWER CARBONIFEROUS SEDIMENTS CALCIFEROUS SANDSSTONE MEASURES AT COVER, SCOTLAND, UK.

BY

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Abstract:- *The lower Carboniferous sediments (Calciferous Sandstone Measure) at Cove in the Cockburnspath area East Berwickshire (Southern Scotland) were dominated by fluvio-deltaic processes. The sandstone bodies in this succession are associated with overbank flood plain and crevasse splay fill coal swamp deposits. The planner cross-bedding and trough-cross bedding in these sandstone bodies are due to migration of bars, which formed during migration of trains of sinuous crested dunes. Some characteristic features, such as alteration of sandstone with silty mudstone, organic materials, moderately sorted sands, desiccation structure and bioturbation suggest channel bar deposits. The mud cracks in these sandstone bodies are due to drying of the inter-dune surfaces and the slumping is due to the straight crested dunes which became potentially unstable as the pore pressure rose due to sediment loading. Presence of conglomerates in a sandstone body is due to mass flow in a channel environment.*

The above mentioned textural and mineralogical variability of the Sandstone bodies present in the succession and their internal composition together suggest deposition in fluvial-channel environments.

INTRODUCTION

The rocks of the lower Carboniferous at Cove Southern Scotland (Fig. 1) are well exposed on the shore and are classified as Calciferous Sand Measures (Grieg 1971). The sediments accumulated in the so called Oldhamstock basin, which is situated on the NE margin of the Southern Upland masif. This depositional basin (Oldhamstock basin) was formed after the culmination of the Caledonian orogeney (Lagios, 1983). This basin was initiated sometime in the upper Devonian. During the Carboniferous time the basin was the site of accumulation of a considerable volume of sediments.

The rock of this basin belong to the Strathclyde Group (Chishalam, McAdam & Brand 1990). The strata are about 320m thick and are confermable on the upper Old Red sandstone.

The aim of this study was to incorporate aspects of facies analysis and sedimentology into a comprehensive paleo-environmental analysis of the sand bodies at cover East Berwickshire Southern Scotland.

Four sandstone bodies such as Kip Carle Sandstone, Heathery Heugh Sandstone, Cover-Harbour Sandstone and Bilsdean Sandstones are present in the sequence (Fig. 1). These are described below in a stratigraphic order.

KIP CARLE SANDSTONE

Lithology:- The Kip Carle Sandstone is about 22m thick (Fig.2a). The sandstone ranges, in colour from grey to yellowish-gray and pale brown toward the base. It is dominantly fine to medium grained. At the base, a l metre thick, Thinly-bedded unit is present with small scale cross ripple lamination. The cross-laminations coalified wood materials and are also bioturbated. In the upper part, The sandstone beds show marked erosional-surfaces, and large 3m is thin to medium bedded and contains, plant roots, plant stems such as *Stigmaria sp.* and wood debris. Plant fragments are pyritized and pyrite concretions are present on some bedding surfaces. Some of the upper beds are also bioturbated.

Petrography:- The sandstone is composed of anhedral quartz and subhedral to euhedral feldspar, cemented by dolomite and hematite. All the grains shows that some compaction occurred prior to cementation forming tangential contacts. The dolomite is pore-filling cement, although it could have replaced a finely crystalline calcite precursor. The lower part of the sandstone is medium

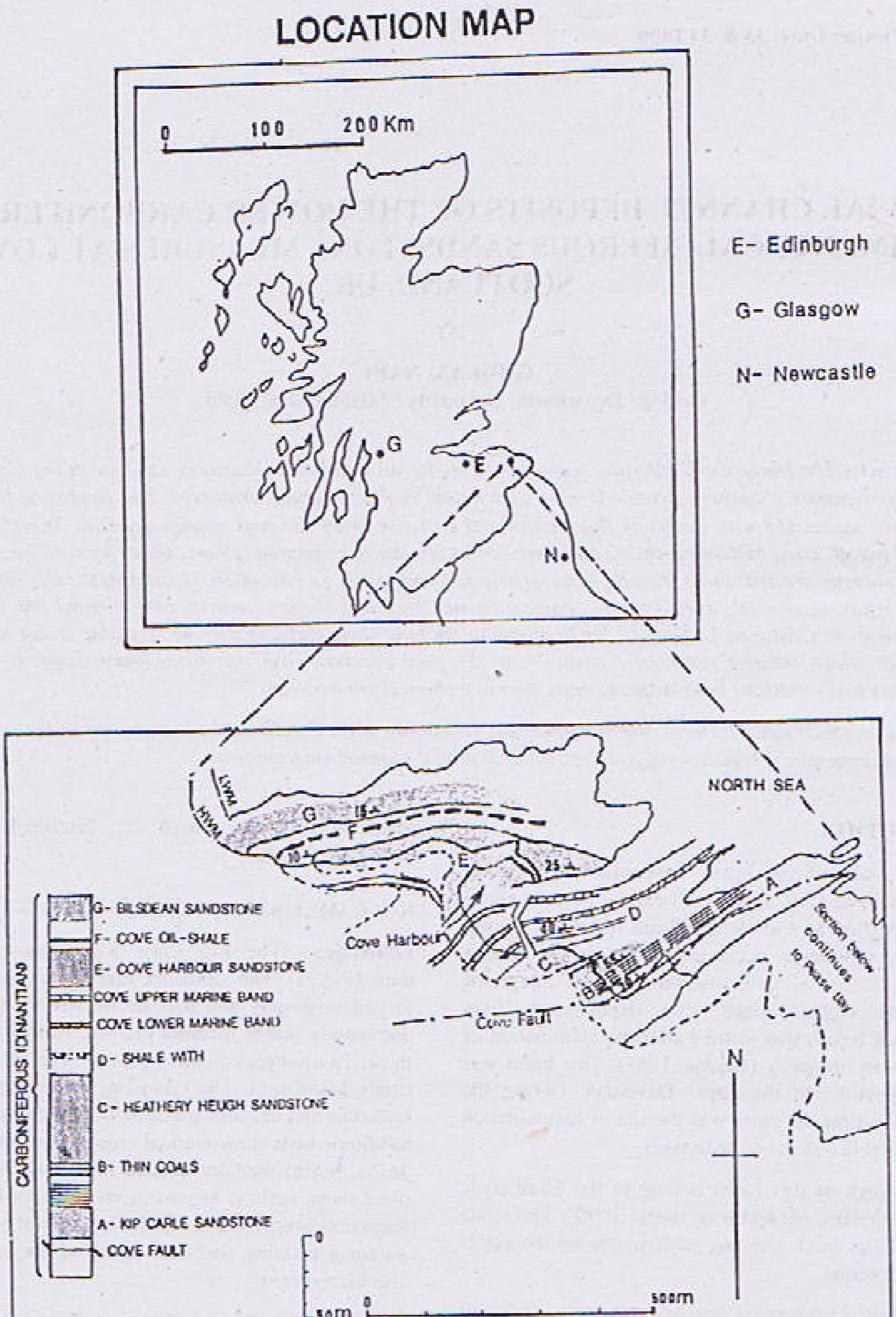

Fig. 1 Showing outcrops of the sequence of Calciferous Sandstone Measures. Between Kip Carle Sandstone and Bilsdean Sandstone.

grained well sorted and mature. Quartz grains are the most aboundant dtrial material and make up 85% of the rock.

Feldspar is noticeably present under cathodo-luminescence (CI) with a maxium of 12% K-feldspar is recognized by its cloudier appearance to the adjacent clear quartz. Some K-feldspars have been altered to kaolinite, which was recognized by its purple colour in CI. A few lithic grains and some carbonized organic material is also present. The rock is classified as quartz-arenite.

HEATHERY HEUGH SANDSTONE

This sandstone forms a multilateral and multistorey sheet sand body internally structured by erosively bounded vertically stacked sandstones and it has been classified into two major units.

a: Sandstone and mudstone unit.

b: Slump and cross-stratified unit.

A: Sandstone and mudstone unit

Lithology:- This 17m thick unit mainly consists of fine to medium grained sandstones and mudstones (Fig. 2b). The sandstones are variably cemented (well and poorly cemented). Some beds have micro scale low angle planner cross bedding, some of which changes into undulose lamination. Some beds are purple coloured having mud cracks, which are usually 10cm to 20cm wide, forming 15cm to 30cm polygons. Honey-comb eathering is present in some beds and there are intensely biotubated beds in places. Coalified plant material is present in some sandstone beds as well as in the mudstones. At some places, iron concretions of about 1cm diameter are present on the top surface of the beds. At the top, it is sharply overlain by the slump and cross-stratified unit.

Petrography:- This unit of the sand-body consists of sub-rounded grains of quartz. These are compacted and highly fractured which probably indicates a metamorphic source and some grains of quartz shows overgrowths. The sphericity of grains ranges from 0.7 to o.75. Feldspar grains ae euhedral and the main consituentsare orthoclase, microcline and palagioclase. Microcline shows cross hatch twinning, while plagioclase shows multiple twinning (ablbite twinning). Some grains of K-feldspar shows perthitic intergrowth, comprising lamella of sodium rich feldspar in potassium rich feldspar. Kaolinization has taken place in K-feldspars grains.

A few grains of biotite and dolomite are also present. Dolomite grains have a rhombic cleavage. All the grains are cemented by the dolomite and hematite. The rock is moderately sorted and sub mature to mature. According to mineral percentages of the above minerals, it falls in the field of quartz arenite.

B: Slump and cross-stratified unit

Lithology:- This unit of the sand-body is composed of a cross-stratified and slumped lower part and an upper cross-stratified part, respectively. At the base, a 6m thick medium-grained sandstone is mainly characterized by small scale planar cross bedding. This sandstone is overlain by 15m of medium to coarse grained sandstone (Fig. 2b), which is characterized by its slump structure and convoluted bedding. The top 5m thick unit is highly cross stratified and mostly the cross bedding is planar. However, some trough cross bedding is present and a few slump forests also occur. The colour of the rock ranges from light reddish purple to purple. The grains are poorly cemented and medium to coarse grained. This portion of the sand-body is more micaceous and friable.

Petrography:- The dominant minerals are quartz, feldspar and muscovite. Quartz makes 70% to 80% the volume. The shape of original detrital quartz grains are sub-rounded generally suggestive of recycling. Feldspar content is very low and rarely reaches 2 to 3%, Micas comprise 2 to 3% and a few grains of dolomite and 10 to 12% rock fragments are also present. The grains are mostly cemented by calcite and clay minerals with kaolinite being dominant. The rock is medium grained, moderately sorted and immature. This is classified as a sub-lithic arenite.

Grain Size Distribution:- Figs. 3 & 5 display cumulative curves as a representation of the main type of grain size distribution encountered in the present study. In these figs.,.the two main size population, i.e. saltation and suspension in the representative curve shows a typical fluvial type size distribution, as defined by Visher (1969).

The statistical parameters estimated from the cumulative curves in Figs. 3 & 5 show that the base of the upper unit of the rock is moderately sorted, coarse-skewed and leptokurtic (Lewis, 1984) and the upper part is moderately sorted, fine skewed and leptokurtic. Figs. 4 and 6 show the distribution of particle sizes.

COVE HARBOUR SANDSTONE

Lithology:- The colour of the sand body ranges from red to yellow brown. It is medium to thickly bedded with obvious internal erosional surfaces. This sand body consists of three components. At the base, a 10m thick unit is medium grained to coarse grained, which is mostly structureless, however some faintly planar and trough cross bedding is present at the base. This structureless and faintly stratified unit is separated from the above conglomerate unit by an erosional surface.

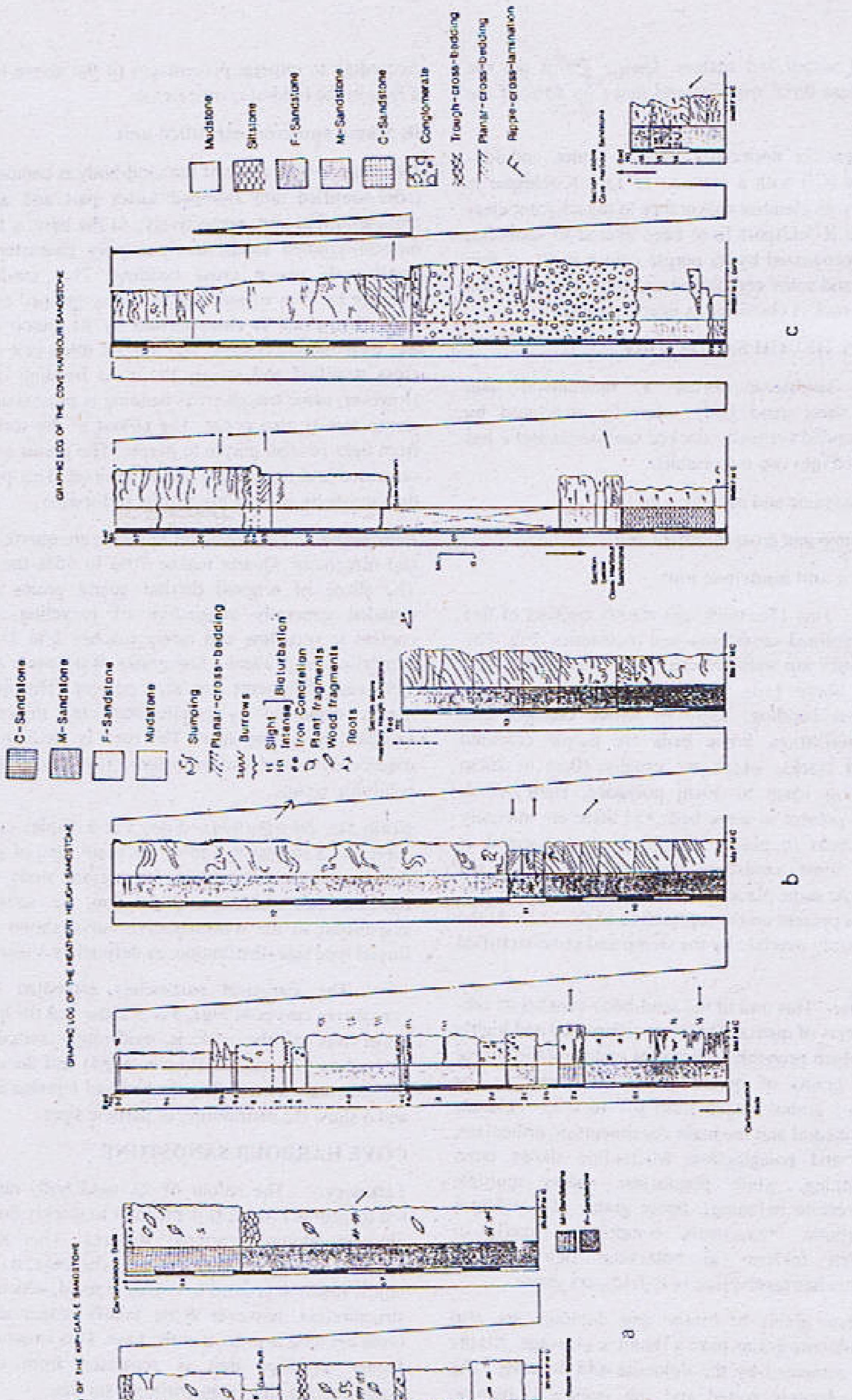

Fig. 2 Graphic logs of sandstone bodies. (a) Kip Carl sandstone (b) Heathery Heaugh sandstone. (c) Cove Harbour sandstone.

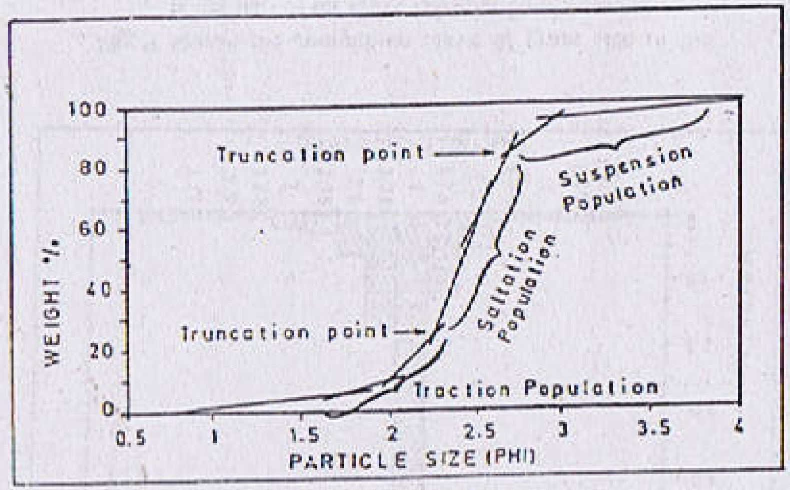

Fig. 3 Representative grain-size distribution comulative curves from Heathery Heugh Sandstone. Samples are plotted showing the populations suggested by Visher (1969).

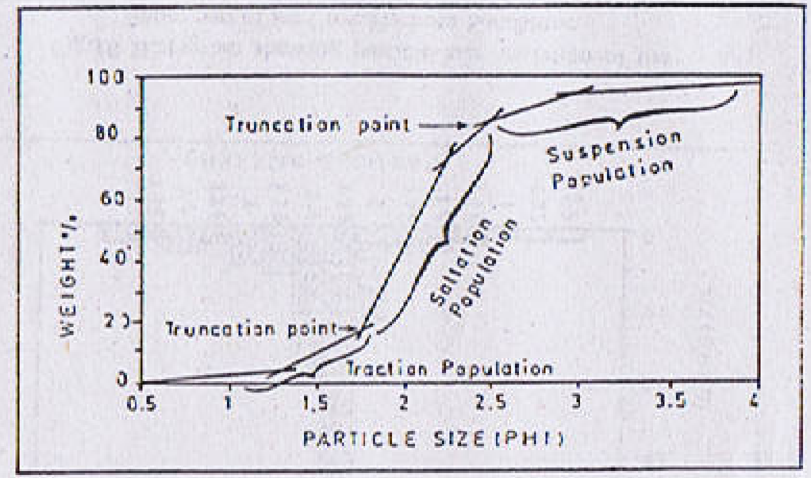

Fig. 4 Shows the histogram of particle size variation of the lower part of the channel unit of the Heathery Heugh Sandstone.

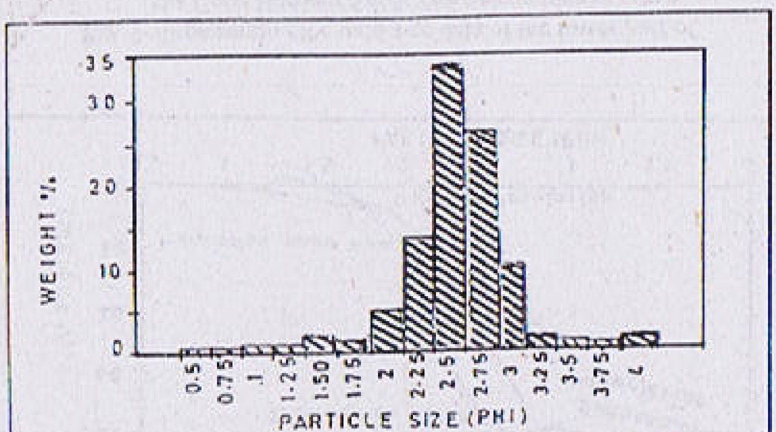

Fig. 5 Shows the cumulative curve of grain size of the upper part of the Heathery Heugh Sandstone.

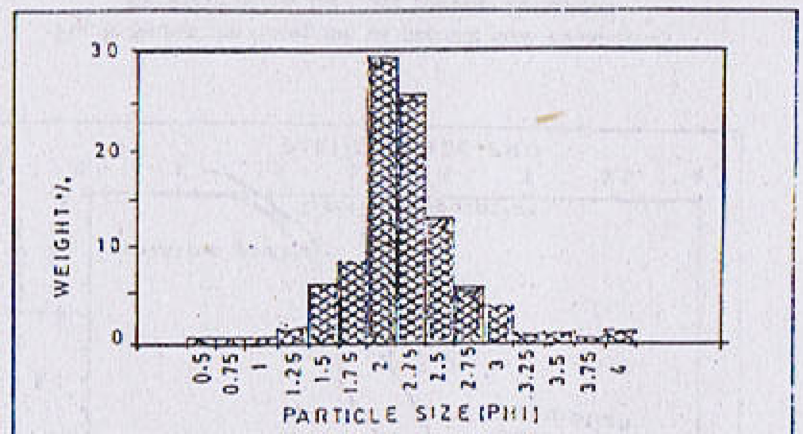

Fig. 6 Histogram showing particle size variation of the upper part of the Heathery Heugh Sandstone.

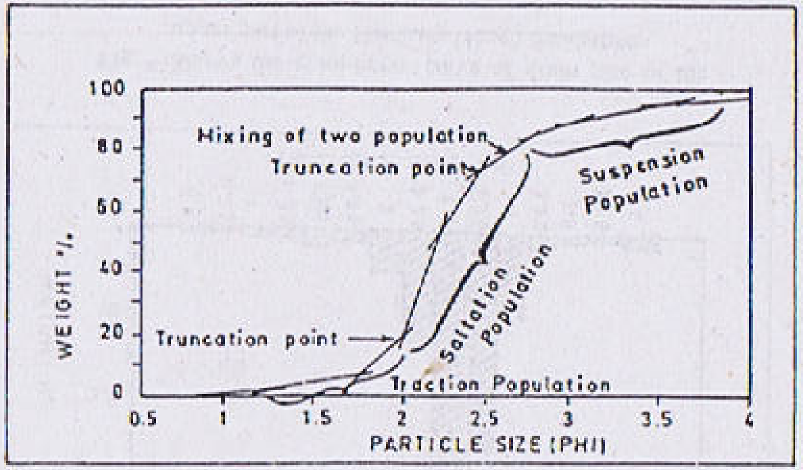

Fig. 7 Representing the gain size data of the lower part of the Cove Harbour Sandstone on cumulative curve.

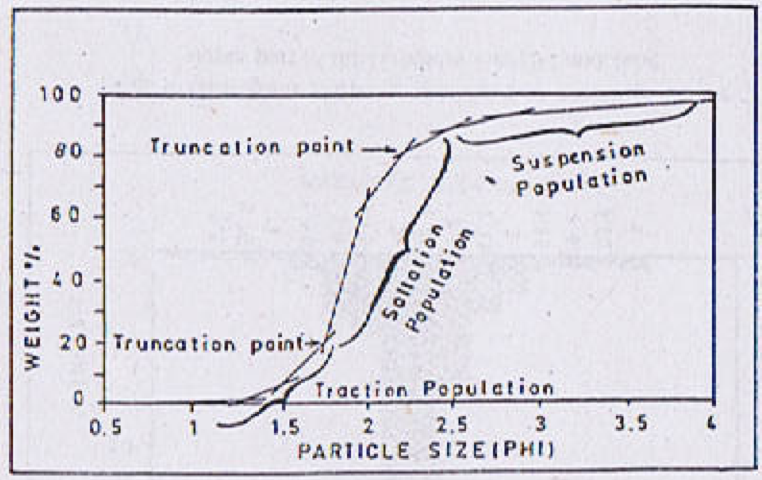

Fig. 8 Shows the histogram of particle size variation of the lower part of the Cove Harbour Sandstone.

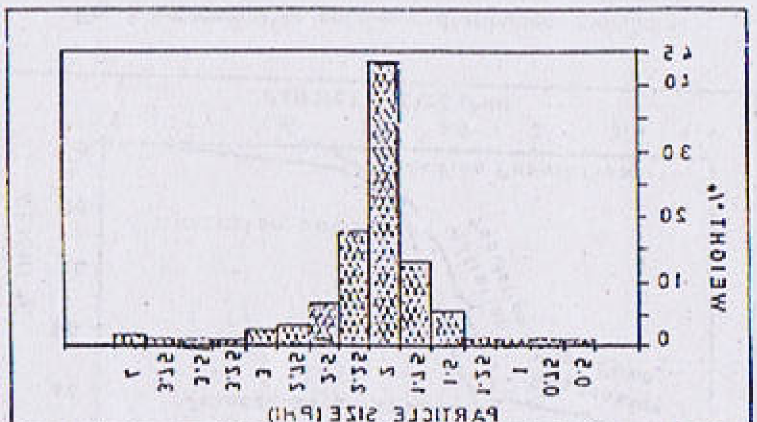

Fig. 9 Shows the cumulative curve of grain size of the upper part of the Cove Harbour Sandstone.

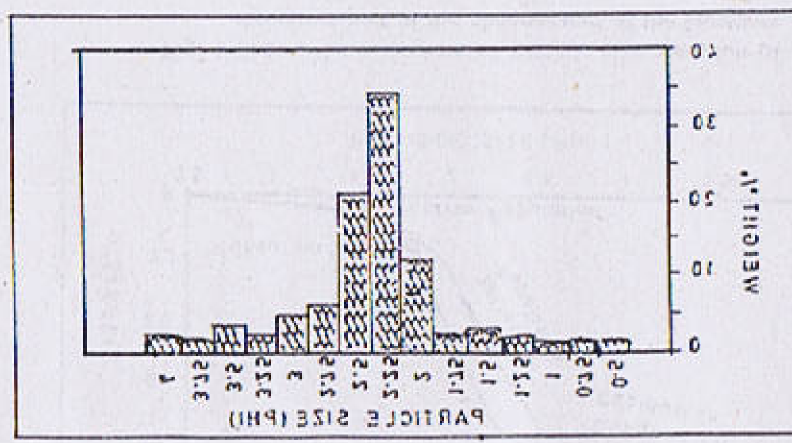

Fig. 10 Histogram showing particle size variation of the upper part of the Cove Harbour Sandstone.

The second portion of this sand body consists of a composite unit of poorly sorted conglomerates (Fig. 2c), approximately 6m thick and capped by sandstone. It contains fragments of sandstone, siltstone and mudstone in a matrix of grayish white sandstone. The clasts are pebble to cobble sized and some of them are deformed.

The upper unit is 11m thick and strongly cross bedded and shows a progressive fining upwards in grain size. Both planar and trough cross bedding is present. The cross beds are in sets from 2cm to 4cm thick and form cosets of decimeter to metre scale. In these consets, both tabular and trough shaped sets are present with maximum dips between 25 to 30 degrees. Palaeocurrents determined from forests of both types of cross strata show a unimodal distribution. A few small slump structures are also present in this portion. At the top of this unit large scale trough cross bedding are present.

Petrography:- This sandstone is composed of angular to sub-angular grains of quartz showing undulose extinction with feldspar grains and compacted biotite. The sandstone grains are cemented by a ferroan dolomite and hematite. The quartz grains show evidence of corrosion and the rock suffered a slight compaction before it was cemented. The majority of quartz grains lying in the region of 2 to 3 roundness scale of Powers (1982) and the sphericity shows a variation of 3 to 4. Feldspars appear to be dominantly potassic and show some alteration. The quartz grains range in percentage from 90% to 95% while the feldspar comprises 5% to 10%. The rock is classified as a quartz-arenite.

Grain Size Distribution:- Sieve analysis on the unconsolidated sand shows that it is well sorted, with strong skewness and very leptokurtic. Figs. 7 and 9 show cumulative curves representing grain size distribution in the lower and upper part of Cove. Harbour Sandstone. These figs. Indicate that the saltation deposition population is greater than the other size populations. These populations demonstrate a high energy environment of deposition. The mixing between the suspension and saltation population. The mixing between the suspension and saltation population appears to be related to highly variable energy conditions (Visher, 1969). Figs. 8 and 10 show the distribution of the particle sizes.

BILSDEAN SANDSTONE

Lithology:- This rock is yellowish brown in colour and the grain size ranges from medium to coarse. Some beds contain tabular cross bedding having 0.06m thick sets. Large cross bedding is present in the upper beds, these are usually tabular having 1m to 1.50m thick cosets and .06m to .1m thick sets. Some beds contain carbonaceous orgainc materials and a few veins containing iron material passes through the bedding.

Petrography:- This sand body is composed predominantly of quartz (75% to 85%) and shows a wide range of mean grain size from medium (0.4mm) to coarse grained (0.6mm). Feldspars comprise 4% to 6% of the grains and 2% to 3% of compacted mica grains were also recorded. A few grains of wood fragments were also recorded.

DISCUSSION

The Carboniferous sequence was laid down in a Varity of contrasting environments. Deposition frequently following a cyclical pattern indicative of alternate raising and lowering of the sea level relative to land. In the lower Carboniferous sedimentation first occurred mainly in shallow enclosed lakes and than in an open marine environments which occasionally gave way to advancing deltas. Sedimentation was controlled by relative uplift of the old Caledonian axes. The above mentioned sandstone bodies have been interpreted such as:-

The Kip Carle sandstone body is vertically associated with underlying mudstones of over-bank floodplaindeposits below and carbonaceous mudastones of crevasse splay fill coal swamp deposits above (Fig.1) (Nabi in press). Association with these deposits suggests that this sandstone represents a channel facies. The planar cross bedding was probably formed during migration of trains of sinuous crested dunes (Okolo, 1983). The absence of mudstone units in the infill sediments suggests that the same current may have successively cut and filled the channels with little evidence of flood plain muds (i.e. the channels were of low sinuosity). The sand ribbons in the upper beds also suggest that it may be a fixed channel and the upper thinbeds could be interpreted as levee deposits of the distributary (Friend, et al., 1981). The fine to medium grain sizes of the sandstone and presence of carbonized wood fragments might suggest deposition during the falling stages of flow rather than flood stage deposits.

The basal unit of the Heathery Heaugh sandstone is associated at the base with fine-grained sediments, which are interbred with thin coals, carbonaceous shales (Fig.1) and rootlet beds (Nabi in press). At the top, it is sharply overlain by the slump and cross stratified unit. The physical characteristic features such as cross bedding, alternation of sandstones with silty mudstones, organic materials, fine grained moderately sorted sand, desiccation structures and bioturbation suggests similarity of the unit to channel mouth bar deposits.

As distributary mouth bars prograded across the site of vertical section, they might be capped by small overbank crevasse splays, composed of alternating silty mudstone and small-scale laminated to cross laminated sands (Coleman and Prior. 1982). The more intensely bioturbated horizon suggests that the sedimentation rate was temporarily decreased allowing an infauna to develop (Elliott, 1986). Bioturbated muds and silts deposited on the bay floor pass upwards into interbedded silty mudstone and sandstone with cross lamination, which is considered to reflect current and wave action on the mouth bar front. The sand dominated members of this unit represent straight crested sand waves, which migrated at high flow stage in channels confined to the bar back and were probably deposited on the bar crest. Maddox and Andrews (1987) described similar sandstones from Burnt island in the Oil Shale Group.

The mud cracked horizons associated with purple colouration indicate conditions of exposure and oxidation. The mud cracks are due to the drying of the inter dune surface, while the purple colour is due to an increase in iron content. As a number of these exposure surfaces occur in the unit, they attest to periodic deposition perhaps associated with channel switching.

The upper unit of the Heathery Heaugh sandstone is associated at the base with mudstone and sandstone of proposed mouth bar deposits and at the top with finer grained sediments of probable crevasse splay deposits (Fig.1) (Nabi in press).

The cross bedding in the lower stratified unit indicates that the bedforms which deposited this unit were probably straight or sinuous crested side-bars. The straight and slightly curved planar set cannot be preciecly distinguished due to poor three dimensional exposures.

In the middle part of the unit the slump structures are attributed to displacement of sediments under the influence of gravity, while convolute bedding indicates rapid sedimentation. The slumping in this sandstone body probably occurred while the sediment was in a fludized stste and may have been initiated by simple gravitational adjustment of the foreset angle. Thus it is concluded that straight crested dunes became potentially unstable as the pore pressure rose due to sediment loading. The driving force for the datachment and block sliding was gravity.

The convolute bedding in this unit is interpreted as being formed through the partial liquefaction and deformation of water saturated sediments under the influence of lateral shearing probably resulting from the movement of large bed forms over an unconsolidated substrata during high flow stages (Plint, 1983).

The tabular cross bedding in the upper part is considered to represent the migration of straight crested mega ripples (Sand wayes or tranverse bars) and the trough cross bedding is attributed to the migration of dunes with sinuous crest lines or sand waves with a more three dimensional commonly lingoid form. Alternatively, they may be the deposits of bed forms with curved crest lines. Both types of cross bedding may be deformed by overturning of forests and by more general convolution and water escape (Collinson, 1986) but the former is not likely in this case. The paleocurrents dispersions probably indicate the presence of large sand dunes which were not necessarily migrating downstream, i.e. they may have been migrating tangential to the main flow. The high sediment loading and non-downstream movement of these bars would suggest that the channel was wide and internally sinuous (probably braided).

The Cove harbour sandstone body is associated with fine grained sediments of probable interdistributary bay fill (Nabi in press) below and is capped by channel abandonment and lake deposits (Fig.1) (Nabi in press). The Cove-Harbour Sandstone is therefore generally interpreted as a channel sandstone body. The channel fill consists of structureless sandstone, massive accumulation of pebbles and cobbles, passing upward into sandstones with aboundant cross-satratified sandstone which markedly fines upward.

At the base, the structureless and faintly cross bedded sandstone is interpreted as the result of rapid sediment dumping from high energy flow and the product of a variable, possibly flashy, discharge regime (Fielding, 1986). The absence of mudstone units between the erosive surface and infill sediments suggests that the same currnt may have cut and filled the channels either contemporaneously or shortly afterwards.

The conglomerate is clearly too thick to be a channel lag deposit, and in any case the rock is too coarse grained and poorly sorted. The clast composition (mud rocks in part) suggest derivation from non channel environments and evidence of plastic deformation Shows that the clasts were coherent but soft. In short, this deposit has the characteristics of mass flow genesis. Generation of mass flows in channel environments could be caused by liquefaction of sands by the generation of water waves, or more likely, by excess channel loading caused by the collapse of bank sediments. Bank under cutting during periods of high discharge is considered to be the most likely mechanism triggering retrogressive slumping of the channel banks and thus the development of large scale high velocity flows (Jones & Rust, 1983). Failure associated with shear at or near high stage flow can lead to the development of excess pore pressure, causing the sediment mass to accelerate (Turner and Monoro, 1987).

In the upper cross stratified unit, the low angle cross bedded sandstone may have been produced during high flood stage. Flood water may than have spread across bar surfaces depositing the sediment and forming low-angle bedded sandstones. The trough cross bedded sandstone might be due to a decrease in energy, causing sands to move as mega ripples (Ramos and Sopena, 1983). The unidirectional (unimodel) palaeoflow in this sandstone indicates a fluvial channel deposition (Rust and Jones, 1987).

The Bilsdean sandstone overlies fine-grained sediments of probable lake deposits (Nabi in press). On the basis of scale and geometry, it is considered that the large scale cross bedding is most probably the product of small fluvial channels with large alternate bars with slip faces. The grain size and the presence of carbonized wood also suggests that the sandstones were deposited in a fluvial channel.

CONCLUSION

The preceeding description of the sandstone bodies have outlined certain salient features regarding their environments of deposition in lower Carboniferous at Cove.

The broad elongated sandstone bodies are interpreted as the deposits of large distributary channels, evidenced from their geometry internal structure and sequence context. These major distributaries were the main source of sedimentary transport into the basin. The channel fills are dominated by unidirectional planar and trough cross bedding, which are attributed to the migration of large, sinuous crested bedforms at flood stage in major channels. Large bedforms in these channels show abundant evidence of sedimentary slumping and gravity sliding. The slumping is thought to have initiated subsequent gravity flows, which moved across the main channel and not necessarily in a downstream direction.

ACKNOWLEDGEMENTS

I am indebted to Dr. Julian E. Andrews for his valuable guidance and supervision. Thanks are due to Dr. Abdul Salam Khan, Department of Geology, University of Balochistan Quetta for the critical review of the paper. I am also very thankful to the Governemnt of Pakistan for the financial support during my stay in England.

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BIOSTRATIGRAPHICAL STUDIES OF SOME UPPER DEVONIAN SECTIONS IN NEW YORK STATE AND PENNSYLVANIA, U.S.A.

BY

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Abstract:-*Sixty four samples from four formations, namely, the Java, Canadaway, Chadakoin and Cattaraugus have been analysed. All of which are collected from six sections extending over 4000 sp./km. through the Upper Devonian in western New York State and northern Pennsylvania, U.S.A. The palynological floras of marine and non marine origin contain a diversity of trilete spores, together with an acritarch component that is relatively inconspicuous qualitatively and quantitaively. Within the area studied correlations are made between sediments of diverse non-marine and marine facies. Biostratigraphical and phytogeographical distributions of the Upper Devonian miospores are described and Implications of their distribution patterns are discussed. Four marine sections such as the Brick Quarries, Hamlet Quadrangle, Pope Hollow, and Lewis Run, except the Walnut Creek Section, are compared palynologically with well dated, non marine the Bush Hill section.*

INTRODUCTION

The Upper Devonian miospores from western New York State and northern Pennsylvania, U.S.A. have been described systematically (see Ahmed 1988) and comparison of miospore assemblages from these areas has been attempted with areas from other parts of North America (see Ahmed 1986).

Ahmed (1986) correlated these assemblages with miospores recorded previously by different workers such as Winslow (1962) from North America, McGregor (1960) from Canada including Southern Ontario, Maritime provinces and Yukon Territory. Moreover, Ahmed (1985) made an attempt to correlate the miospore assemblages recorded from the Upper Devonian Strata of western New York State and northern Pennsylvania, U.S.A. with those known from sediments of similar age elsewhere. The areas with which comparison was made were Belgium (Streel in Becker *et al*, 1974), British Isles (Clayton *et al.* 1974; Higgs 1975 and Utting & Neves 1970), Poland (Turnau 1975), Byelerussia; Kedo 1957, 1962, 1963 and Goloubstov *et al.* 1968), North Africa (Massa & Moreau-Benoit 1976) and Australia (Balme & Hassell 1962). In another paper Ahmed (1985) described the geographical variations in the Upper Devonian miospore assemblages.

Marine and non-marine facies may contain many species in common. In the Upper Devonian of New York State and Pennsylvania, this phenomenon has been observed in the marine Ellicott Member of the Chadakoin Formation and in the lower part of the non- marine Ellicott Member of the above mentioned formation, which have most species in common and concluded to be coeval.

In marine facies miospores range from 5 to 90 percent; whilst in continental strata they are hundred percent of the total assemblages. The occurrence of acritarchs is surprisingly erratic and range from 2 to 74 percent.

In the samples from the Bush Hill Section (approximately 3 km E of Smethport, road cut on rout 6, Pennsylvania, Fig.1) no acritarchs or chitinozoa have been found and, since these micro-fossils are often abundant in brackish and marine sediments, their absence strongly support the prevalent view that the sediments of the Bush Hill Section were laid down in continental regime.

Aneurospora greggsii (McGregor) Streel in Becker *et al.* 1974 is the most numerous component in some of the samples of the present study. This is especially true in sequences in the lower part of the Ellicott Member of the Chadakoin Formation where the population of *A. greggsii* ranges from 30 to 43.5 percent. In the assemblages of the overlying Cattaraugus Formation this taxon decline in abundance to only one percent or less of the total assemblages. This species is most abundant in the continental strata e.g. the Bush Hill Section, whilst in marine facies its numbers are reduced. The abundance of *A. greggsii* in sediments of siltstone and fine sandstone can be correlated

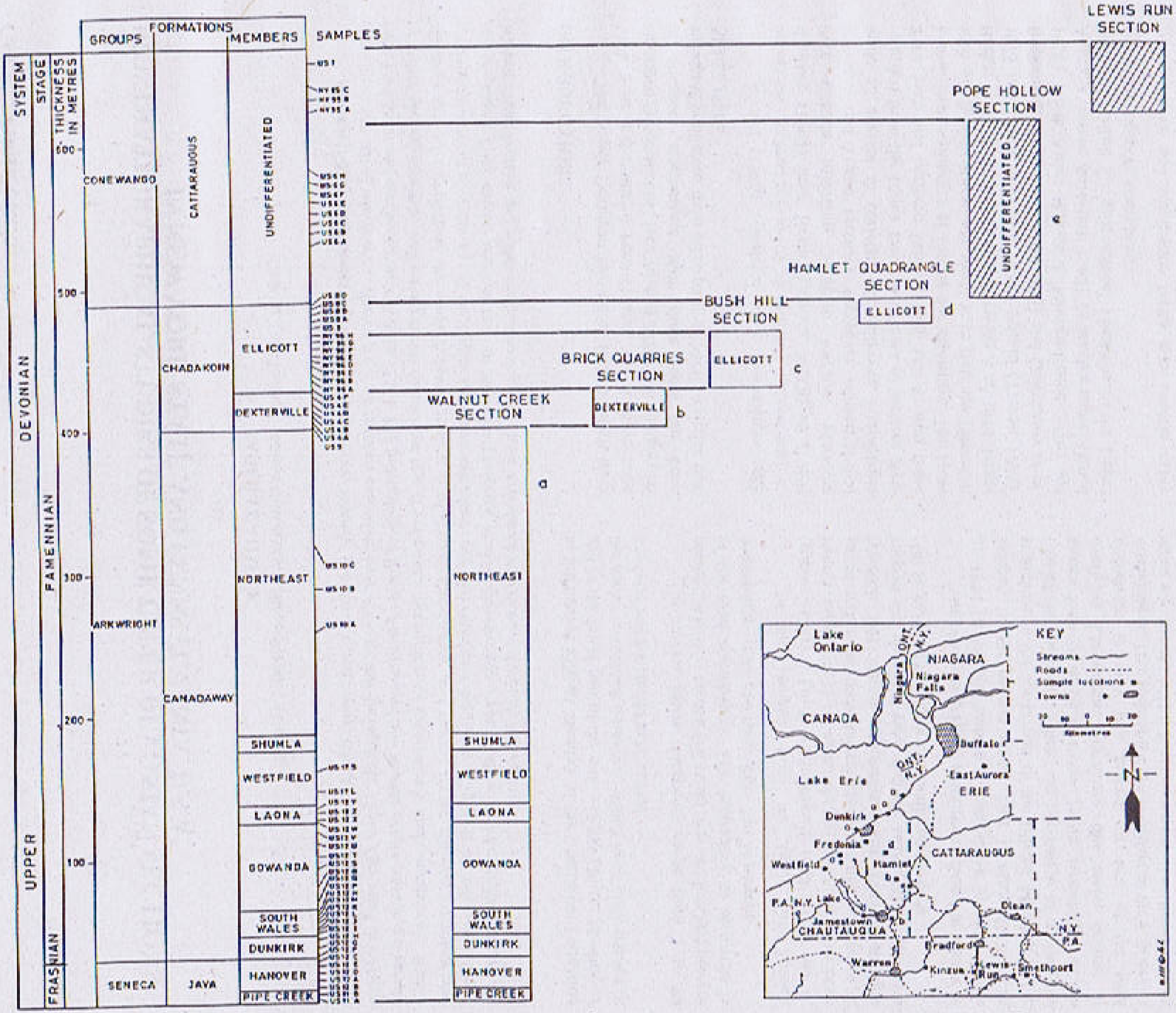

FIG. 1. GENERALIZED SUCCESSION AND THE GEOGRAPHICAL LOCATIONS OF THE SECTIONS INVESTIGATED (Letters near each section correspond to the letters on the location map.)

THE LOCATION OF SAMPLING AREA

with the presence of sporangia containing this spore species. In many of the samples, however, *Streelispora catinata* (Higgs) Ahmed 1988 is by far the most abundant species ranging from 10 to 20 percent. The species *Auroraspora torquata* Higgs 1975 is also common and ranges from 5 to 10 percent in many samples. A miospore with multifurcate spines, *Ancyrospora multifurcata* (Winslow) Ahmed 1991 is relatively abundant in certain samples namely the siltstone from the Bush Hill, Brick Quarries; samples US9-US4F (the Dexterville Member) and Walnut Creek Sections; sample US11A- US10C. It is persistent component in both marine and non-marine facies, in other samples it is relatively rare (less than one percent) or absent.

The species *Synorisporites flexuosus* Richardson & Ahmed 1988 has frequently been observed in younger part of the sequences investigated. It has been found in almost all the samples of younger two assemblage zones namely the FV and HL(Table 1). The species could be considered as an index fossil of middle Famennian (Fa2b - Fa2c), since it has been reported from almost equivalent stratigraphical levels in many parts of the world e.g. western Europe, North Africa and North America.

The miospore species of the genus *Auroraspora* have been found from throughout the sequences. In particular, the samples from the Bush Hill Section yielded well preserved and many forms of the above mentioned genus. It is evident from Table 1 that there is a gradual increase (quantitative and qualitative) in different forms of the genus *Auroraspora* from bottom to top of the sequences investigated. The CN zone is characterized by only two species; whilst in the overlying FV zone eight species of *Auroraspora* have been recorded. The total number of *Auroraspora* species is eight in the youngest HL zone. In consequence, eighteen species (forms) of the genus *Auroraspora* have been arranged stratigraphically and are considered to be related morphologically (Ahmed 1990). It is worth mentioning that the palynological assemblage obtained from material from the Bush Hill Section is excellently preserved, when compared with the nature of preservation in other parts of the sequences. The miospores of the genus *Auroraspora* recorded from the Bush Hill material exhibit conspicuous patern of coarse radial folding on the pseudosaccus. For a detailed account on a miospore genus *Auroraspora* readers are referred to (Ahmed 1988 & 1990).

COMPARATIVE PALYNOLOGY WITHIN THE AREAS STUDIED

In this part of the paper, comparison within the studied areas has been made. Four marine sections namely the Brick Quarries, Hamlet Quadrangle, Pope Hollow, and Lewis Run are compared palynologically with well dated, non-marine the Bush Hill Section. The stratigraphical horizons and geographical locations of all the six sections together with their samples investigated and ranges of miospores observed in marine strata are shown in text Fig.1, and in Table 2.

COMPARATIVE PALYNOLOGY OF THE BUSH HILL (ELLICOTT MEMBER) AND BRICK QUARRIES (DEXTERVILLE MEMBER) SECTIONS

The stratigraphical ranges and the levels of occurrence of all the miospores analysed from the Brick Quarries (Dexterville Member) and the Bush Hill (Ellicott Member) Sections are shown in Table 1.

The miospore assemblages recorded from the Brick Quarries have been assigned to the *Synorisporites flexuosus* - *Auroraspora varia* (FV) Zone, while those recorded from the Bush Hill have been attributed to the *Vallatisporites vallatus* var. *hystricosus* - *Retispora lepidophyta* (HL) Zone because of the first appearance of the index fossils, Ahmed 1978, Ahmed 2000 (in Press).

The material from the Brick Quarries Section yielded 45 species of miospores. Of the 78 species recorded from the two sections, only 32 are common to both assemblages. Forty-one species are regarded as common to both the Bush Hill and the Brick Quarries assemblages Table 6.

By comparison with material from the Bush Hill, assemblages from the Brick Quarries are carbonized and the state of preservation is also poor. However, miospores which were quantitatively determined accounts for between 30 and 82 percent, acritarchs range 5 and 52 percent. and indeterminate elements 12 and 22 percent of the miospore/microplankton assemblages.

In the Brick Quarries assemblage *Vallatisporites vallatus* var. *hystricosus* and *Retispora lepidophyta* have not been observed. The presence of these index fossils in the Bush Hill assemblage (in non-marine sequence) and in material from the Hamlet Quadrangle (in marine sequence) is a widespread biological event. Consequently, the base of the Bush Hill and Hamlet Quadrangle Sections is of Famennian age or Fa2c/Fa2d boundary within the Upper Famennian (in Belgian terminology) Ahmed 1985.

The Bush Hill assemblage contains, in addition, a number of distinctive forms that were not encountered in material from the Brick Quarries. These forms may prove to be a potential value as stratigraphical indicator: *Pulvinispora quasilabrata* Higgs 1975, *Convolutispora definita* Ahmed 1978, *Knoxisporites literatus*, (Wltz) Playford 1963, *Synorisporites richardsonii* Ahmed 1978, *Auroraspora prostata* Ahmed 1980, *A. prostata* var. *prostata* Ahmed 1980, *A. prostata* var. *elongata* Ahmed 1978, *A. versabilis*

Table 1

Stratigraphical Ranges of all the Miospores recorded from the Brick Quarries and Bush Hill Sections.

MIOSPORE SPECIES	BRICK QUARRIES SECTION DEXTERVILLE MEMBER								BUSH HILL SECTION ELLICOTT MEMBER						
	US9	US4A	US4B	US4C	US4D	US4E	US4F	NY96A	NY96B	NY96C	NY96D	NY96E	NY96F	NY96G	NY96H
Acanthotriletes horridus var. minutus	o	o													
Ancyrospora acadensis	o	o	o	o	o	o									
Auroraspora pseudocrista	o	o	o	o	o	o	o								
Ancyrospora neograndispinosa	o	o	o	o		o	o								
Samarisporites kaedoae	o	o	o		o	o	o								
Aneurospora incohata	o	o	o	o			o	o	o			o			
Auroraspora torquata	o	o					o			o		o			
Auroraspora pallida	o	o	o	o	o		o	o		o		o	o	o	
Auroraspora submirabilis	o	o	o			o	o				o		o	o	
Auroraspora solisorta	o	o	o	o	o	o		o	o	o	o	o		o	
Auroraspora varia	o		o	o	o	o	o	o	o	o	o	o	o	o	o
Synorisporites flexuosus	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Apiculiretusispora plicata	o	o				o	o	o		o	o	o		o	o
Ancyrospora multifurcata	o	o	o	o	o	o	o			o		o		o	o
Streelispora catinata	o	o	o		o	o		o	o	o	o	o	o	o	o
Retusotriletes concretus	o	o			o	o	o	o			o			o	o
Samarisporites inusitatus		o													
Dictyotriletes sp.		o													
Ancyrospora ancyrea var. ancyrea		o		o	o										
Rhabdosporites langi		o			o										
Grandispora macroseta		o			o										
Grandispora echinata		o	o	o	o	o		o							
Grandispora echinula		o	o		o	o				o					
Calamospora nigrata		o		o	o		o	o	o			o	o		
Hystricosporites sp. aff. porrectus		o												o	
Punctatisporites glaber		o	o	o		o	o	o	o	o	o	o	o	o	o
Punctatisporites platirugosus		o							o	o	o				o
Auroraspora micromanifesta			o												
Aneurospora greggsii var. minuta			o			o	o	o	o	o	o	o	o	o	o
Streelispora distincta			o					o	o	o	o		o	o	o
Retusotriletes caperatus				o		o	o								
Retusotriletes sp.				o	o					o					
Apiculiretusispora fructicosa				o	o	o	o	o		o	o	o			
Calyptosporites perclarus				o	o	o	o	o	o	o	o	o	o	o	
Aneuraspora greggsii				o	o	o	o	o	o	o	o	o	o	o	o
Punctatisporites minutus				o	o	o	o	o	o		o	o	o	o	o

Direction of younging →

Rhabdosporites parvulus					o			o	o	o					
Ambitisporites cf. avitus					o			o		o					
Auroraspora commutata					o		o		o	o	o	o	o	o	o
Grandispora corunata							o								
Auroraspora callosa							o					o			
Acanthotratriletes sp.							o						o		
Spelaeotriletes densatus							o		o	o	o	o		o	
Pulvinispora depressa							o	o	o	o	o	o	o	o	
Auroraspora poljessics							o	o	o	o	o	o	o	o	o
Raistrickai clavata								o	o						
Auroraspora paPapillara								o	o						
Auroraspora cf. paPapillara								o	o						
Retusotriletes cf. concinnus								o	o	o					
Pulvinispora quasilabrata								o	o	o	o				
Calamospora pedata								o				o			
Calamospora liquida								o	o	o		o			o
Biharisporites parviornatus								o	o	o	o	o	o	o	o
Auroraspora prostata								o	o	o	o	o	o	o	o
Auroraspora prostata var. prostata								o			o	o			o
Auroraspora prostata var. elongata								o				o		o	o
Synorisporites variegatus								o	o	o	o	o	o	o	o
Knoxisporites literatus								o	o		o		o		o
Knoxisporites pristinus								o	o	o		o	o	o	o
Convolutispora definita								o	o	o	o	o	o	o	o
Verrucosisporites maculosus								o	o	o				o	o
Convolutispora mellita								o	o	o	o	o	o	o	o
Vallatisporites vallatus var. hystricosus								o	o	o	o	o	o	o	o
Synorisporites richardsonii									o						
Raistrickia baculosa									o	o		o			
Punctatisporites stabilis									o			o	o		
Retispora lepidophyta									o	o		o		o	
Retispora ledpidophyta var. granda									o					o	
Lophozonotriletes curvatus									o	o				o	o
Verrucosisporites microtuberosus									o					o	o
Auroraspora versabilis										o	o	o		o	o
Raistrickia ampullaceae										o	o	o			o
Auroraspora varia var. multifaria										o		o	o	o	o
Emphanisporites rotatus										o					
Leiotriletes ornatus												o	o		o
Dibolisporites sp.														o	o
Hystricosporites porcatus														o	
Hystricosporites mitratus														o	o

(Kedo) Turnau 1975 and *Retispora lepidophyta* var. *granda* (Kedo) Ahmed 1978.

The Brick Quarries microflora contains four miospore forms which do not extend upward in the sequence: *Samarisporites inusitatus* Allen 1965, *Auroraspora pseudocrista* Ahmed 1980 *Rhabdosporites langi* (Eisenach) Richardson 1960 and *Ancyrospora ancyrea* var. *ancyrea*, Richardson 1962.

The species *Auroraspora torquata* Higgs 1975 and *Ancyrospora multifurcata* (Winslow) Ahmed 1991 are well preserved in material from the Bush Hill, whereas these species were found to be poorly preserved in the marine sequence

Retusotriletes caperatus Ahmed 1978, *Ancyrospora neograndispinosa* Ahmed 1991 and *A. acadensis* Ahmed 1991 are commonly present in Dexterville sample but have not been encountered in material from the Bush Hill Section.

The sporadic occurrence of a distinctive species, *Samarisporites kedoae* (Riegel) Ahmed 1978 in samples from the Brick Quarries and Hamlet Quadrangle may, however, be due to recycling.

In conclusion, the palynological evidence suggests that the strata of the Brick Quarries Section (Exterville member) are older than those at the Bush Hill Section (Ellicott member). However, Techudy (1969, p.112) concludes that "dissimilarity of assemblages is not always indicative of differing ages; " because different origins or occupied different ecological habitats play an important role for the deposition of plant-microfossil assemblages.

COMPARATIVE PLAYNOLOGY OF THE BUSH HILL AND HAMLET QUADRANGLE (ELLICOTT MEMBER) SECTIONS

The stratigraphical distribution of the 77 species and forms of miospores recorded from these two sections is summarised in Table 2.

The miospore assemblages obtained from the Bush Hill and Hamlet Quadrangle (Ellicott member) Sections have been assigned to the *Vallatisporites vallatus* var. *hystricosus* (Winslow) Clayton *et al.* 1977 - *Retispora lepidophyta* Playford 1976 (HL) Zone because of the continuous occurrence of the index fossils.

From Table 2 & 5, it is evident that 41 species are observed as common to both the Bush Hill and Hamlet Quadrangle assemblages. However, two of these, *Auroraspora varia* (Naumora) Ahmed 1980 and *A. submirabilis* (Luber) Ahmed 1978 appear to be almost mutually exclusive - the former being much more characteristic of the Bush Hill assemblage, and the latter of the Hamlet Quadrangle.

Auroraspora prostata Ahmed 1980 and its varieties which were quantitatively determined accounts for up to 20 percent of the total assemblage. These forms were not encountered in material from the Hamlet Quadrangle. The species which are confined to the Hamlet Quadrangle assemblage include *Spelaeotriletes microverrucosus* (Kaiser) Ahmed 1978, *Samarisporites* sp. cf. *S. kedoae* (Riegel) Ahmed 1988, *Dictyotriletes* cf. *trivialis* Naumova in Kedo 1963, and *Auroraspora* sp. Ahmed 1978.

In comparison with the Bush Hill assemblage, the Hamlet Quadrangle microflora is notably less diverse. Moreover, its constituent miospores are generally less well preserved, a circumstance which is perhaps the result of different depositional environments. In the Hamlet Quadrangle assemblage average percentage of *Vallatisporites vallatus* var. *hystricosus* (Winslow) Clayton *et al.* 1977 present is only 2 percent, whereas well preserved specimens of *Retispora lepidophyta* (Kedo) Playford 1976 were encountered only from one sample.

As has been mentioned above, of the 77 miospore forms from two sections, only 41 are common to both assemblages. A total of fifty-three species is apparently confined to the Hamlet Quadrangle assemblage. Fifty-three percent species are regarded as common to both the Bush Hill and Hamlet Quadrangle assemblage (Table 8).

In material from the Hamlet Quadrangle, the miospores at certain horizons constitute up to 80 percent of miospore/marine micro-plankton assemblages indicating for some of the samples a near shore environment. However, at specific level indeterminate elements comprised up to 21 percent in some of the samples. Acritarchs have frequently been encountered throughout the section and comprise up to 48 percent of the total assemblage.

It might be argued that as the Hamlet Quadrangle Section is marine and the Bush Hill Section is non-marine, palynofacies differences might affect the range of the spores so as to invalidate direct correlation. Admittedly more work needs to be done to determine the extent of relationship between environmental factors and spore assemblages in the Devonian. However, those studies that have been done suggest that the representation of species in isochronous assemblages from different lithofacies tends to vary quantitively rather than qualitatively, i.e. that whereas relative abundances of the certain constituent species may vary, the assemblages commonly may be correlated on the presence of many of the same constituent species, and a similar succession of groups of species (Richardson 1969, p.202 and Kuyl *et al.* 1955). The assemblages from the Bush

Table 2

Stratigraphical Ranges of all the Miospores recorded from the Bush Hill and Hamlet Quadrangle Sections.

MIOSPORE SPECIES	BUSH HILL SECTION ELLICOTT MEMBER								HAMLET QUADRANGLE SECTION ELLICOTT MEMBER				
	NY96A	NY96B	NY96C	NY96D	NY96E	NY96F	NY96G	NY96H	US5	US8A	US8B	US8C	US8D
Raistrickia clavata	o	o											
Auroraspora Papillara	o	o											
A. cf. Papillara	o	o											
Retusotriletes cf. concinnus	o	o	o										
Pulvinispora quasilabrata	o	o	o	o									
Calamospora pedata	o	o	o		o			o					
Biharisporites parviornatus	o	o	o	o	o	o	o	o					
Auroraspora prostata	o	o	o	o	o	o	o	o					
Auroraspora prostata var. prostata	o			o	o			o					
Auroraspora prostata var. elongata	o				o		o	o					
Knoxisporites literatus	o	o		o		o		o					
Verrucosisporites maculosus	o	o	o				o	o					
Convolutispora definita	o	o	o	o	o	o	o	o					
Convolutispora mellita	o	o	o	o	o	o	o	o					
Apiculiretusispora fructicosa	o		o	o	o		o			o			
Calyptosporites perclarus	o	o	o	o	o	o	o			o			
Knoxisporites pristinus	o	o	o		o	o	o	o		o			
Auroraspora varia	o	o	o	o	o	o	o	o	o	o			
Auroraspora poljessica	o	o	o	o	o	o	o	o	o	o			
Aneurospora greggsii var. minuta	o	o	o	o	o	o	o	o	o	o	o		
Vallatisporites vallatus var. hystricosus	o	o	o	o	o	o	o	o			o	o	
Pulvinispora depressa	o	o	o	o	o	o	o		o	o	o	o	
Aneurospora incohata	o	o			o				o	o		o	
Grandispora echinata	o								o	o	o	o	
Ambitisporites cf. avitus	o		o							o		o	
Streelispora distincta	o	o	o	o		o		o				o	
Auroraspora solisorta	o	o	o	o	o		o		o	o	o		o
Synorisporites flexuosus	o	o	o	o	o	o	o	o	o		o	o	o
Calamospora pedata	o				o							o	o
Retusotriletes concretus	o				o							o	o
Synorisporites variegatus	o	o	o	o	o	o	o	o		o			o
Calamospora nigrata	o	o			o	o			o	o	o		o
Auroraspora pallida	o		o		o	o	o		o	o	o	o	o
Streelispora catinata	o	o	o	o	o	o	o	o	o	o			o
Punctatisporites minutus	o	o		o	o	o	o	o	o	o	o		o
Punctatisporites glaber	o	o	o	o	o	o	o	o	o	o	o	o	o
Aneurospora greggsii	o	o	o	o	o	o	o	o					o
Apiculiretusispora plicata	o		o	o	o		o	o	o			o	o

Direction of younging →

Raistrickia baculosa		o	o		o								
Punctatisporites stabilis		o			o	o							
Retispora ledpidophyta var. granda		o					o						
Auroraspora commutata		o	o	o	o	o	o	o					
Lophozonotriletes curvatus		o	o				o	o					
Synorisporites richardsonii		o							o				
Retispora lepidophyta		o	o		o		o		o				
Spelaeotriletes densatus		o	o	o	o		o			o			
Punctatisporites platirugosus		o	o	o				o			o	o	o
Verrucosisporites microtuberosus		o					o	o					o
Rhabdosporites parvulus			o										
Emphanisporites rotatus			o										
Auroraspora versabilis			o	o	o		o	o					
Auroraspora varia var. multifaria			o		o	o	o	o					
Retusotriletes sp.			o						o	o			
Raistrickia ampullaceae			o	o	o			o			o		
Ancyrospora multifurcata			o		o		o	o	o	o	o	o	o
Auroraspora tarquata			o		o				o	o	o	o	o
Grandispora echinula				o							o		
Auroraspora callosa				o							o	o	
Auroraspora submirabilis				o			o	o	o	o	o	o	o
Leiotriletes ornatus					o	o		o		o			
Dibolisporites sp.						o	o						
Acanthotriletes sp.						o							o
Hystricosporites porcatus							o						
Hystricosporites mitratus							o	o					
Hystricosporites sp. aff. porrectus							o				o	o	
Grandispora macroseta									o				
Spelaeotriletes microverrucosus									o				
Retusotriletes goensis									o	o		o	
Retusotriletes caperatus									o	o	o		
Samarisporites kedoae									o	o	o		o
Ancyrospora neograndispinosa										o		o	o
Samarisporites sp. cf. S. kedoae											o		
Auroraspora sp.											o		
Geminospora lemurata													o
Dictyotriletes cf. trivialis													o
Acanthotriletes horridus var. minuta													o
Ancyrospora acadensis													o

Hill and Hamlet Quadrangle Sections are remarkably similar qualitatively, although the rocks differ in lithology. It can be suggested that the spores in them were derived from a common vegetational source on the margin of the sedimentary basin and were contemporaneous.

In summary, the miospore assemblages obtained from the sediments of the Bush Hill and Hamlet Quadrangle Sections are assigned to the HL Zone. The palynological evidence suggests the upper Famennian Fa2d age for these sections.

COMPARATIVE PALYNOLOGY OF THE BUSH HILL AND POPE HOLLOW SECTIONS

Distribution of all the miospore forms recognised in both of these sections together with the ranges of restricted species, which are and may prove to be of potential value as stratigraphical indicators, are plötted in Table 3.

The miospore sequences from the two sections reflects overlap in that the assemblages yielded from the Bush Hill Section are clearly comparable with those recorded from the Pope Hollow Section although the latter are younger in age. It is relevant to indicate here the extent of similarities and differences.

The miospore assemblages obtained from these sections have been assigned to *Vallatisporites vallatus* var. *hystricosus* (Winslow) Clayton *et al.* 1977 - *Retispora lepidophyta* (Kedo) Playford 1976 Assemblage Zone because of the continuous occurrence of the index fossils.

Eight samples from the Chadakoin Formation, together with same amount of material indicated in text Fig.1, as undifferentiated Cattaraugus Formation are approximately 70kms. apart. Material from the Chadakoin Formation belongs to northern Pennsylvania exposed at approximately 3kms. East of Smethport, Road cut on route 6 and the other, containing specifically more or less identical assemblage, is from New York state outcropped along boundary between Carroll and South Valley Townships, Jamestown Quadrangle. The area at Pennsylvania called Bush Hill Section while that of New York known as Pope Hollow Section.

Fifty-five species have been recorded from the Pope Hollow Section. The material from the Bush Hill Section yielded sixty-five species of spores. Of the 80 species recorded from two sections, only 40 are common to both assemblages. Fifty percent species are regarded as common to both the Bush Hill and Pope Hollow Sections (Table 6). Following points could be forwarded for such an unequal balance in the species distribution. Firstly, most of the rest are confined to either sections. Secondly, some of the forms terminate stratigraphically within the Bush Hill Section, while others are indeterminate at specific level. These factors are apparently controlled by state of preservation of plant microfossils influenced by depositional environments which are entirely different in both of these areas.

The prolific and highly varied assemblages of the Bush Hill Section is marked by abundant representatives of species *Aneurospora greggsii* (McGregor) Streel in Becker *et al.* 1974, and *Auroraspora varia* var. *multifaria* Ahmed 1980 which were quantitatively determined accounts for up to 43.5 percent and 39 percent respective-ly. Both of these elements are either absent or less than one percent as encountered in case of sampls from the Pope Hollow Section. This factor could be environmentally controlled (Tschudy 1969, p105).

In the Bush Hill Section average percentage of *Vallatisporites vallatus* var. *hystricosus* (Winslow) Clayton *et al.* 1977 present is only 7 percent whereas *Retispora lepidophyta* (Kedo) Playford 1976 was rarely encountered in the counts of 500 specimens. This section yielded abundant and in many cases well preserved miospores. The microfossils that could not be identified due to various reasons i.e. squashed, collapsed or ruptured nature of exine or partly covered with organic tissue, range 4-10 percent of the total assemblages. Other commonly dominant constituents include *Auroraspora prostata* Ahmed 1980, *A. prostata* var. *elongata* Ahmed 1978, *A. prostata* var. *prostata* Ahmed 1980, *Apiculiretusispora plicata* (Allen) Streel 1967, *Aneurospora greggsii* var. *minuta* Ahmed 1978, *Synorisporites flexuosus* (Jush) Richardson & Ahmed 1988, *S. variegatus* Richardson & Ahmed 1988, *Knoxisporites literatus* (Waltz) Playford 1963, *K. pristinus* Sullivan 1968, *Punctatisporites glaber* (Naumova) Playford 1962, *Aneurospora incohata* (Sullivoan) Streel in Becker *et al.* 1974, *Rhabdosporites parvulus* Richardson 1965, *Biharisporites parviornatus* Richardson 1965 and *Streelispora catinata* (Higgs) Ahmed 1988.

No acritarchs have been observed in this section showing a strong evidence of non-marine influence and deposition was entirely in continental regime.

By comparison with the material from Bush Hill, assemblages from the Pope Hollow Section are impoverished and the state of preservation is also poor. Most of the microfossils, are highly carbonized and identification is frequently only possible at suprageneric level. The miospores at certain horizons constitute up to 90 percent of the miospore/marine microplankton assemblage indicating for some of the samples a near shore environment. However, at specific level indeterminate elements comprised up to 30 percent in some of the samples. Acritarchs have frequently been encountered throughout the section and comprise up to 24 percent of the total assemblage; 10 percent being sphaeromorphitae, 8 percent acanthomorphitae and 6 percent

Table 3
Stratigraphical ranges of all the miospores recorded from the Bush Hill and Pope Hollow Sections.

MIOSPORE SPECIES	BUSH HILL SECTION ELLICOTT MEMBER								POP HOLLOW SECTION CATTARAUGUS Fm.							
	NY96A	NY96B	NY96C	NY96D	NY96E	NY96F	NY96G	NY96H	US6A	US6B	US6C	US6D	US6E	US6F	US6G	US6H
Raistrickia clavata	o	o														
Auroraspora Papillara	o	o														
A. cf. Papillara	o	o														
Retusotriletes cf. concinnus	o	o	o													
Pulvinispora quasilabrata	o	o	o	o												
Apiculiretusispora fructicosa	o	o	o	o	o											
Calamospora pedata	o				o											
Calamospora liquida	o	o	o		o			o								
Biharisporites parviornatus	o	o	o	o	o	o	o	o								
Auroraspora prostata	o	o	o	o	o	o	o	o								
Auroraspora prostata var. prostata	o			o	o			o								
Auroraspora prostata var. elongata	o				o		o	o								
Apiculiretusispora plicata	o		o	o	o		o	o								
Knoxisporites literatus	o	o		o		o		o	o			o				
Streelispora distincta	o	o	o	o		o		o				o				
Synorisporites variegatus	o	o	o	o	o	o	o	o	o	o	o	o				
Knoxisporites pristinus	o	o	o		o	o	o	o					o			
Auroraspora varia	o	o	o	o	o	o	o	o		o			o			
Convolutispora definita	o	o	o	o	o	o	o	o	o			o		o		
Verrucosisporites maculosus	o	o	o				o	o		o				o		
Streelispora catinata	o	o	o	o	o	o	o	o			o	o		o		
Grandispora echinata	o								o	o	o	o		o		
Aneurospora greggsii	o	o	o	o	o	o	o	o			o	o	o	o	o	
Punctatisporites minutus	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Punctatisporites glaber	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Aneurospora incohata	o	o			o								o	o	o	o
Ambitisporites cf. avitus	o		o		o	o	o								o	o
Auroraspora pallida	o		o		o	o	o								o	o
Retusotriletes concretus	o			o			o	o			o				o	o
Calamospora nigrata	o	o			o	o				o			o	o		o
Auroraspora poljessica	o	o	o	o	o	o	o	o					o		o	o
Pulvinispora depressa	o	o	o	o	o	o	o		o	o	o	o	o			o
Calyptosporites perclarus	o	o	o	o	o	o	o				o	o	o	o		o
Auroraspora solisorta	o	o	o	o	o		o			o	o	o	o	o	o	o
Aneurospora greggsii var. minuta	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Synorisporites flexuosus	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Vallatisporites vallatus var. hystricosus	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o

Direction of younging →

Raistrickia baculosa		o	o		o											
Punctatisporites stabilis		o			o	o										
Lophozonotriletes curvatus		o	o				o	o								
Auroraspora commutata		o	o	o	o	o	o	o								
Retispora ledpidophyta var. granda		o					o		o							
Verrucosisporites microtuberosus		o					o	o			o					
Punctatisporites platirugosus		o	o	o				o					o			
Synorisporites richardsoni		o										o	o			
Retispora lepidophyta		o	o		o		o		o		o		o			o
Retusotriletes sp.			o													
Auroraspora versabilis			o	o	o		o	o	o							
Raistrickia ampullaceae			o	o	o			o	o							
Emphanisporites rotatus			o									o	o			
Auroraspora tarquata			o		o						o	o		o		
Auroraspora varia var. multifaria			o		o	o	o	o						o	o	
Ancyrospora multifurcata			o									o	o		o	
Rhabdosporites parvulus			o						o		o	o	o	o	o	o
Auroraspora callosa				o												
Grandispora echinula				o					o	o	o	o		o		
Auroraspora submirabilis				o			o	o	o	o	o			o	o	o
Leiotriletes ornatus					o	o		o								
Acanthotriletes sp.					o											
Dibolisporites sp.					o	o										
Hystricosporites sp. aff. porrectus							o									
Hystricosporites porcatus							o									
Hystricosporites mitratus							o	o								
Dictyotriletes sp.									o			o	o			
Ancyrospora neograndispinosa									o	o	o		o	o		
Spinozonotriletes sp.									o				o			
Vallatisporites vallatus var. major										o						
Grandispora corunata										o	o		o			
Retusotriletes goensis										o	o		o			
Ancyrospora acadensis										o	o	o	o	o		
Acanthotriletes horridus var. minuta											o		o	o		o
Retusotriletes caperatus											o	o	o	o		o
Grandispora macroseta												o	o	o		
Convolutispora vermiformis													o			
Auroraspora multirugata													o			
Auroraspora commutata var. major													o			
Emphanisporites cf. annulatus													o			
Spore type													o			
Grandispora sp. cf. G. Spinosa														o		
Auroraspora micromanifesta																o

Table 4
Stratigraphical ranges of all the miospores recorded from the Bush Hill and Lewis Run Sections.

MIOSPORE SPECIES	BUSH HILL SECTION ELLICOTT MEMBER								LEWIS RUN SECTION CATTARAUGUS Fm			
	NY96A	NY96B	NY96C	NY96D	NY96E	NY96F	NY96G	NY96H	NY95A	NY95B	NY95C	US7
Raistrickia clavata	o	o				Direction of younging →						
Auroraspora Papillara	o	o										
A. cf. Papillara	o	o										
Retusotriletes cf. concinnus	o	o	o									
Pulvinispora quasilabrata	o	o	o	o								
Calamospora pedata	o				o							
Apiculiretusispora fructicosa	o		o	o	o							
Calyptosporites perclarus	o	o	o	o	o	o	o					
Calamospora pedata	o	o	o		o			o				
Auroraspora prostata	o	o	o	o	o	o	o	o				
Auroraspora prostata var. prostata	o			o	o			o				
Auroraspora prostata var. elongata	o				o		o	o				
Knoxisporites literatus	o	o		o		o		o				
Knoxisporites pristinus	o	o	o		o	o	o	o				
Convolutispora definita	o	o	o	o	o	o	o	o				
Biharisporites parviornatus	o	o	o	o	o	o	o	o				
Streelispora distincta	o	o	o	o		o		o				
Leiotriletes ornatus	o		o	o	o		o	o				
Retusotriletes concretus	o			o			o	o	o			
Grandispora echinata	o								o			
Auroraspora varia	o	o	o	o	o	o	o	o	o			
Aneuraspora greggsii	o	o	o	o	o	o	o	o	o	o		
Synorisporites variegatus	o	o	o	o	o	o	o	o		o		
Verrucosisporites maculosus	o	o	o				o	o			o	
Pulvinispora depressa	o	o	o	o	o	o	o				o	
Ambitisporites cf. avitus	o		o						o	o	o	
Aneurospora greggsii var. minùta	o	o	o	o	o	o	o	o	o	o	o	
Streelispora catinata	o	o	o	o	o	o	o	o	o	o	o	
Punctatisporites minutus	o	o	o	o	o	o	o	o	o	o	o	o
Punctatisporites glaber	o	o	o	o	o	o	o	o	o		o	o
Aneurospora incohata	o	o			o				o			o
Auroraspora pallida	o		o		o	o	o		o			o
Auroraspora solisorta	o	o	o	o	o		o					o
Synorisporites flexuosus	o	o	o	o	o	o	o	o	o		o	o

Calamospora nigrata	o	o			o	o						o
Auroraspora poljessica	o	o	o	o	o	o	o	o				o
Convolutispora mellita	o	o	o	o	o	o	o	o				o
Vallatisporites vallatus var. hystricosus	o	o	o	o	o	o	o	o	o	o	o	o
Punctatisporites stabilis	o	o			o	o						
Retispora ledpidophyta var. granda	o	o					o					
Punctatisporites platirugosus		o	o	o				o				
Lophozonotriletes curvatus		o	o			o	o					
Auroraspora commutata		o	o	o	o	o	o	o				
Spelaeotriletes densatus		o	o	o	o		o		o	o		
Retispora lepidophyta		o	o		o		o				o	
Verrucosisporites microtuberosus		o					o	o			o	
Synorisporites richardsoni		o									o	
Raistrickia baculosa		o	o		o						o	o
Retusotriletes sp.			o									
Auroraspora versabilis			o	o	o		o	o				
Raistrickia ampullaceae			o	o	o			o				
Auroraspora varia var. multifaria			o		o	o	o	o				
Auroraspora tarquata			o		o				o			
Rhabdosporites parvulus			o						o	o		o
Emphanisporites rotatus			o						o			o
Ancyrospora multifurcata			o		o		o	o	o			o
Auroraspora callosa				o								
Auroraspora submirabilis				o			o	o				
Grandispora echinula				o						o		
Leiotriletes ornatus					o	o		o		o		
Acanthotriletes sp.						o						
Dibolisporites sp.						o	o		o			
Hystricosporites sp. aff. porrectus							o					
Hystricosporites mitratus							o	o				
Hystricosporites porcatus							o					o
Ancyrospora acadensis									o			
Punctatisporites solidus									o			
Retusotriletes caperatus									o	o		
Convolutispora sp. aff. V. congestus											o	
Convolutispora vermiformis												o
Acanthotriletes horridos var. minuta									o			

Table 5:

A Checklist of Miospore observed from five of the Sections during the present investigation.

BRICK QUARRIES	BUSH HILL	HAMLET QUADRANGLE	POPE HOLLOW	LEWIS RUN	SECTIONS / MIOSPORE SPECIES
o					1. Ancyrospora ancyrea var. ancyrea
o					2. Auroraspora pseudocrista
o	o	o			3. Hystricosporites sp. aff. Porrectus
	o	o	o		4. Leiotriletes ornatus
o		o	o		5. Ancyrospora neograndispinosa
o	o	o	o	o	6. Auroraspora torquata
o	o	o	o	o	7. Streelispora catinata
o	o	o	o	o	8. Punctatisporites minutus
o	o	o	o	o	9. Punctatisporites glaber
o					10. Samarisporites inusitatus
o	o	o	o	o	11. Aneurospora greggsii
	o		o	o	12. Emphanisporites rotatus
o	o	o	o	o	13. Ancyrospora multifurcata
		o	o		14. Retusotriletes goensis
o	o	o	o	o	15. Grandispora echinula
o	o	o	o	o	16. Aneurospora incohata
o	o	o			17. Apiculiretusispora plicata
o					18. Dictyotriletes sp.
o	o	o	o		19. Punctatisporites platirugosus
o	o	o	o	o	20. Grandispora echinata
	o				21. Camptotriletes verrucosus
o	o	o	o	o	22. Aneurospora greggsii var. minuta
o	o	o			23. Retusotriletes sp.
o	o		o	o	24. Ambitisporites cf. avitus
o	o	o	o		25. Streelispora distincta
			o	o	26. Convolutispora vermiformis
o		o	o	o	27. Ancyrospora acadensis
o	o				28. Leiotriletes tortilus
	o	o			29. Calamospora pedata
o		o			30. Samarisporites kedoae
o	o	o	o		31. Auroraspora submirabilus
o	o	o	o	o	32. Auroraspora varia
o	o	o	o	o	33. Auroraspora pallida
	o	o	o	o	34. Verrucosisporites microtuberosus
o	o	o	o	o	35. Auroraspora solisorta
o	o	o	o	o	36. Synorisporites flexuosus
o	o	o	o		37. Knoxisporites sp. cf. R. Crassus
	o				38. Punctatisporites stabilis
				o	39. Convolutispora sp. aff. V. Conjestus
o	o	o	o	o	40. Retusotriletes concretus
o		o	o	o	41. Acanthotriletes horridus var. minutus
	o	o	o	o	42. Synorisporites variegatus
o					43. Rhabdosporites langi
o		o	o		44. Grandispors macroseta
o	o	o	o	o	45. Calamospora nigrata
o			o		46. Auroraspora micromanifesta
o	o	o			47. Apiculiretusispora fructicosa

o	o	o	o		48. Calyptosporites perclarus
o		o	o	o	49. Retusotriletes caperatus
o	o				50. Auroraspora commulata
o	o		o	o	51. Rhabdosporites parvulus
o	o	o			52. Acanthotriletes sp.
o	o	o			53. Auroraspora callosa
o			o		54. Grandispora corunata
o	o	o	o	o	55. Spelaeotriletes densatus
o	o	o	o	o	56. Pulvinispora depressa
o	o	o	o	o	57. Auroraspora poljessica
	o				58. Raistrickia clavata
	o				59. Auroraspora Papillara
	o				60. Auroraspora cf. Papillara
	o				61. Retusotriletes cf. concinnus
	o				62. Pulvinispora quasilabrata
	o				63. Clamospora liquida
	o				64. Biharisporites parviornatus
	o				65. Auroraspora prostata
	o				66. Auroraspora prostata var. prostata
	o				67. Auroraspora prostata var. elongata
	o		o		68. Knoxisporites literatus
	o	o	o		69. Knoxisporites pristinus
	o	o	o		70. Convolutispora definita
	o		o	o	71. Verrucosisporites maculosus
	o	o		o	72. Convolutispora mellita
	o	o	o	o	73. Vallatisporites vallatus var. hystricosus
	o				74. Lophozonotriletes curvatus
	o		o		75. Retispora lepidophyta var. granda
	o	o	o	o	76. Retispora lepidophyta
	o	o	o	o	77. Synorisporites richardsonii
	o			o	78. Raistrickia baculosa
	o		o		79. Auroraspora versabilis
	o	o	o		80. Raistrickia ampullacea
	o		o		81. Auroraspora varia var. multifaria
	o			o	82. Dibolisporites sp.
	o				83. Hystricosporites mitratus
	o			o	84. Hystricosporites porcatus
		o			85. Spelaeotriletes microverrucosus
		o			86. Samarisporites sp. cf. S. kedoae
		o			87. Auroraspora sp.
		o			88. Geminospora lemurata
		o			89. Dictyotriletes cf. trivialis
			o		90. Spinozotriletes sp.
			o		91. Vallatisporites vallatus var. major
			o		92. Auroraspora multirugata
			o		93. Auroraspora commutata var. major
			o		94. Inphanisporites cf. annulatus
			o		95. Spore type
			o		96. Grandispora sp. cf. G. Spinosa
				o	97. Puntatisporites solidus

polygonimorphitae. Simple laevigate miospores are profusely represented whereas sculptured forms are rare.

This section contains, in addition, a number of distinctive forms that were not encountered in the material from the Bush Hill Section. The distinctive forms are as follows:

Retusotriletes caperatus Ahmed 1978, *R. goensis* Lele & Streel 1969, *Dictyotriletes* Ahmed 1978, *Convolutispora vermiformis* Hughes & Playford 1961, *Emphanisporites* cf. *annulatus* McGregor, *Vallatisporites_vallatus* var. *major* Ahmed 1978, *Auroraspora multirugata* (Kedo) Ahmed 1978, *Ancyrospora neograndispinosa* Ahmed 1991 and *A. acadensis* Ahmed 1991, *Auroraspora commutata* var. major (Kedo) Ahmed 1978, *Grandispinosa* sp. cf. *G. spinosa* Hoffmeister, Staplin & Malloy in Massa & Moreau-Benoit 1976 and *Auroraspora micromanifesta* (Hacquebard) Richardson 1960.

Some other forms that are present in the Bush Hill Section but not observed in the Pope Hollow Section include *Lophozonotriletes curvatus* Naumova 1953, *Auroraspora prostata* Ahmed 1980 and its varieties, *A. callosus* (Kedo) Ahmed 1980, *A. papillara* (Kedo) Ahmed 1980 *Hystricosporites mitratus* Allen 1965, *H. porcatus* (Winslow) Allen 1965 and *H.* sp. aff. *H. porrectus* (Balme & Hassel) Allen 1965.

In both areas the species *Vallatisporites vallatus* var. *hystricosus* (Winslow) Clayton *et al.* 1977 is consistently, and *Retispora lepidophyta* (Kedo) Playford 1976 is less consistently present. Morphologically identical forms are encountered including *R. lepidophyta* var. *granda* (Kedo) Ahmed 1988 in both sections. Both of these forms have been observed having size range varying from 50-158μ m. The only difference recorded is the state of preservation. As has been discussed above the Bush Hill Section yielded well preserved miospores while in case of the Pope Hollow Section the preservation is rather corroded, and darker and in an inferior state of preservation when compared with material from the Bush Hill Section.

It can be concluded, keeping in mind the differences and points of similarities discussed, that discrepancies in stratigraphic ranges may be real in that these may reflect biochronological variations between the two geographically separated areas as well as lithologically distinct units; (Bush Hill Section of Chadakoin Formation belongs to Arkwright Group, Pope Hollow Section of Cattaraugus Formation belongs to Conewango Group). The paucity of certain species reflects the discontinuous distribution in its stratigraphical range.

On the other hand, since the two assemblages reflect two different environments, it would be rather reasonable to interpret that the absence of certain taxa including laevigate pseudo-saccate miospores, some elements of megaspore dimension and a few species of anchor spined miospores in the Pope Hollow Section is because of distinct off shore depositional environment rather than a distinct temporal disparity.

COMPARATIVE PALYNOLOGY OF THE BUSH HILL AND LEWIS RUN SECTIONS

Table 4 shows the distribution of miospores observed from material analysed from the Bush Hill (Ellicott member) and the Lewis Run (Cattaraugus Formation) Sections.

The miospore assemblages obtained from these sections have been assigned to *Vallatisporites vallatus* var. *hystricosus - Retispora lepidophyta* (HL) Assemblage Zone, because of the continuous occurrence of the index fossils.

A total of thirty-eight species are apparently confined to the Lewis Run assemblage (Table 6). Of the 71 species recorded from two sections, only 32 are common to both assemblages. Forty-five percent species have been regarded as common to both the Bush Hill and Lewis Run assemblages (Table 6).

Table 6

A comparison in number of species from the Upper Devonian of New York State and Pennsylvania with those from other parts of the world.

AREAS	NUMBER OF SPECIES	COMMON WITH NEW YORK STATE AND PENNSYLVANIA	ENDEMIC	PALAEOLATITUDE
POLAND	11	4	1	3°5
AUSTRALIA	53	8	24	10°5
THE BRITISH ISLES	43	26	5	12°5
BELGIUM	70	25	4	15°5
NEW YOR STATE AND PENNSYLVANIA	97	-	-	22°5
NORTH AFRICA	145	22	11	33°5

By comparison with material from the Bush Hill, assemblages from the Lewis Run are rather corroded, darker and in an inferior state of preservation. Pyritized specimens are common. Most of the microfossils are highly carbonized. The miospores which were quantitatively determined accounts for between 54 and 78 percent of the miospore/marine microplankton assemblages. Indeterminate elements comprised up to 20 in one of the samples. Acritarchs have freq-uently been encountered throughout the section and comprise up to 30 percent of the total assemblage.

In the Lewis Run assemblage average percentage of *Vallatisporites vallatus* var. *hystricosus* present is only 2 percent whereas *Retispora lepidophyta* was encountered only from one sample.

The Lewis Run assemblage contains, in addition, a few miospore forms that have not been encountered in material from the Bush Hill. Those are as follows:

Retusotriletes caperatus Ahmed 1978, *Punctatisporites solidus* Hacquebard 1957, *Convolutispora* sp. aff. *verrucosisporites congestus* Playford 1964, *Convolutispora vermiformis* Hughes & Playford 1961, *Ancyrospora acadensis* Ahmed 1991.

The Lewis Run microflora yielded three species that have been reported from the Lower Carboniferous of Eastern Canada (Horton Group). These are *Punctatisporites solidus* Hacquebard 1957, *Convolulisporites* sp. aff., *Verrucosisporites congestus* Playford 1964 and *C. vermiformis* Huggs & Playford 1964. The last named has also been recorded from the Lower Carboniferous of Spitsbergen (Hughes & Playford 1961, Playford 1962). *P. solidus* Hacquebard 1957 and *C. vermiformis* Hughes & Playford 1964 are dominantly Carboniferous species but have been reported from the Upper Devonian. The presence of above mentioned species is not an indicative of Carboniferous age but of the early appearance of some Carboniferous forms.

A checklist of miospores recorded from five of the sections during the present investigation is given in table 5. The plynological contents of the Walnut Creek Section and the biostratigraphical studies of this area would be discussed in the next paper.

ACKNOWLEDGEMENT

The author is grateful to Dr. John B. Richardson of the British Museum (Natural History) London for suggestions and critically reading the manuscript.

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Geol. Bull. Punjab Univ. 33 & 34, 1999.

GEOTECHNICAL PROPERTIES OF BALAMBAT NORITE, PANJKORA DIORITE AND HORNBLENDITE OF TIMARGARA AREA, DIR DISTRICT, NWFP.

BY

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Abstract:- *Gabbronorite, norite, diorite and hornblendite occur as very large to large deposits in the Kohistan Island Arc of Timargara area Dir district. These rocks are very fresh and compact at many places. Texturally Balambat norite and Panjkara diorite are fine to medium grained whereas hornblendite are medium to coarse grained. The rocks were tested to know their geotechnical properties for usefulness as building material and as polished dimension stones/slabs. The tests carried out are like absorption of water, soundness, compression/crushing strength. Absorption value of norite is 0.59% maximum, of diorite is 1.01%, and and that of hornblendite is 0.98%, soundness value for fine losses is 0.85%, 1.05% and 1.05% respectively for sieve size ¼". Unconfined compressive strength is 8644, 6483 and 6915 PSI respectively. These rocks take good to very good polish and are thus useful as decorative stones and for building purposes.*

INTRODUCTION

The use of different stones as facing material for concrete structures is increasing day by day, for this purpose mostly those stones are selected which show attractive appearance after polishing. Marble of varying colours has been in use for centuries, as a building material, because of its beautiful colours and attractive appearance, ease of quarrying and finishing. But the on going problem of air pollution and rain effects and trend of making multistoreyed concrete buildings have decreased its value as building stone, and as facing material. However, it is still in use as interior decorative stones.

Engineers and architects are now turning towards the decorative stones which could be used as facing material over concrete structures, for this purpose rocks which shows higher degree of polishing and resistance to weathering are thought to be favourable. The appearance of rocks after polishing is also kept in mind for this purpose.

The plutonic rocks like granites, gabbros, hornblendite and metamorphic rocks gneisses and amphibolite shows attractive appearance after polishing. The degree of polishing and resistance to chemical and thermal effects, have made these rocks valuable dimension stones.

Large deposits of norite, gabbronorite, diorite, tonalite, trondhjemite, adamellites, granites, porphyries and hornblendites are exposed covering an area of more than 300 sq. km in Timargara area of Dir district, NWFP. The blocks of these rocks are used as building stone in the area by local peoples. Realising the importance of these rocks as building material and their probable use as polished dimension stones/slabs, studies were carried to find out possibility of the rocks exposed in the area. Therefore, three representative rock samples of Balambat norite, Panjkora diorite and hornblendite were subjected to different tests like absorption of water, soundness test, sieve analysis, compressive strength and crushing strength were carried out to analyse the geotechnical properties of these rocks to evaluate their tests values as a building material as well as facing material.

In the following will be discuss different engineering tests which were carried out to the selected samples, to evaluate their value as a building and dimension stones.

GEOLOGICAL SETTING

The area under investigation is part of the Kohistan Island Arc lying in westernmost corner of the complex (Fig.1). The rocks of Kohistan are well exposed in Timargara area. The geology of the area can be divided into three stratigraphic provinces which are juxtaposed to each other due to tectonic movements (Ashraf and Hamood,

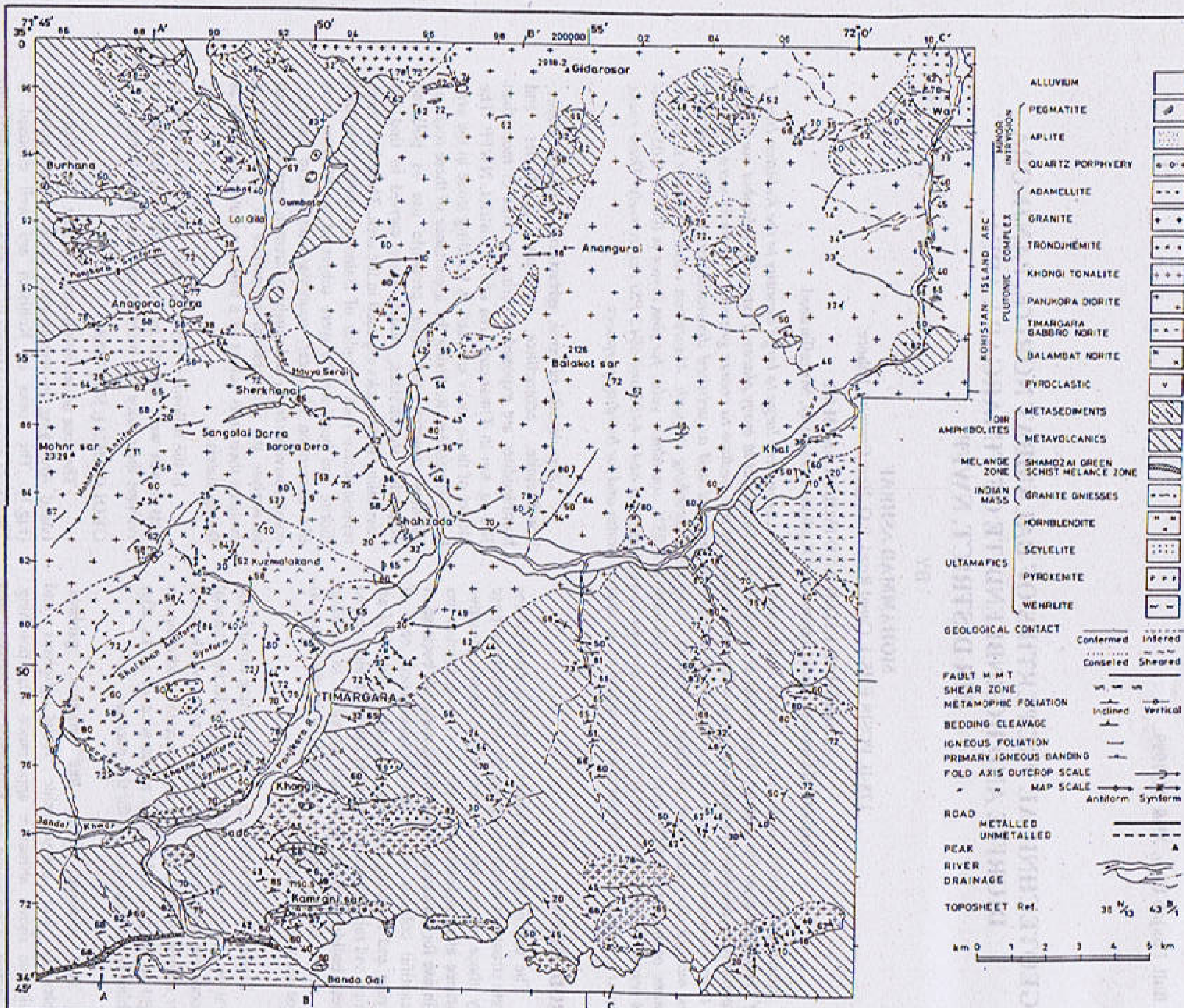

Fig. 1 Geological Map of Timargara Area, District Dir, N.W.F.P.

1997). These major tectonic elemets are Indopak continental mass, Shamozai greenschist melange and rocks of the Kohistan Island Arc. The Indopak mass consists of gneisses underplating the Kohistan. The Shamozai melange consist of ultramafics like serpentinized dunite and wherlite, talc carbonates, carbonates, phyllites etc. The phyllites dominate in the melange with S_1 and S_2 foliations

The eastern and central portion of the Kohistan has been studied by and interpreted by Dewey and Bird (1970), Crawford (1974), Powell and Conaghan (1973), Gansser (1974), and subsequently applied to the area of Kohistan by Tahirkheli et al. (1979), Powell (1979), Chaudhry et al. (1974a,b, 1983 and 1984), Butt et al. (1980), Jan and Howie (1981), Kazmi et al. (1984), Coward et al. (1986), Baig (1989), Miller et al. (1991), Khan et al. (1997) and Ashraf and Hamood (1997).

The rocks for geotechnical studies are part of the Kohistan complex occurring as large plutons in the case of Balambat norite and Panjkora diorite whereas small to medium size hornblendite bodies occur as plutons, sills and dykes. The norite and gabbronorite are regarded as the oldest plutons in the area underplating the Dir amphibolites whereas diorites, tonalites, trondjhemite, granites, adamelites, aplites and pegmatites are the younger differentiates.

PETROGRAPHY

Petrography of the three rock types is also presented to know the nature of deletarious and innocous minerals present in them. The Balambat norite is quite fresh as compared to Panjkora diorite. Mineralogically norite contains Plagioclase (30-41%), orthopyroxene (16-35%) and clinopyroxene (7-10%) as major constituents. Quartz (1-5%), hornblende (0.5-4%), biotite (0.1-1%) and ore minerals (1-2%) are present as minor and accessories whereas sericite (4-11%), kaolinite (5-17%), epidote (0-1%), epidote (0-1%), uralite (1-5%) and talc (1-3%) are the common alteration products. The Panjkora diorite contain plagioclase (28-59%), hornblende (15-26%), orthopyroxene (0.5-8%), clinopyroxene (3-5%), quartz (5-16%), biotite (0.3-5%), rutite (0.1-1.8%), and other accessories like sphene, apatite and ore minerals. The hornblendite are very pure with hornblende (93-98%) with minor epidote, zoisite, chlorite etc.

TESTS

Following tests have been carried out to measure the durability of rocks as decorative stones for facing walls and as aggregate:-

1.Absorption, 2.Soundness, 3.Compressive strength, 4.Specific gravity, and 5.Degree of polishing (ASTM, 1986; Alexander, 1960; Franklin et al., 1989; Cook and Dancy, 1967).

Absorption

Absorption is the measure of the quantity of water which a rock sample will absorb when immersed in water. It was measured by the difference between the dry weight (W_1) of a sample and wet weight of sample after soaking (W_2). It is expressed in percentage by following formula:-

$$(W_2 - W_1)/W_2 \times 100$$

A low absorption value in turn means that rock has high resistance to weathering. These rocks have very low disintegration effect of frost action and chemical weathering (Blyth and de Freitas, 1974).

The representative rock samples of Balambat norite, Panjkora diorite and hornblendite were taken and kept in oven for 24 hours at 105°C, dry weight of the samples taken as W_1. After that the samples were immersed in water for 24 hours, after 24 hours the wet weight of samples (W_2) were measured after drying sample with damp cloth. The procedure was repeated for 48, 72 and 96 hours. The mean absorption values were calculated as illustrated in Table 1.

Table 1

Absorption Capacity of Balambat Norite, Panjkora Diorite and Hornblendite

Rock Name	(W_0)gms	(W_1)gms	Wet Weight (W_2)gms Time in Hr				Absorption Capacity=(W_2-W_1/W_2) x 100 Time in Hr			
			24	48	72	96	24	48	72	96
Balambat norite	320.1	319.4	320.5	321.0	321.2	321.3	0.343	0.498	0.56	0.59
Panjkora diorite	313.6	312.8	313.7	314.4	315.2	316.0	0.286	0.508	0.761	1.01
Hornblendite	272.7	272.2	273.0	274.5	274.5	274.9	0.293	0.693	0.837	0.982

W_0 - Original weight of the sample.

W_1 - Dry weight of the sample.

W_2 - Wet weight of the sample

From Table 1, it is clear that the maximum absorption value for Balambat norite is 0.59 wt%, for Panjkora diorite it is 1.01 wt%, and for hornblendite it is 0.98 wt%, showing that these rocks have low porosity. These plutonic rocks having absorption value less than 1% by weight can be used as dimension stone because the rocks having low absorption values has high resistance to weathering (Blyth and de Freitas, 1974). This suggests that the absorption capacities of the tested rocks are in the range which permits their use as facing tiles and dimension stones.

Soundness

The soundness of rocks samples is its resistance against weathering. The soundness test is carried out in order to judge the stability and durability of rocks against weathering agencies.

To estimate soundness a seven cycle test proposed by ASTM, (1986), was conducted on representative samples of Balambat norite, Panjkora diorite and hornblendite. In the test an accelerated weathering condition was produced in laboratory by socking the specimen in saturated solution of sodium sulphate (Na_2SO_4) and by subjecting them to alternating wet and dry conditions.

A saturated solution of sodium sulphate was prepared in water at a temperature of about 25° to 30°C. The rock specimens were crushed and graded to 1", ½" and ¾" mesh in size by sieving. The 500 gm of 1" mesh size, 300 gm of ½" mesh size and 200 gm of ¾" mesh size was taken for the test. Each fraction was thoroughly washed and dried. The proper weight of the sample for each fraction (i.e. 1", ½" and ¾" mesh sizes) were weighted and placed in separate container for the test.

The samples were immersed in the prepared solution of sodium sulphate for 24 to 168 hours. The tests contain seven cycles and each cycle completes after 24 hours. In each cycle the container is covered to reduce evaporation. The samples were removed from the solution after every 24 hours, were washed and dried for about 15 minutes at room temperature and then were placed in the oven at temperature 105°C. The samples were dried to a constant weight, were allowed to cool at room temperature and their weight was recorded. The constant weight of dried samples before soaking into the solution was taken as X_1 and the constant weight of dried sample after washing and oven drying was taken as X_2. The loss of fines produced after every cycle of test was calculated in percentage by Formula = $(X_1 - X_2)/X_2 \times 100$. Seven cycles of tests have been carried out.

The amount of fines produced after each cycle of soundness test is given in Tables 2,3 and 4 showing that in Balambat norite total loss of fines is 0.12% that was produced in 1" mesh size, 0.16% in ½" mesh size and 0.85% in ¾" mesh size in aggregates of norite. The value of losses in all the fractions are decreasing with time showing the rock is remarkably resistant and sound.

Table 2

Soundness test for Balambat Norite

Time (Hr)	Sieve Size 1			Sieve1/2"			Sieve3/4"		
	X1(gm)	X2 (gm)	Loss (%)	X1(gm)	X2 (gm)	Loss (%)	X1(gm)	X2 (gm)	Loss (%)
24	499.8	499.5	0.060	300	299.7	0.10	199.3	199.2	0.050
48	499.5	499.4	0.020	299.7	299.7	0.00	199.2	198.4	0.400
72	499.4	499.4	0.000	299.7	299.7	0.00	198.4	198.0	0.300
96	499.4	499.4	0.000	299.7	299.6	0.03	198.0	198.0	0.000
120	499.4	499.2	0.000	299.6	299.6	0.00	198.0	198.0	0.000
144	499.3	499.2	0.020	299.6	299.5	0.03	198.0	197.8	0.100
168	499.2	499.2	0.000	299.5	299.5	0.00	197.8	197.8	0.000
	Total Loss 0.12%			Total Loss 0.16%			Total Loss 0.85%		

Table 3
Soundness test for Panjkora Diorite

Time (Hr)	Sieve Size 1			Sieve1/2"			Sieve3/4"		
	X1(gm)	X2 (gm)	Loss (%)	X1(gm)	X2 (gm)	Loss (%)	X1(gm)	X2 (gm)	Loss (%)
24	499.9	498.9	0.20	299.5	299.4	0.03	199.6	198.8	0.40
48	498.9	498.5	0.08	299.4	298.6	0.27	198.8	198.5	0.15
72	498.5	498.4	0.02	298.6	298.6	0.00	198.5	198.4	0.05
96	498.4	498.1	0.06	298.6	298.5	0.06	198.4	198.2	0.10
120	498.1	498.0	0.02	298.5	298.4	0.06	198.2	198.0	0.10
144	498.0	497.9	0.02	298.4	298.2	0.06	198.0	197.9	0.05
168	497.9	497.4	0.10	298.4	298.1	0.03	197.9	197.5	0.20
	Total Loss 0.50%			Total Loss 0.5%			Total Loss 1.05%		

Table 4
Soundness test for Hornblendite

Time (Hr)	Sieve Size 1			Sieve1/2"			Sieve3/4"		
	X1(gm)	X2 (gm)	Loss (%)	X1(gm)	X2 (gm)	Loss (%)	X1(gm)	X2 (gm)	Loss (%)
24	499.9	499.5	0.08	299.5	298.6	0.30	199.7	199.5	0.10
48	499.5	499.4	0.02	298.6	298.5	0.03	199.5	199.4	0.05
72	499.4	497.9	0.30	298.4	298.4	0.03	199.5	199.4	0.00
96	497.9	497.8	0.02	298.4	298.3	0.00	199.4	199.1	0.15
120	497.8	497.6	0.04	298.4	298.3	0.03	199.1	199.1	0.00
144	497.6	497.5	0.02	298.3	298.2	0.03	199.1	198.8	0.15
168	497.5	497.4	0.02	298.2	297.8	0.13	198.8	197.6	0.60
	Total Loss 0.50%			Total Loss 0.55%			Total Loss 1.05%		

X_1 - The weight of sample before solutioning.
X_2 - The weight of sample after solutioning washing and drying.
Loss - Loss of fines after solutioning washing and drying calculated by the Formula.

In Panjkora diorite total losses of fines is about 0.50% produced in 1" sieve size, 0.52% is produced in ½" sieve size and 1.05% is produced in ¾" sieve size. The value of losses of fines in all fractions decreased after second cycle of test. Most of the losses of fines were produced in second cycle of the test, after second cycle the value of losses of fines decreased.

In hornblendite total losses of fines is about 0.50% that were produced in 1" sieve size, 0.55% were produced in ½" sieve size and 1.05% were produced in ¾" sieve size. The value of fines progressively decreased with time, after the removal of most reactive material in the shape of fines in first cycle of test.

Compressive Strength

The compressive strength of rocks was measured to estimate their crushing strength, which helped in estimating whether the rock can be used as building material or not, assuming this we have measured the compressive strength of representative sample of Balambat norite, Punkora diorite and hornblendite.

The samples of Balambat norite, Panjkora diorite and hornblendite were cut by diamond cutter into cubes of 4" x 4", 4" x 4" and 3" x 3" respectively, and their surfaces were smoothened by grinder and vinyl liquid so that the load applied by the hydraulic compressive machine on the sample could be distributed equally.

The cubes of representative samples were weighed before testing and then subjected to the compressive test by a hand operated hydraulic compressive machine, which has measuring capacity of a maximum pressure of about 180 tons. The readings were noted at the appearance of first crack on the surface of the sample.

The results of compressive strength test are given in Table 5 which shows unconfined compressive strength value of norite, diorite and hornblendite in PSI.

Table 5
Compressive Strength of Balambat Norite, Panjkora Diorite and Hornblendite

Rock Name	Weight (lbs)	Area (sq/ft)	Crushing value (lbs)	UnconfinedCompressive Strength
Balambat norite	7.6058	0.09	110230	8644.17
Panjkora diorite	3.8360	0.06	55115	6483.19
Hornblendite	7.6058	0.09	66138	6915.33

The unconfined compressive strength of Balambat norite is 8644 PSI, Panjkora diorite is 6483 PSI and hornblendite is 6915 PSI. Showing that these rocks are strong enough to bear heavy load and could be used as material in heavy construction along with as decorative facing materials. The low values of unconfined compressive strength are due to alteration of plagioclase to kaolin and sericite in Panjkora diorite and larger size of crystals of the hornblendite.

Specific Gravity

It is the relative density of material. It is considered to be measure of strength and quality of the materials. That rocks having high specific gravity from 2.55 to above are considered to be a suitable for heavy construction work (Blyth and de Freitas, 1974).

The apparent specific gravity of representative sample of Balambat norite is 3.044 and effective specific gravity is 3.017. The apparent specific gravity of Panjkora diorite is 3.043 and effective specific gravity of that is 2.997. The apparent specific gravity of hornblendite is 3.102 and effective specific gravity is 3.056 calculated according to standard formula.

The values of specific gravity show these rocks are also suitable for heavy construction building materials and as facing materials.

Degree of Polishing

The degree of polishing of a rock reflects the texture and structure of rocks after the process of polishing. It is the assessment of the smoothness and appearance of a rock sample obtained after polishing. It depends upon the colour, texture, grain size, grain bonding and hardness of different mineral grains present in rocks. The three rock samples under study contain mineral grain which are compact, homogeneous and with hardness around 6-7 on Moho's scale shows good to excellent degree of polishing. Their polished surfaces are durable and do not need any emulsion coating even after several years of use.

To assess the degree of polishing for Balambat norite, Panjkora diorite and hornblendite, one representative sample of each rock type was selected. The fresh and unaltered samples of Balambat norite, Panjkora diorite and hornblendite were taken and were cut into small slabs by diamond saw cutter. The polishing of these samples were done by grinder using varying number of grinding wheels, one after another. Final finishing was done by smoothening the surface by using No.600 grade aluminium oxide abrasive paper.

The Balambat norite shows excellent degree of polishing, as compared to Panjkora diorite which shows good polished surface. Hornblendite also shows good and smooth polish surface.

DISCUSSION

It is clear from the above test that the mechanical properties of Panjkora diorite, Balambat norite and hornblendites exposed in the area are in the ranges which permit their use both as decorative stone and building material for heavy constructions. In addition to these properties following factors must also be kept in mind.

Reserves

The Balambat norite is exposed in an area of about 25 sq. km. In the Timargara area although most of the surface exposures seem to be kaolinized and affected by weathering but fresh and unaltered exposures of the rocks were observed near Islam Dheri and Balambat, where local peoples are quarrying it for the construction of their buildings. It is observed from these quarries that the weathered cover and over burden on the rocks is very thin and large blocks of rocks could be easily mined by ordinary methods of blasting. The joints in the rocks mostly cuts each other at about 70° to 120°C permitting the exploitation of blocks which may range in size from 1, 2 and 2.5m (i.e. spacing between joint at some station is 1 to 2.5m). The roof pendants of amphibolites were observed in the norite at some localities which might spoil the homogeneity of the rock.

The Panjkora diorite covers about 50% of the mapped area. Its fresh and unaltered exposures are present along the road from Khal to Wari from where it can be easily mined as many quarries were observed along the road. In this sections peoples are mining diorite to use it as aggregate and building material. Such type of small quarries were also observed along Timargara-Lal Qila road. The over burden and weathering cover in most of the localities are very thin therefore, there is no major hazard in its mining by open pit methods. The joint angles and spacing are similar as in Balambat norite, the only problem is the presence of roof pendants of amphibolite which were observed in it in many localities. Therefore, the concentration of roof pendants must be kept in mind before selecting a quarry site.

About 9 large bodies of hornblendites are exposed in the Timargara area most of which are easily approachable except two bodies in Lajbok Darra which are far away from any jeep track or road. The hornblendites bodies also have very little over burden or cover of weathered rock, joint spacings in the rocks are also favourable for quarrying large blocks.

Market Demand

The development in the cutting and polishing industry of dimension stone have acquired the ability to cut and polish hard rocks, due to which hard plutonic rocks like granite, gabbros and hornblendites could also be cut and polished. The texture of these rocks also give an attractive look after polishing. Due to these facilities and attractiveness most of the peoples associated with construction industries are paying attentions towards these stones. They mostly use them as polished slabs on concrete structures and floors instead of building blocks.

The trend for the use of hornblendites, granite, gabbros and other medium to coarse grained plutonic rocks which show good polishing and attractive appearance after polishing is also increasing in Pakistan. But most of the processed polished floor and wall tiles of these rocks are imported from Italy which costs Rs.400 to 1000 per square foot. Only few rock cutting industries are present in the country having ability to cut and polish these rocks. If we improve our rock cutting and polishing industry to facilitate the cutting and polishing of hornblendites, norites, gabbros, diorites and granite then we would not only be able to save enormous amount of foreign exchange used in the import of facing tiles but we would be able to export our processed mineral wealth in the form of large reserves of these rocks (i.e. hornblendites, norites, gabbronorite, diorites and granite) present in our country.

Availability of Water and Power

Timargara is linked to the main power grids of the country and electric power is supplied to nearly all the villages even present on the top. Water is also available all over the area which may be needed during cutting and polishing of stone.

ACKNOWLEDGEMENT

The authors are thankful to their students who extended help during the geological mapping and selection of the samples for geotechnical tests. They are also grateful to AJK University for financial help.

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ACKNOWLEDGEMENTS

The Association of Commonwealth Universities in UK financed the studies. All the petrogaphic studies and most of the analytical work were performed at the University of Leicester, UK. A. D Saunders, Department of Geology, University of Leicester (UK), and David Vaughan, Department of Geology, University of Machester (UK), are thanked for useful discussions and reading an earlier version of the manuscript.

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