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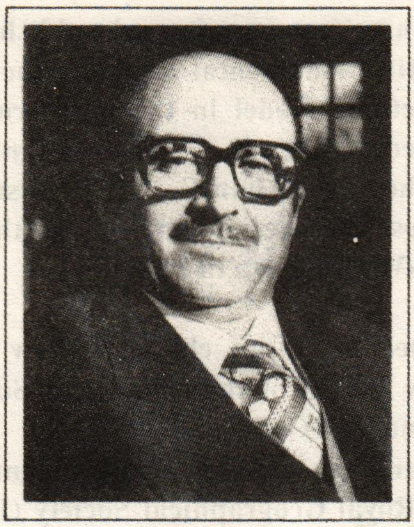
DEDICATED
TO
PROF. DR. R.A. KHAN TAHIRKHELI



LIFE SKETCH OF
PROFESSOR R. A. KHAN TAHIRKHELI

Prof. Dr. R.A. Khan Tahirkheli was born at Ghazi Haripur, Hazara in 1928. After graduation in geology from Muslim University, Aligarh in 1950 he joined the Geological Survey of Pakistan in 1951. In 1964, after earning his Ph.D from St. Andrews Scotland, his services were acquired by the University of Peshawar.

He joined the University of Peshawar in 1964 as Associate Professor and became Chairman, Department of Geology on August 22, 1964. In 1969 he was appointed as Professor. He succeeded in establishing the National Centre of Excellence in Geology in 1975 and served as founder Director till his retirement in 1988.

In 1982 he was offered the position of Vice Chancellor, University of Peshawar where he successfully completed a tenure of five years.

He was the editor of three monographs and published 120 papers at National and International level. His monumental work in the realm of geology is the establishment of a new tectonic model in the northern Pakistan by discovering Kohistan Island Arc trapped between the Indo-Pakistan and Eurasian Plates and locating a Himalaya megashear, the Main Central Thrust which occurs in Pakistan as Shontargali Thrust. These discoveries have solved the long standing issues of tectonic correlation of the NW Himalaya in Pakistan.

Besides, Dr. Tahirkheli is (i) an elected Fellow of Pakistan Academy of Sciences, (ii) an honourary Fellow of the Geological Society of America, (iii) an Adjunct Professor, Dartmouth College, USA, (iv) a Member of National Commission on Science and Technology, Government of Pakistan, (v) Lead Pakistani Scientists in the Royal Geographical Society (London) Expedition to the Karakorum in 1979, (vi) served as Vice Chairman of International Lithosphere Programme (UNESCO) Committee-6 pertaining to the Himalaya and the neighbouring region for five years and (vii) was appointed Chairman of the Specialists Committee in formulating fifth five years plan on exploration and development of minerals.

For his meritorious services in the field of Geological Sciences and for his work in the Karakorum, Himalaya and Hindukush, he was awarded Sitara-i-Imtiaz by the President of Pakistan in 1982.

INSTRUCTIONS TO THE CONTRIBUTORS OF THE KASHMIR JOURNAL OF GEOLOGY

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GEOCHEMICAL EVIDENCE FOR AN OCEANIC AFFINITY OF THE PANJAL VOLCANICS IN KAGHAN VALLEY, PAKISTAN

By

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ABSTRACT: The Panjal volcanic rocks in Kaghan area have been analysed for major and trace elements. These rocks have been altered and spilitized considerably because Na_2O varies from 0.38 to 6.4 wt. %. Inspite of alteration of these rocks the whole rock composition retains a strong igneous imprint (TiO_2 1.28 to 2.34%, P_2O_5 0.1 to 0.24%, Zr 77 to 179 ppm and Y 19 to 39 ppm). The abundance of incompatible and immobile elements when plotted on discrimination diagrams to infer tectonic setting, indicate geochemical signature of an ocean floor basalts. These rocks are transitional between within-plate to ocean floor basalts based on major and trace element abundances.

INTRODUCTION

The western and eastern limbs of Kashmir Hazara syntaxial bend in Kaghan and Azad Kashmir are characterized by Permian to Triassic basaltic volcanic rocks with intercalation of limestone bands.

In Kaghan area the Panjal volcanic rocks comprise the autochthonous fold belt of Wadia (1934, '1931). The older metasediments thrust onto the Panjal volcanics while volcanics thrust over the younger sedimentary rocks of Tertiary age (mostly Murree Formation). The volcanic belt extends southeast into Indian held Kashmir.

The tectonic environment in which the Panjal volcanic rocks were formed has been the subject of discussion. Principally, the three regimes have been described: within-plate flood basalts (Papritz and Rey, 1989; Humayan *et al.*, 1987; Honegger *et al.*, 1982) and ocean floor basalts (Khan and Ashraf, 1989; Ashraf and Khan, 1991; Butt *et al.*, 1985). Ghazanfar and Chaudhry (1984) described these rocks as ophiolite and island arc sequence in the Kaghan area. However, upto recent geochemistry of the Panjal volcanic rocks was poorly known and interpretation of a few chemical analyses resulting into rather ambiguous conclusions.

This paper presents geochemical data for the Panjal volcanic rocks collected from the Kaghan area (Fig. 1). The main objective is to discriminate and constrain the tectonic setting of the Panjal volcanic rocks in Kaghan area. Geochemical evidences are presented to infer tectonomagmatic environment of the Panjal volcanics in Kaghan area.

The Panjal volcanics lie in the Pir Panjal Range of the Lesser Himalaya. These rocks outcrop as a northwest-southeast trending elongated belt of mafic volcanics (Fig. 1). The volcanics are sandwitched between the Panjal Thrust and the Main Boundary Thrust (Fig. 1).

The Tanol formation has been recognized to the north of the Panjal Thrust (Ghazanfar *et al.*, 1983). A granite gneiss occurs near the contact of Agglomeratic slates in Muzaffarabad area. Rocks along the Panjal Thrust have been deformed and mostly have been metamorphosed to lower greenschist facies.

Immediately west southwest of the Main Boundary Thrust (MBT) in Kaghan and Muzaffarabad area the sedimentary rocks of Miocene age of Murree Formation are exposed (Fig. 1). The constitutents of Murree Formation were derived from north during uplifting of the Himalayas (Chaudhry and Ashraf 1985). The Panjal volcanics have been thrust onto the rocks of Murree Formation along MBT.

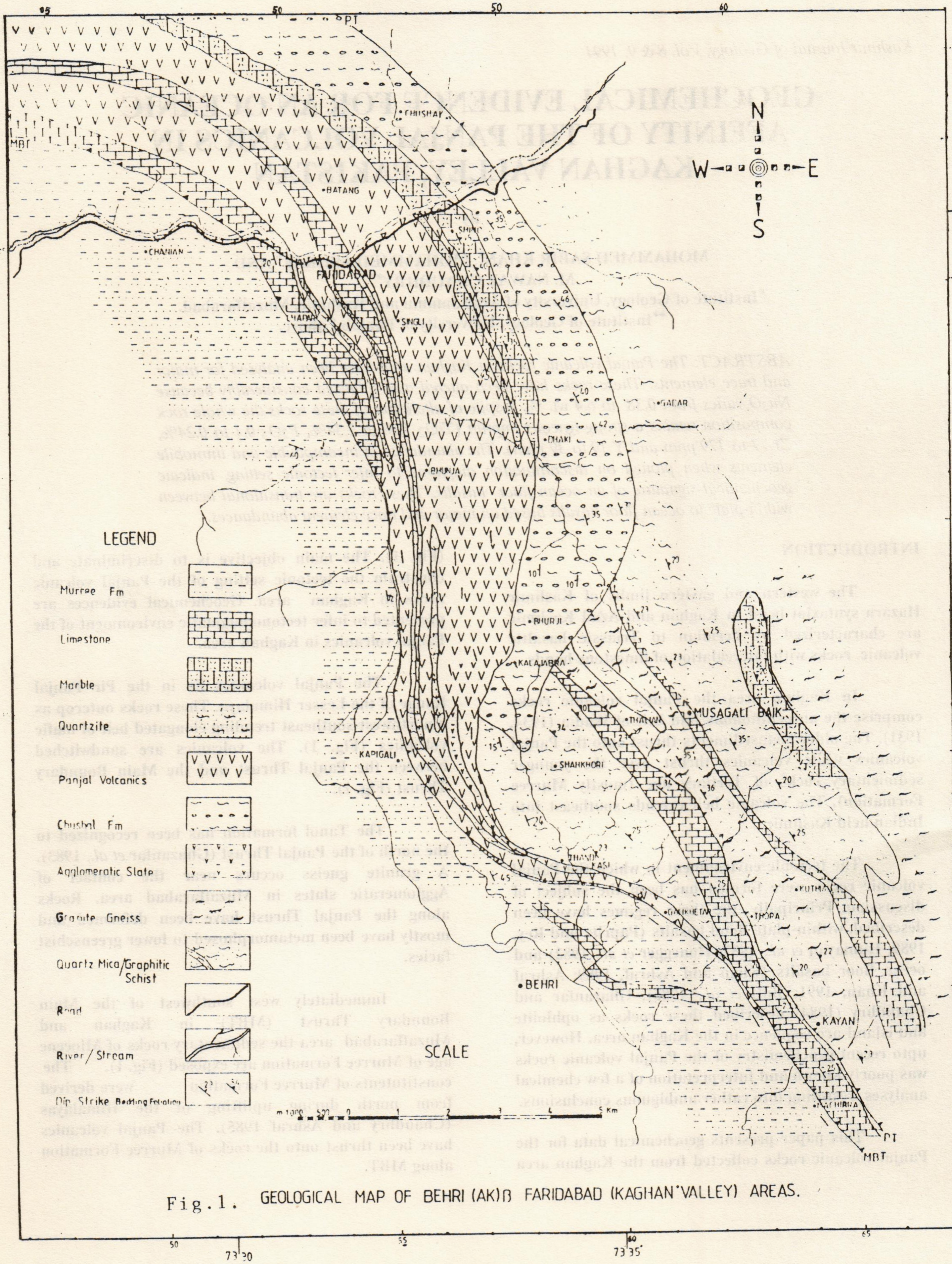

Fig. 1. GEOLOGICAL MAP OF BEHRI (AK) & FARIDABAD (KAGHAN VALLEY) AREAS.

The Panjal volcanics consist of Agglomeratic slates, lava flows and Triassic limestone. The volcanics and associated rocks represent oceanic conditions in this area (Khan and Ashraf, 1989). They have variable thickness but a maximum upto 1500m and consist of massive lava flows with pillow structures at some horizons. The sedimentary rocks include limestones and chert. Thin layers of chert commonly occur within the Panjal volcanics. The Kaghan road section was measured to show detail lithology and sampling sites (Fig. 2).

In Kaghan the Panjal volcanics comprise mainly pillowed, amygdaloidal, massive flows and basic to acidic agglomerates.

The Panjal volcanic rocks throughout the area contain a metamorphic mineral assemblage of sodic plagioclase, chlorite, epidote, calcite,sphene etc: showing that they have been metamorphosed upto greenschist facies. Amygdules are filled with calcite, chlorite and chalcedony. Calcite and quartz veins crosscut these rocks. These features indicate alteration of these rocks.

The Panjal volcanic rocks are interbedded with limestone in Kaghan area . More than three lava flows were identified in the field on the basis of intercalated limestone, colour of the lava flows and their degree of vesiculation.

The volcanic activity initiated during Carboniferous when Agglomeratic slates were formed. The lava flows erupted from Permian to Triassic time (Greco, 1989 and Wadia, 1934).

PETROGRAPHY

The Panjal volcanics are mafic rocks which comprise massive lava flows with pillow structures. The rocks have altered, somewhat spilitized and metamorphosed but they still retain igneous texture and structure. However, some plagioclase and opaque grains are the only primary magmatic phases found preserved in these rocks.

Texturally the Panjal volcanics are intersertal to subophitic and glomeroporphyritic. These rocks are vesiculated. Amygdules of calcite, chlorite and epidote are common. Alteration clearly evident as even in the least altered rocks calcic plagioclase has altered to epidote, sericite, chlorite and albite. In some rocks plagioclase is completely altered to secondary phases and even plagioclase twinning and grain boundaries have been completely obliterated. Chlorite is abundant interstitiaal material and was probably derived from the devitrification of glassy material and alteration of pyroxene. Petrographic composition of these rocks is presented in Table-1.

GEOCHEMISTRY

The major and trace elements of the Panjal volcanic rocks are presented in Table-2 and the variation diagrams for major oxides plotted are shown in Fig. 3a. The SiO_2 values in these samples range from 47.67 to 52.72 wt.% except for one sample (K-10) all fall below the basalts-basaltic andesites boundary of Ewart (1982) Fig. 4.

Some of major oxides like P_2O_5, K_2O, Na_2O and CaO plotted against SiO_2 show trends consistent with differentiation, but other elements like TiO_2, Al_2O_3 and MgO have scattered patterns (Fig. 3a).The scatter in all the plots is due to secondary alteration. The alteration is supported by the high contents of K_2O, Sr. and slightly lower values of CaO in these rocks. When immobile elements like P, Ti and Y are plotted against Zr they show a good positive corelation (Fig. 3b).

In the case of the Panjal volcanics that have suffered alteration processes, the major elements are generally not useful for the recognition of the original tectonic environment. The metamorphism and the sea-floor alteration processes are responsible for mobility of major elements and spilitization (Pearce, 1975; Vallance, 1974).

In view of secondary changes in the Panjal volcanics, the elements that were not mobilized during the alteration processes (i.e. high field strength elements : Ti, P, Zr and Nb) were used to characterize the original magma type and tectonic setting of these rocks. These elements were considered immobile under conditions of low grade alteration to greenschist facies metamorphism (Pearce and Cann, 1971, 1973; Floyd and Winchester, 1975; Winchester and Floyd, 1977; Smith and Smith, 1976; Pearce and Norry, 1979; Pearce, 1982; Floyd and Winchester, 1991). These high field strength elements have successfully been used by many workers since many years for characterization of original magma type and to discriminate tectonomagmatic environment of the basaltic rocks and in terms of magma series (i.e alkalic and subalkalic) and degree of differentiation (basalts and andesites).

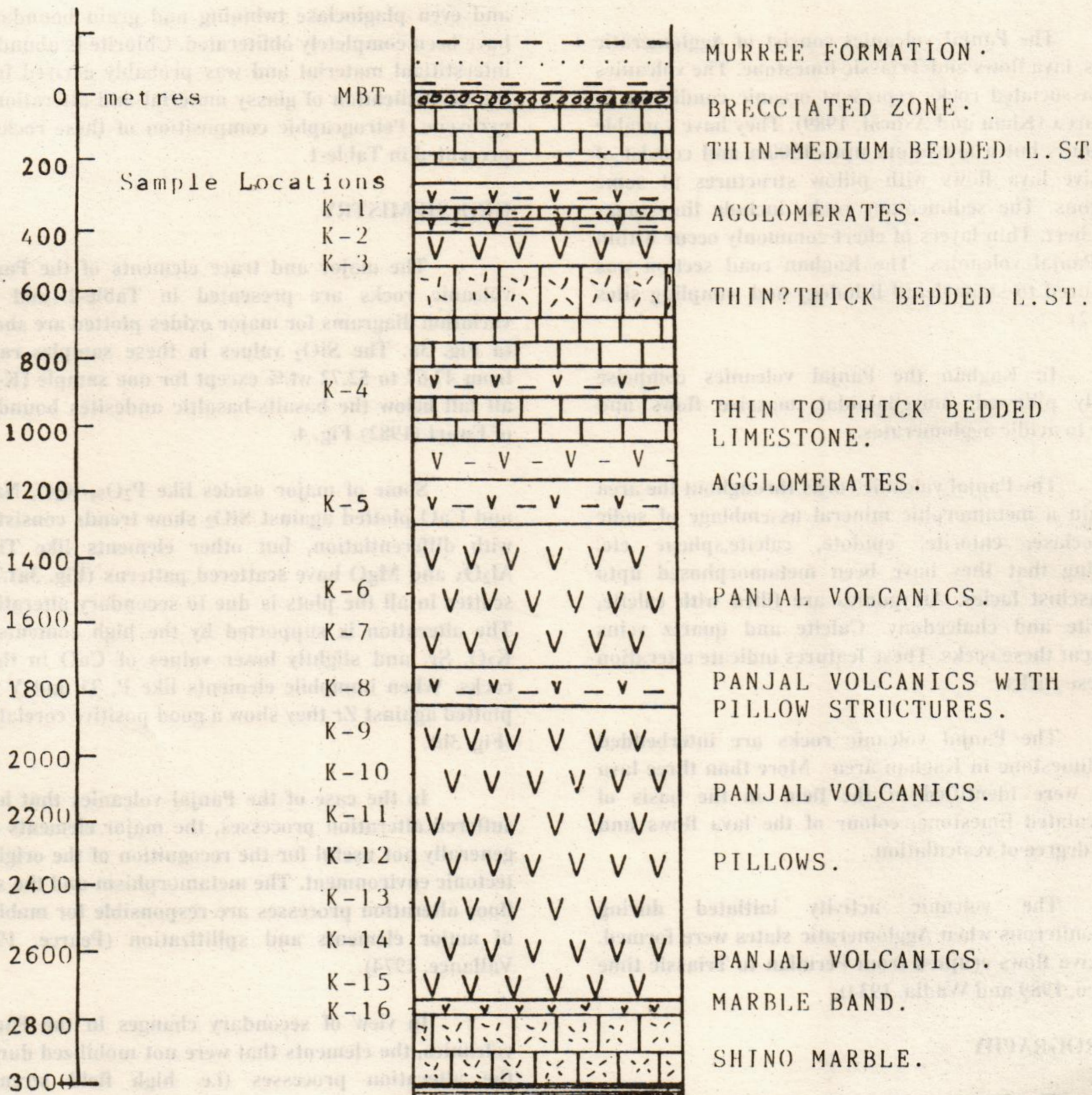

Fig. 2 Stratigraphic Section of the Panjal Volcanics near Malkandi-Shino in Kaghan Valley.

Table-1 Petrographic Composition of The Panjal Volcanics in Kaghan Area.

	K-1	K-2	K-3	K-4	K-5	K-6	K-7	K-8
Plagioclase	39	55	45	44	30	30	20	55
Epidote	15	24	20	10	20	30	35	20
Chlorite	35	15	15	40	40	35	42	20
Sericite	5	--	12	4	2	2	--	--
Quartz	1	--	1	--	--	--	--	--
Calcite	1	--	2	--	--	1	--	--
Actinolite	--	1	1	--	2	--	--	2
Sphene	3	4	3	--	5	1	--	2
Chalcedony	1	--	--	1	--	--	1	--
Hematite	--	1	1	--	--	1	--	--
Magnetite	--	--	--	1	1	--	2	1

	K-9	K-10	K-11	K-12	K-13	K-14	K-15
Plagioclase	35	20	20	15	18	15	22
Epidote	30	40	25	40	35	25	30
Chlorite	25	34	45	31	30	40	40
Sericite	4	5	5	4	5	2	--
Quartz	--	1	--	--	2	1	--
Calcite	1	--	--	2	--	--	1
Actinolite	--	--	--	--	1	1	--
Sphene	5	--	4	8	9	16	4
Chalcedony	--	--	1	--	--	--	1
Hematite	--	--	--	--	--	--	1
Magnetite	--	--	--	--	--	--	1

Table-2 Chemical Analyses of the Panjal Volcanics in Kaghan area along Kaghan road section

	K-1	K-2	K-3	K-4	K-5
SiO_2	51.37	49.76	49.84	48.01	50.52
TiO_2	2.21	1.38	1.32	2.34	1.48
Al_2O_3	14.65	14.36	14.34	15.43	14.53
Fe_2O_3*	13.40	10.69	10.70	12.79	10.39
MnO	0.15	0.18	0.16	0.17	0.19
MgO	5.44	8.13	8.57	7.66	7.28
CaO	4.16	7.81	6.98	4.56	7.74
Na_2O	4.60	4.10	3.96	4.34	3.97
K_2O	1.04	0.57	0.70	0.51	0.55
P_2O_5	0.24	0.12	0.12	0.23	0.16
LOI	2.7	2.5	2.9	3.6	2.7
CIPW NORM					
Q	--	--	--	--	--
Or	6.15	3.37	4.13	3.01	3.25
Ab	38.92	34.69	33.51	36.72	33.59
Ne	--	--	--	--	--
Di	2.39	15.39	11.91	.01	14.03
Hy	20.52	2.35	7.04	10.94	11.32
Ol	4.40	15.98	14.89	15.53	8.32
Mt	2.73	2.9	2.18	2.60	2.10
Cm	.077	.05	.059	.009	.05
Il	4.20	2.62	2.62	4.44	2.81
Ap	.56	.28	.28	.53	.37

Table-2 (continued)

	K-6	K-7	K-8	K-9	K-10
SiO_2	50.81	49.70	51.60	52.12	52.12
TiO_2	1.48	1.51	1.55	1.70	1.28
Al_2O_3	15.41	14.63	15.66	15.73	13.95
Fe_2O_3	10.18	10.88	12.44	10.28	10.11
MnO	0.12	0.20	0.11	0.24	0.19
MgO	7.43	7.50	4.84	6.88	7.32
CaO	8.72	8.05	4.52	7.07	7.01
Na_2O	2.82	3.61	6.41	4.13	4.22
K_2O	0.17	0.60	0.73	0.50	0.46
P_2O_5	0.17	0.14	0.14	0.18	0.10
LOI	2.8	1.6	3.1	2.5	2.1
CIPW NORM					
Q	2.52	--	--	--	--
Or	1.01	3.55	4.31	2.96	2.72
Ab	23.86	30.55	46.54	34.95	35.71
An	28.90	21.95	11.81	22.91	17.77
Ne	--	--	4.17	--	--
Di	10.90	14.07	8.13	9.04	13.38
Hy	23.68	11.04	--	11.79	19.79
Ol	--	9.36	16.18	8.38	2.45
Mt	2.07	2.20	2.52	2.09	2.06
Cm	0.01	0.09	0.03	0.03	0.07
Il	3.50	2.87	2.95	3.93	2.43
Ap	0.40	0.33	0.33	0.42	0.23

Table-2 (continued.)

	K-11	K-12	K-13	K-14	K-15
SiO_2	50.50	47.67	50.26	48.57	51.59
TiO_2	1.28	1.32	1.89	1.50	1.57
Al2O3	16.53	16.35	15.72	14.96	15.92
Fe_2O_3	10.46	10.71	13.72	11.24	8.34
MnO	0.17	0.20	0.16	0.26	0.22
MgO	5.64	6.38	4.90	7.26	6.28
CaO	8.62	10.88	4.81	9.75	8.09
Na_2o	4.26	2.24	1.26	2.58	3.91
K_2O	0.12	0.80	3.47	0.33	0.37
P_2O_5	0.14	0.12	0.16	0.15	0.17
LOI	2.1	3.1	3.3	3.1	3.1
CIPW NORM					
Q	0.71	4.72	5.55	--	0.30
C	--	--	1.48	--	--
Or	0.71	4.72	20.51	1.95	2.19
Ab	36.05	18.95	10.66	21.38	33.08
An	25.64	32.20	22.95	28.27	24.81
Di	13.37	17.71-	15.71	11.61	
Hy	7.58	12.29	27.30	20.60	18.69
Ol	8.58	5.33	27.30	20.60	8.69
Mt	2.12	2.18	2.78	2.28	1.70
Cm	0.09	0.03	0.05	0.03	0.05
Il	2.43	2.51	3.59	2.85	2.98
Ap	0.33	0.28	0.37	0.35	0.39

Table-2 Trace Elements in ppm

	K-1	K-2	K-3	K-4	K-5
Ba	276	200	386	202	143
Rb	--	12	--	--	--
Sr	76	93	105	57	121
Cr	34	293	287	41	233
Ni	30	100	105	32	71
La	28	17	14	17	10
Ce	51	20	20	20	20
Y	37	22	19	39	21
Nb	22	<9	<9	<9	18
Zr	116	88	76	179	91
V	252	--	--	230	--
Co	65	45	55	48	65
Cu	5	111	47	5	6
Zn	160	170	109	141	136
Y/Nb	1.68	>2.44	>2.1	>4.33	1.17
Zr/Y	4.49	4.48	4.00	4.00	4.59
Ti/Y\	367	386	429	375	436

Table-2 Trace Elements (continued.)

	K-6	K-7	K-8	K-9	K-10
Ba	47	332	222	160	75
Rb	45	-	10	255	-
Sr	442	324	119	177	149
Cr	55	411	116	109	342
Ni	25	180	65	55	28
La	25	8	21	18	6
Ce	36	20	40	35	20
Y	31	25	28	27	21
Nb	24	11	12	<9	27
Zr	146	88	107	108	86
V	--	170	172	--	--
Co	49	45	55	62	22
Cu	28	120	13	94	5
Zn	116	94	86	123	84
Y/Nb	1.29	2.27	2.33	>3.00	0.78
Zr/Y	4.33	4.21	3.52	3.82	4.00
Ti/Y	363	158	338	390	376

	K-11	K-12	K-13	K-14	K-15
Ba	70	130	460	112	53
Sr	77	276	129	213	189
Cr	410	151	233	144	219
Ni	5	115	148	175	104
La	14	17	12	12	15
Ce	39	20	50	20	20
Y	21	19	28	22	29
Nb	<9	<9	<9	<9	<9
Zr	91	77	104	79	114
V	--	--	--	--	132
Co	33	57	64	72	62
Cu	31	117	74	97	363
Zn	92	113	126	115	191
Y/Nb	>2.33	>2.1	>3.1	>2.44	>3.11
Zr/Y	4.10	4.33	4.05	3.71	3.59
Ti/Y	373	432	419	422	337

Table-3 Major and trace element data for continental flood basalts, ocean island tholeiites, normal and enriched MORB and Mid Atlantic Ridge (MAR) 45 N. for comparison with Panjal volcanics.

	Snake River Plain	Ocean island tholeiite	N-MORB	P-MORB	MAR 45 N	Pan Vol.
	1	2	3	4	5	6
SiO_2	46.18	50.36	50.40	51.18	50.16	50.3
TiO_2	2.06	3.62	1.36	1.69	1.51	1.59
Al_2O_3	14.47	13.41	15.19	16.01	17.71	15.21
Fe_2O_3	13.52	13.63	10.01	9.40	3.59	11.09
FeO	--	--	--	--	4.36	--
MnO	0.19	0.18	0.18	0.16	0.17	0.18
MgO	9.99	5.52	8.96	6.90	3.77	6.77
CaO	9.88	8.80	11.48	11.48	10.07	7.25
Na_2O	2.63	2.80	2.30	2.74	3.98	3.76
K_2O	0.61	0.77	0.09	0.43	1.76	0.73
P_2O_5	0.44	0.42	0.14	0.15	0.35	0.16
ppm						
Ba	298	191	<20	86	447	191.2
Sr	285	395	98	155	28.9	169.8
Cr	256	81	346	225	206	205.2
Ni	193	78	177	132	108	82.53
La	18.3	24	2.95	6.92	42.2	15.6
Ce	41.2	53	12.0	17.8	68.2	28.73
Y	31	42	37	39	28.9	25.93
Nb	15.1	21.5	2.1	8.6	77.2	<13
Zr	167	227	97	121	206	103.3
Co	--	--	--	--	32	53.27
Cu	59	98	--	--	--	74.4
Zn	97	119	--	--	33	124
Y/Nb	2.05	1.95	0.06	0.22	2.67	>2.3
Zr/y	5.39	5.40	2.62	3.10	7.13	4.08
Ti/Y	398	516	220	259.5	313	373

Data sources: 1, Thompson et al. (1983); 2, Thompson et al. (1984); 3, 4, Humphris et al. (1985); 5, Wood et al. (1979b) 6 Panjal volcanics (Pan. Vol.) geochemical data (average) from Kaghan area.

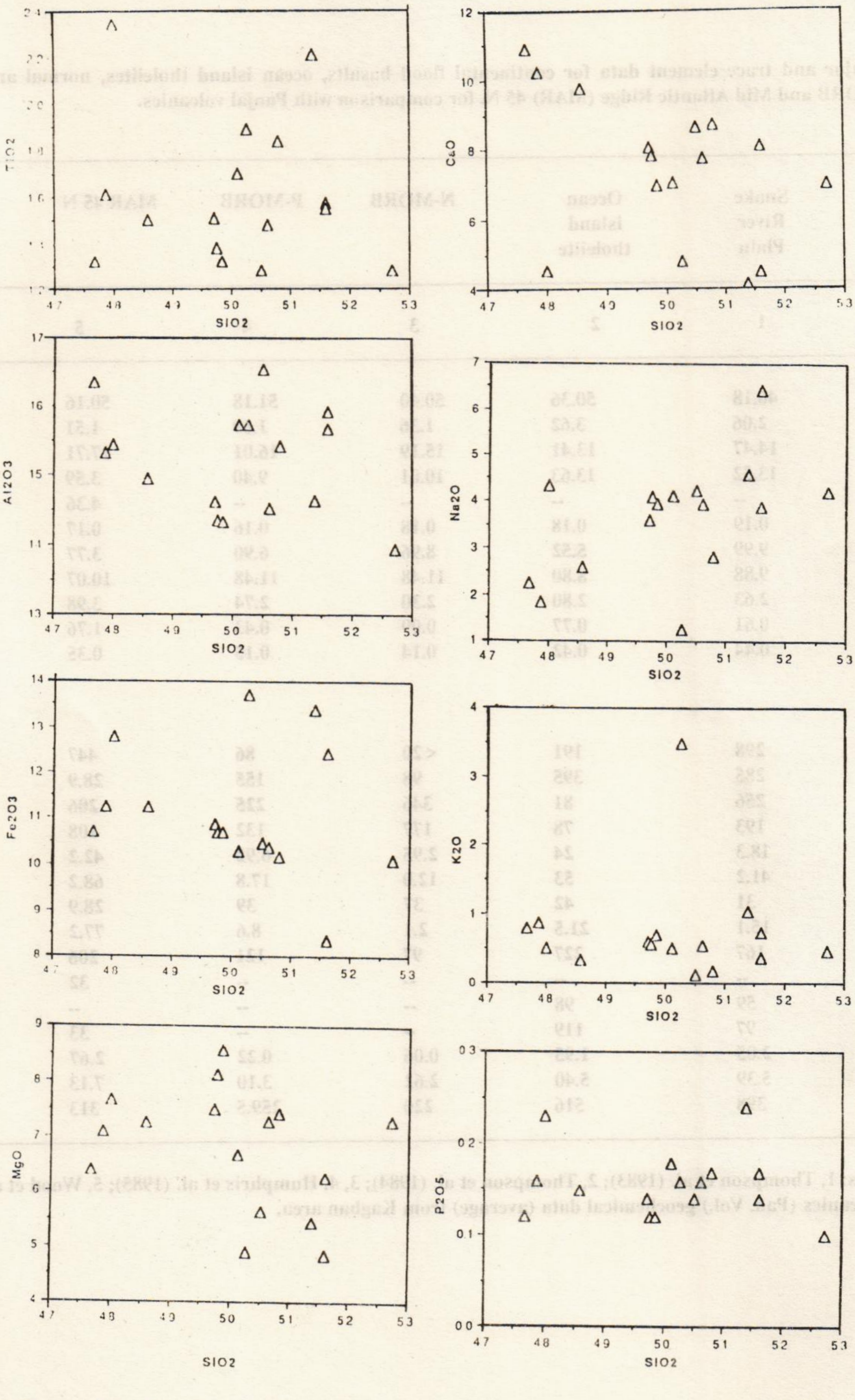

Fig. 3a. Harker diagrams for the Panjal volcanics from Kaghan area.

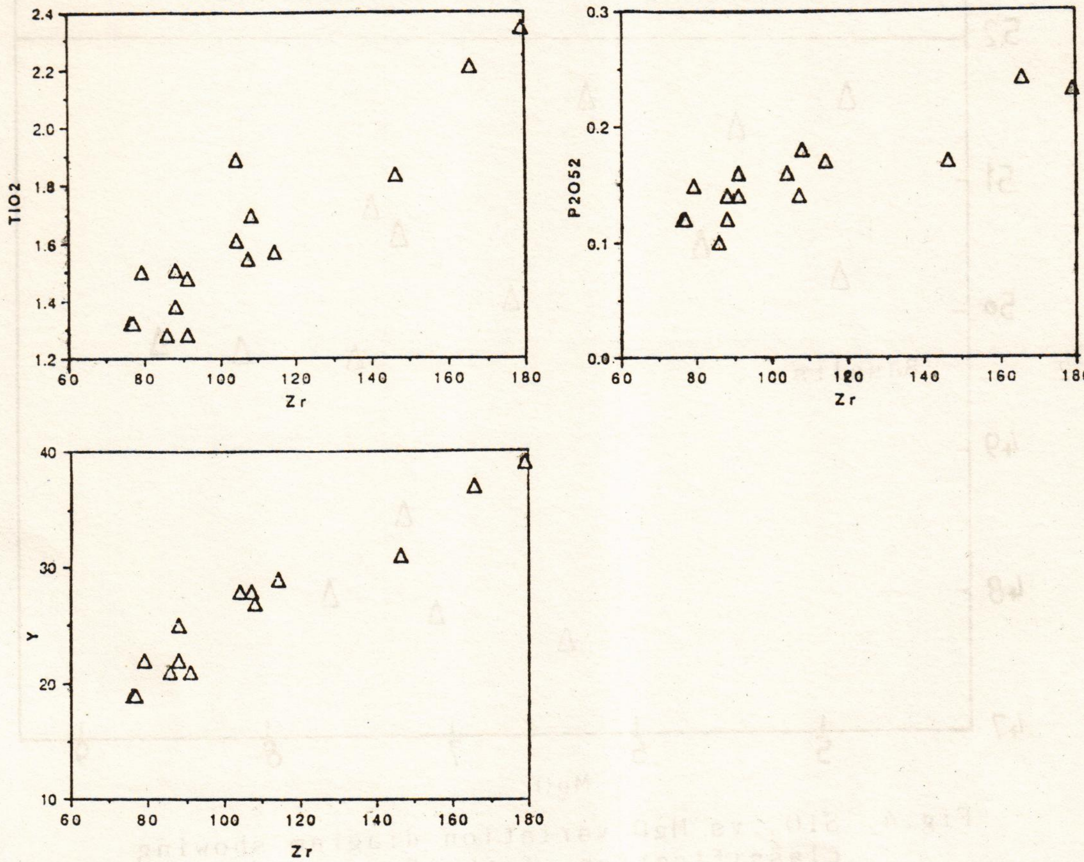

Fig. 3b. TiO_2 P_2O_5 Y vs Zr plots showing good positive correlation for the Panjal volcanics.

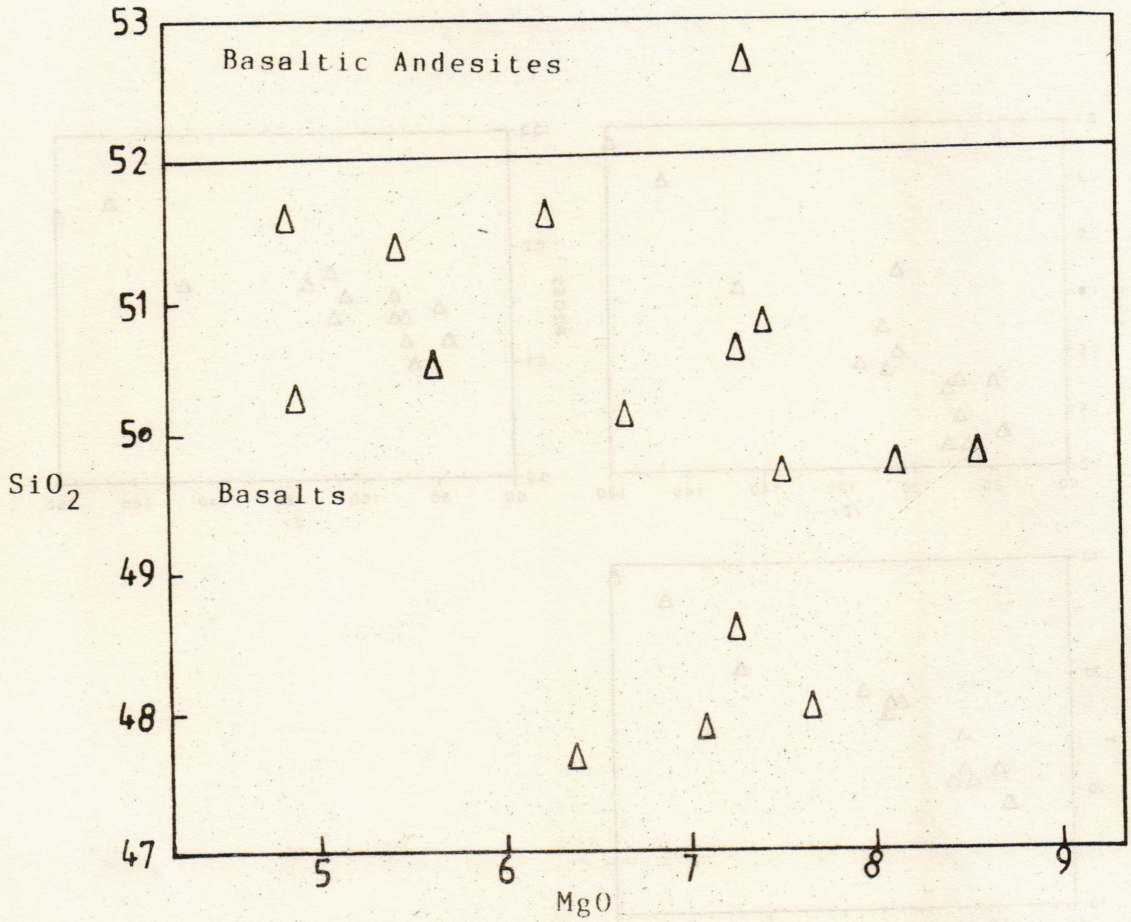

Fig.4. SiO_2 vs MgO variation diagram showing classification of the Panjal volcanics (after Ewart, 1982).

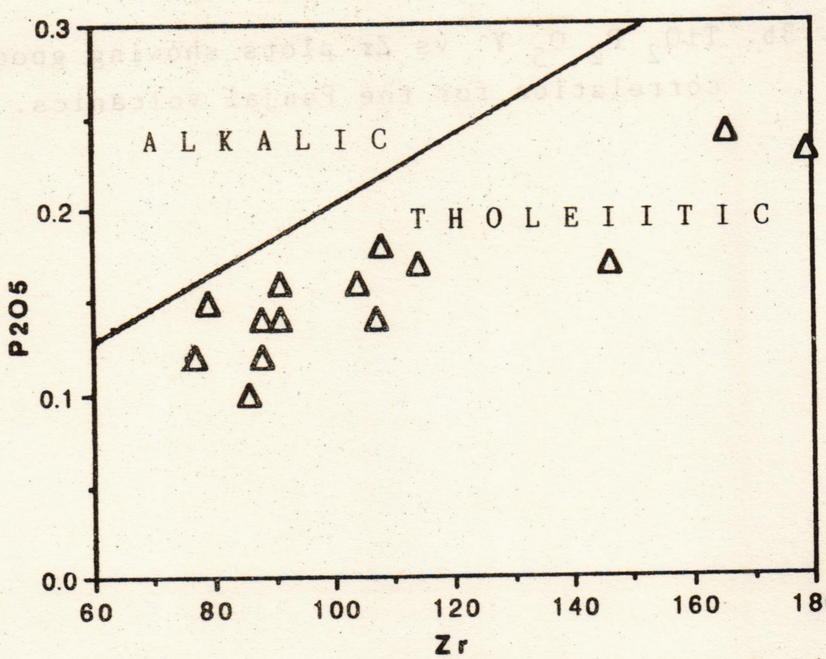

Fig.5. P_2O_5 (Wt.%) plotted against Zr (ppm) showing alkaline and tholeiitic fields (After Winchester and Floyd, 1976).

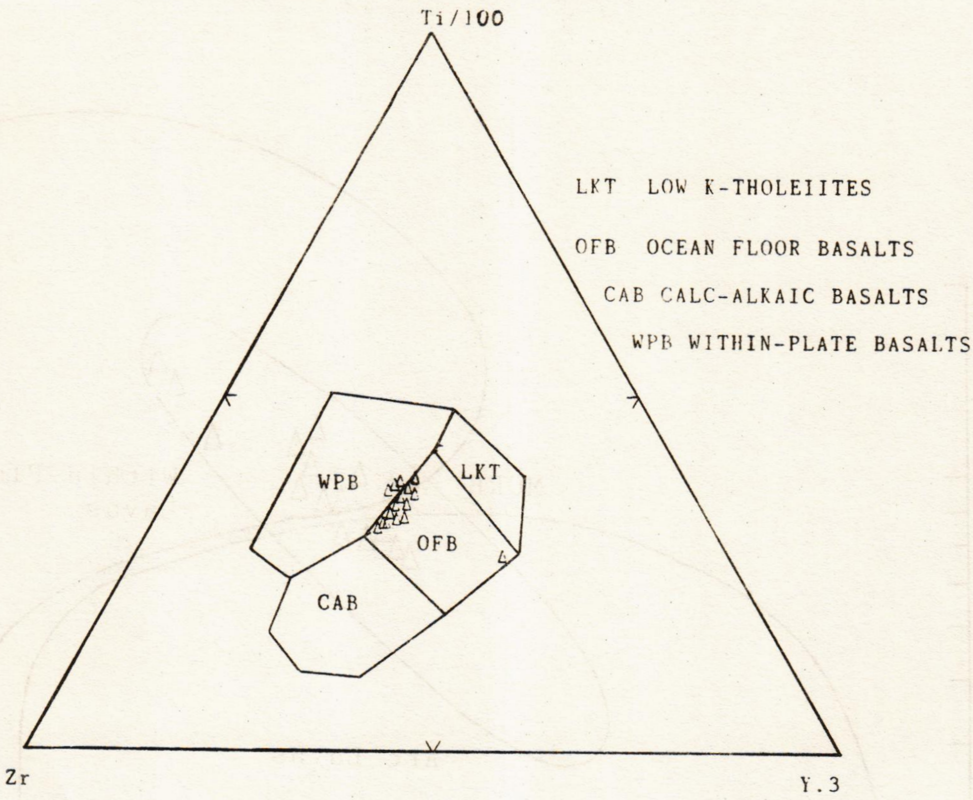

Fig. 6 Ti/100-Zr-Y.3 Tectonomagmatic geochemical discriminant diagram for the Panjal volcanics from the Kaghan area. (After Pearce and Cann, 1973)

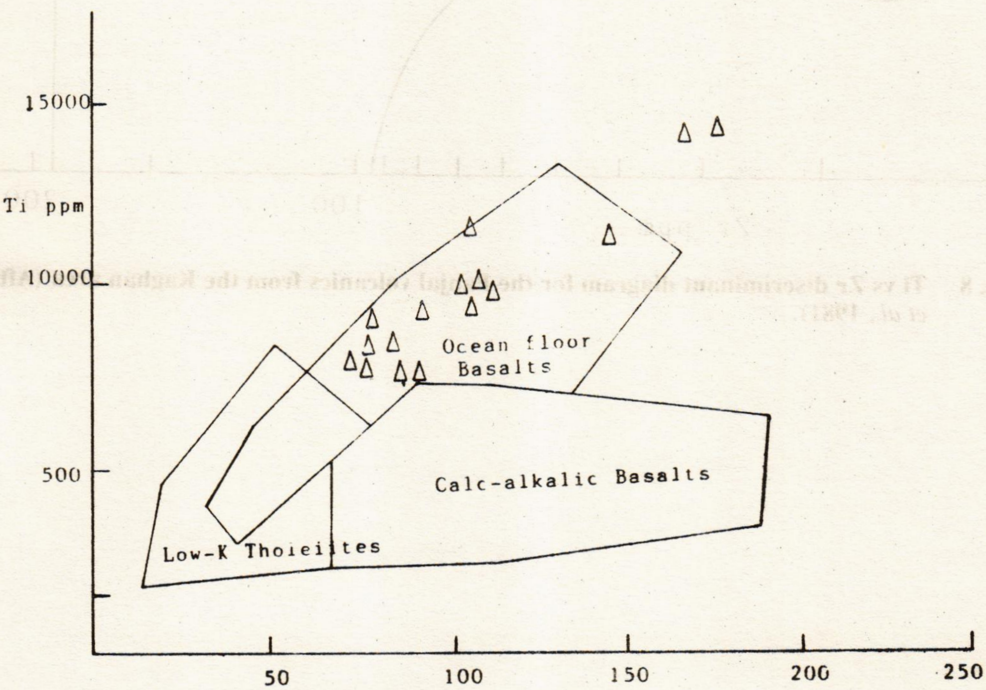

Fig.7 Ti vs Zr discriminant diagram for the Panjal volcanics from Kaghan area (After Pearce and Cann, 1973).

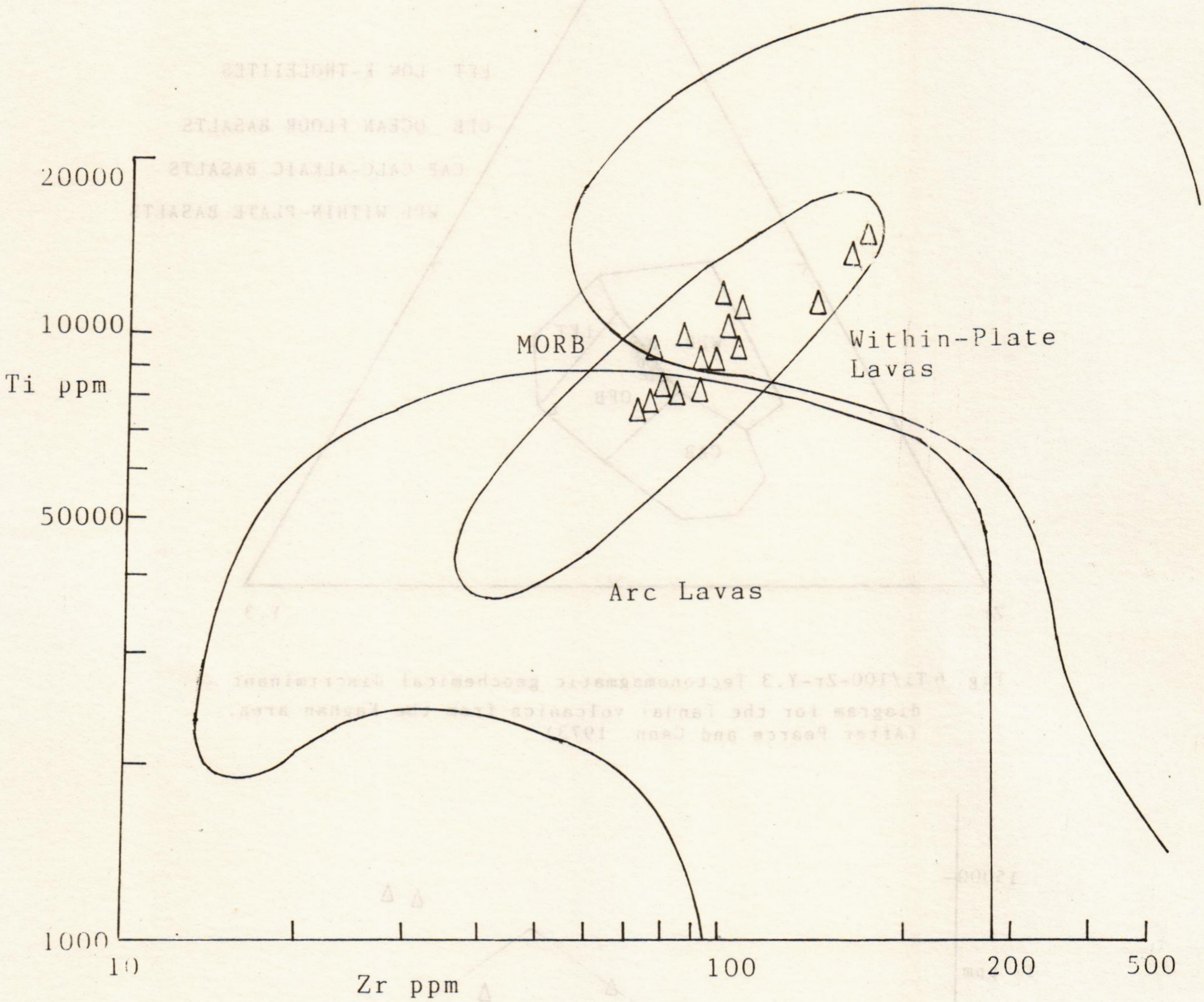

Fig. 8 Ti vs Zr discriminant diagram for the Panjal volcanics from the Kaghan area (After Pearce *et al.*, 1981).

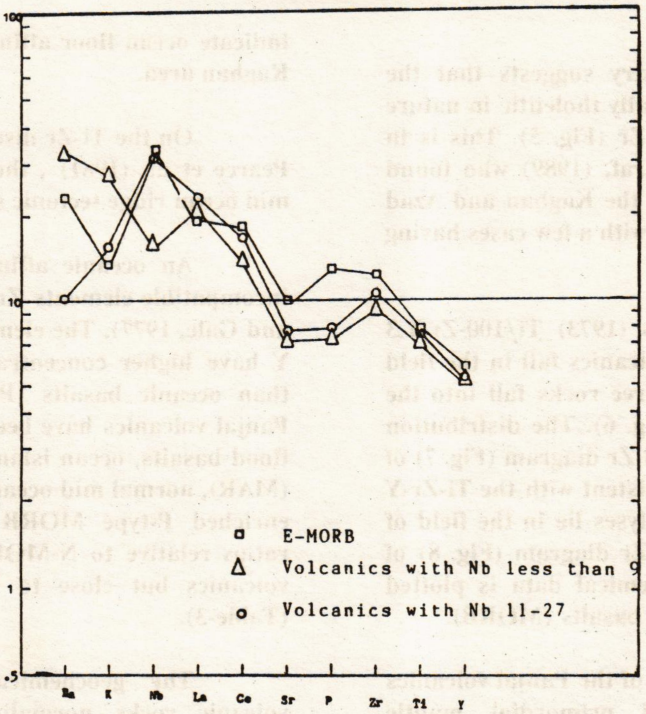

Fig. 9a. Mean H-element abundances of the Panjal volcanics from Kaghan area normalized with primordial mantel material (after Wood et al., 1979b). The geochemical data is compared with E-MORB after Wood et al. (1979). E-MORB values are : Ba=174, K= 3478, Nb= 20.5, La= 13.5, Ce= 34, Sr= 244, P= 1175, Zr= 141, Ti= 12063 and Y= 28.7.

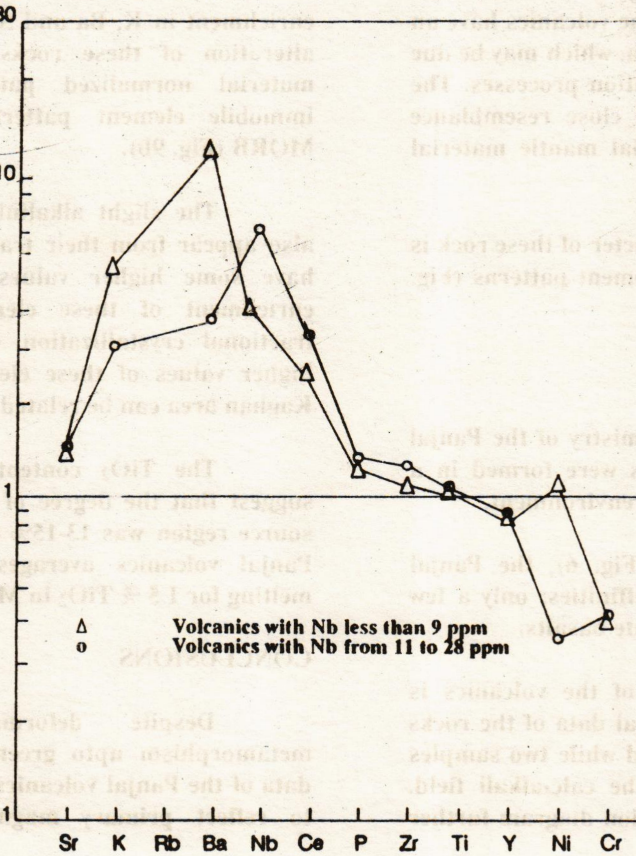

Fig. 9b. Geochemical patterns (normalized to MORB) of the Panjal volcanics from Kaghan area. Normalizing values are from Pearce, (1982).

Whole rock geochemistry suggests that the Panjal volcanic rocks are generally tholeiitic in nature as shown by plots of P_2O_5 vs Zr (Fig. 5). This is in agreement with Khan and Ashraf, (1989) who found the Panjal volcanic rocks from the Kaghan and Azad Kashmir mainly to be tholeiitic with a few cases having alkalic affinity.

On Pearce and Cann,s (1973) Ti/100-Zr-Y.3 diagram, most of the Panjal volcanics fall in the field of ocean floor basalts. Only three rocks fall into the field of within-plate basalts (Fig. 6). The distribution of the Panjal volcanics on the Ti-Zr diagram (Fig. 7) of Pearce and Cann, 1973) is consistent with the Ti-Zr-Y discriminant diagram. The analyses lie in the field of ocean floor basalts. On the Ti-Zr diagram (Fig. 8) of Pearce et al. (1981) the geochemical data is plotted into the field of mid ocean ridge basalts (MORB).

Trace element patterns of the Panjal volcanics (normalized by MORB and primordial mantle material) are shown in Fig. 9a & b for characterization of magma type and their tectonic setting in the Kaghan area. The primordial mantle material normalized patterns (after Holm, 1985) of the Panjal volcanics are compared with the rocks of known tectonic setting (Fig. 9b). These patterns of the Kaghan volcanics show some lower values for Cr and Y. The volcanics have an overall high abundance of K and Ba, which may be due to their mobilization during alteration processes. The patterns for other elements show close resemblance with enriched MORB in primordial mantle material normalized diagram (Fig. 9b).

The tholeiitic alkalic character of these rock is further indicated by their trace element patterns (Fig. 9 a & b).

DISCUSSION

The petrology and geochemistry of the Panjal volcanics suggest that these rocks were formed in a within-plate to ocean floor tectonic environment.

From the Ti-Zr-Y plot (Fig. 6), the Panjal volcanics have clear ocean floor affinities; only a few rocks show an affinity to within-plate basalts.

The Ti-Zr plot (Fig. 7) of the volcanics is somewhat unusual. The geochemical data of the rocks plot in the ocean floor basalts field while two samples fall in its extension away from the calc-alkali field. This tectonomagmatic discrimination diagram further indicate ocean floor affinity of the Panjal volcanics in Kaghan area.

On the Ti-Zr discriminant diagram (Fig. 8) of Pearce et al. (1981) , the Panjal volcanics indicate a mid ocean ridge tectonic setting.

An oceanic affinity is also indicated by the incompatible elements Zr/Y and Zr/Ti ratios (Pearce and Gale, 1977). The element Ti, Zr and Nb relative to Y have higher concentration in within plate basalts than oceanic basalts (Pearce and Gale, 1977). The Panjal volcanics have been compared with continental flood basalts, ocean islands, Mid Atlantic Ridge 45 N (MAR), normal mid ocean ridge basalts (N-MOR) and enriched P-type MORB (Table-2). The Zr/Y Ti/Y ratios relative to N-MORB are higher in the Panjal volcanics but close to P-MORB and MAR 45 N (Table-3).

The geochemical patterns of the Panjal volcanic rocks normalized to an average MORB composition (Fig. 9a) of Pearce, (1982) and primordial mantle material values of Wood et al. (1979) give additional clues to the tectonic setting of these rocks. The elements Ti, Nb, P, Zr and Y which are immobile, have been slightly enriched in the Panjal volcanics relative to normal MORB composition. The enrichment in K, Ba and Sr may be due to secondary alteration of these rocks. The primordial mantle material normalized pattern readily match the immobile element pattern character of enriched MORB (Fig. 9b).

The slight alkalinity of the Panjal volcanics also appear from their trace element patterns, which have some higher values of Ti, P and Zr. The enrichment of these elements is caused by the fractional crystallization (Pearce, 1982). Therefore, higher values of these elements in the volcanics of Kaghan area can be related with differentiation.

The TiO_2 content of the Panjal volcanics suggest that the degree of partial melting in magma source region was 13-15% as the TiO_2 content of the Panjal volcanics averages 1.6%. (13-15 % partial melting for 1.5 % TiO_2 in MORB : Sun et al., 1979).

CONCLUSIONS

Despite deformation, alteration and metamorphism upto greenschist facies, geochemical data of the Panjal volcanics from Kaghan area appear to reflect primary magmatic characteristics. The volcanics are dominantly tholeiitic in nature.

Limestone bands are associated with the Panjal volcanics. Deformed pillow structures were found in these rocks. These features indicate their submarine origin in this area.

The enrichment in Ti, P and Zr appear to be due to fractionation. On the basis of trace element geochemistry the Panjal volcanics in Kaghan area can be interpreted as ocean-floor basalts. The Ti/Zr and Ti/Y ratios also indicate an ocean floor affinity to within plate tectonic setting. The trace element patterns normalized to primordial mantle material indicate an enriched type ocean floor tectonic setting.

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A DISCOVERY OF LATE ARCHEAN TO EARLY PROTEROZOIC KOMATIITE FROM THE NORTHWESTERN MARGIN OF THE INDIAN PLATE, BESHAM AREA, NORTHWEST HIMALAYA PAKISTAN

BY

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ABSTRACT: In northern Pakistan, near the village of Besham, the Besham block of Indian plate is exposed in the core of the Indus syntaxis. This basement block is separated from low-to high-grade Precambrian to Mesozoic metamorphic rocks to the east and west by high-angle ramp faults and from low-grade to unmetamorphosed sedimentary rocks to the south by thrust faults. The Besham block consists of epidote amphibolite to upper amphibolite facies late Archean to Middle Proterozoic Besham basement complex and unconformably overlying lower greenschist facies Middle to Late Proterozoic cover sediments of the Karora group.

Precambrian komatiites are known from the basement rocks of the southern Indian plate. No komatiites have previously been reported from the Indian basement rocks of the northwest Himalayan collision zone. This paper reports late Archean to Early Proterozoic komatiites from the Besham basement complex of the Besham area, northwest Himalaya, Pakistan. It is the first report of komatiites from the northwest Himalayan basement rocks of the Indian plate. An amphibolite from the Besham basement complex is herein characterized as a alumina depleted basaltic komatiite on the basis of high SiO_2 *(55.0%), high MgO (15.94%), < 0.5%* K_2O *(0.24%), < 0.9%* TiO_2 *(0.25%), low Fe/Mg ratio (0.89) at given* Al_2O_3 *(3.77%) and > 1* CaO/Al_2O_3 *ratio (3.45).*

Precambrian komatiites are commonly associated with the rift-related extensional environments. The presence of late Archean to Early Proterozoic mafic komatiites in the Besham basement complex shows that the late Archean to Early Proterozoic mafic volcanism occurred during the rifting of Indian plate.

INTRODUCTION

South of Indus suture zone, near the village of Besham, a basement block of the leading edge of the Indian plate is exposed in the core of the Indus syntaxis (Baig and Snee, 1989). The basement block is known as the Besham block (Baig *et al.,* 1989). The Besham block is separated from the Mansehra and Swat blocks by the Thakot and Puran ramp faults respectively (Fig. 1). The Precambrian rocks of the Besham block are the northwestern most exposed basement rocks of the Aravalli orogenic belt of southern India.

The Precambrian komatiites are lavas of high ultramafic composition and are commonly associated with the Precambrian rifts. These have been found in the Precambrian shields of Africa (Bickle *et al.,* 1975), Australia (Williams, 1972), Canada (Arndt *et al.,* 1977) and India (Viswanathan, 1974). No Komatiites have previously been reported from the Indian basement rocks of the Himalayan collision zone. This paper reports rocks of komatiitic affinity from the Besham basement complex of the Indian plate, Besham area (Fig. 1, location K), northwest Himalaya Pakistan.

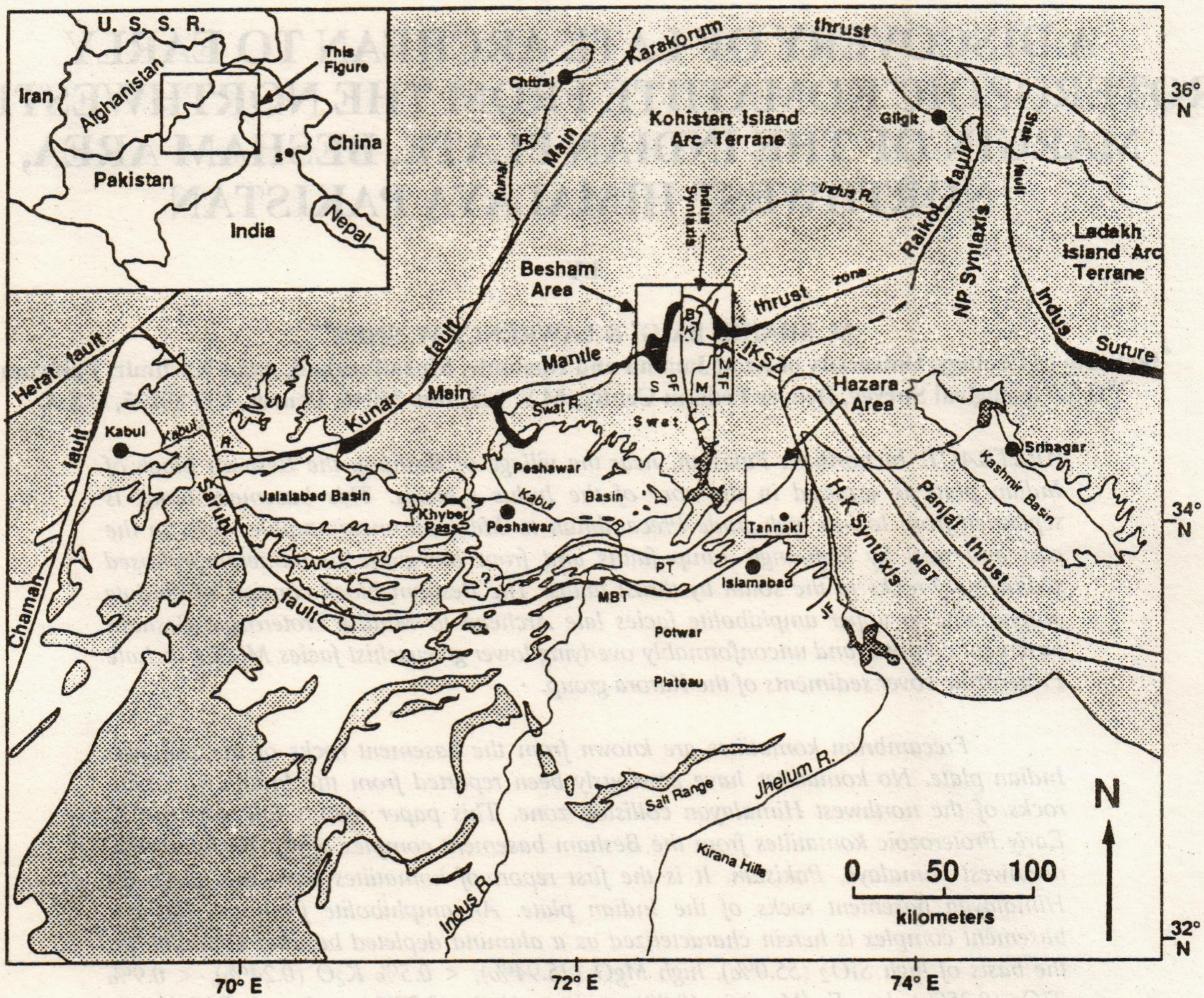

Figure-1. Tectonic map of the northwest Himalaya, showing location of the Besham area (modified after Kazmi and Rana, 1982; Baig and Lawrence, 1987; Baig *et al.*, 1989). Abbreviations are: komatiite (K), Besham block (B), Swat block (S), Mansehra block (M), NP syntaxis (Nanga-Parbat syntaxis), H-K syntaxis (Hazara-Kashmir syntaxis), Indus Kohistan seismic zone (IKSZ), Main Boundary thrust (MBT), Jhelum ramp fault (JF), Punjal thrust (PT), Puran ramp fault (PF) and Thakot ramp fault (TF). Ophiolite along Main Mantle thrust zone (black).

GEOLOGIC SETTING OF KOMATIITES

The komatiites occur within the Besham basement complex of the Besham block (Fig. 1, location K). The basement rocks are unconformably overlain by the cover sediments of the Karora group (Ashraf *et al.*, 1980; Fletcher *et al.*, 1986; La Fortune, 1988; Baig and Lawrence, 1987; Baig and Snee, 1989; Baig *et al.*, 1989). The Besham basement complex is divided into the late Archean to Early Proterozoic metasediments of the Besham group and the Early to Middle Proterozoic intrusive granites and granodiorites (Baig, 1990).

The Besham group is composed of quartzo-feldspathic gneiss, albite gneiss, amphibolite, graphitic schist and gneiss, banded quartzite, tremolite-diopside-bearing marbles, calc-pelite, barite, magnesite (Ashraf, verbal commu., 1990), soapstone, talc and serpentinite. The thickness of soapstone, talc and serpentinite varies from 0.5 m to 3 m. Serpentinite also occurs as pods and lenses within the soapstone horizons of the Besham group. The soapstone, serpentinite and talc-bearing horizons may be the metamorphic equivalents of peridotitic komatiites.

Amphibolite of komatiitic affinity occurs within the psammites of the Besham group. It shows concordant field relationship with the metasediments of the Besham group. The thickness of amphibolite varies from about 1 m to 1.5 m. Its extent is not mapped in the field. It is greenish grey to dark green grey in colour. It is medium grained and shows gneissic texture. Volcanic spinifex texture is absent due to Early Proterozoic pre-Himalayan deformation and metamorphism. However, in certain areas, some of the amphibolites still preserve pillow structures. The preservation of pillow structures in amphibolites shows that these are metamorphosed subareal volcanic flows.

PETROGRAPHY AND CHEMISTRY OF KOMATIITIC AMPHIBOLITE

Mineralogically, amphibolite is composed of amphibole, epidote, biotite, quartz and plagioclase. It is schistose to gneissic and lacks volcanic spinifex texture of a komatiite. In Besham basement complex, on the basis of schistose to gneissic texture and metamorphic mineral assemblage, it is difficult, to identify an amphibolite as a komatiite. Because, the spinifex texture and the original mineralogy of komatiite have been modified by the Early Proterozoic amphibolite facies metamorphism and deformation. An amphibolite from the Besham basement complex is herein identified as a basaltic komatiite on the basis of major element chemistry and its comparison with the basaltic komatiite of the Barberton mountain of South Africa (Table-1). Most of the major elements data correlate within one to two sigma error.

Table-1 Comparison of Major Element Chemistry (in weight %) of Besham Amphibolite and Barberton Basaltic Komatiite of South Africa.

	[1]Besham amphibolite basaltic komatiite (331/779)	[2]Barberton
SiO_2	55.00%	53.65%
Al_2O_3	3.77%	4.42%
FeOt	10.9 %	11.10%
MgO	15.94%	14.94%
CaO	13.0 %	12.70%
Na_2O	0.56%	1.89%
K_2O	0.24%	0.05%
TiO_2	0.25%	0.50%
P_2O_5	$< 0.05\%$	0.04%
MnO	0.24%	0.18%
LOI	nd	1.08%
Total:	99.95%	100.6%

Note: LOI = loss on ignition, nd = not determined. 1 = analysis is recalculated to 100%. 2 = analysis 331/779 is from Nesbitt *et al.* (1979).

DISCUSSION

Precambrian komatiitic lava flows are known from the Precambrian shields of India (Viswanathan, 1974), Australia (Williams, 1972), Africa (Bickle *et al.*, 1975) and Canada (Arndt *et al.*, 1977). They are characteristic of the Late Archean to Early Proterozoic rifts of the Precambrian shields.

Komatiites are generally recognized on the basis of following criteria: (1) high ultramafic compositions in noncumulate lavas, (2) volcanic spinifex texture, (3) high SiO_2, (4) low Fe/Mg ratio at a given Al_2O_3, (5) $TiO_2 < 0.9\%$, (6) low alkali elements ($K_2O < 0.5\%$), (7) high CaO/Al_2O_3 ratio (> 1) and (8) high MgO (10-30%) (Viljoen and Viljoen, 1969a and 1969b; Brooks and Hart, 1974; and Arndt *et al.*, 1977).

On the basis of above mentioned criteria and comparison with the Barberton basaltic komatiite (Table-1), the Besham amphibolite is appropriate for an alumina depleted basaltic komatiite, because of high SiO_2 (55.0%), high MgO (15.94%), < 0.5% K_2O (0.24%), < 0.9% TiO_2 (0.25%), low Fe/Mg ratio (0.89) at given Al_2O_3 (3.77%) and > 1 CaO/Al_2O_3 ratio (3.45).

Besides basaltic komatiite, the soapstone, talc and serpentinite are present in the Besham group. The soapstone, serpentinite and talc-bearing horizons may be the metamorphic equivalents of peridotitic komatiites. In contrast, some of the ultramafics of the Besham block are the klippes of once overlying ultramafic rocks of the Indus suture zone. The high-angle strike-slip faults, those offset the Indus syntaxis, contain lenses and blocks of mafic to ultramafic rocks, dragged from the Indus suture zone and Kohistan island arc (Baig and Lawrence, 1987; Baig and Snee, 1989). This indicates that the mafic to ultramafic rocks, those occur as klippes or found within the faults zones, are not the part of the Besham komatiites.

The barite, dolomite, magnesite, quartzite and quartzo-feldspathic sediments of the Besham group represent shallow water depositional environments. The shallow water depositional environments are the characteristics of rifting. The Besham group metasediments have been metamorphosed and deformed under amphibolite facies metamorphism at > 2,000 Ma (Baig *et al.*, 1989; Baig, 1990). These data show that the upper age limit for the deposition of the Besham group is certainly Early Proterozoic and lower age limit may be late Archean or older. The presence of mafic komatiites in the late Archean to Early Proterozoic Besham group indicates that the mafic volcanism occurred during the late Archean to Early Proterozoic rift-related deposition of the Besham group.

CONCLUSIONS

This paper is the first report of komatiites from the Indian basement rocks of the northwest Himalaya. On the basis of major element chemistry, Besham amphibolite is characterized as a basaltic komatiite. This shows that the some of the Besham amphibolites are komatiitic in nature. The talc, soapstone and serpentinite horizons within the Besham basement complex may be the metamorphic equivalents of peridotitic komatiites.

The presence of komatiites in the late Archean to Early Proterozoic rocks of the Besham basement complex, indicates that the leading edge of the Indian plate, in northern Pakistan, passed through a late Archean to Early Proterozoic phase of rifting.

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SEDIMENTARY PETROLOGY OF LAGARBAN PHOSPHORITE, NORTHERN PAKISTAN

By

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ABSTRACT: The Lagarban phosphorite of Cambrian age occurs in the Hazara District of Northern Pakistan in the upper dolomite member of the Sarban formation. The geology is complicated by imbricate reverse faults which run more or less parallel to the regional strike and separate the phosphorite into the different structural blocks of Lagarban phosphorite, Batkanala phosphorite, East phosphorite, South phosphorite and Middle phosphorite. The displacement along the imbricate faults appears to be large, because the rocks of different facies of phosphorite have been brought into juxtaposition. The faults separate the East phosphorite of shallow water marine facies from the western phosphorite of open-marine facies. This is confirmed by petrographic study of the two major types. The former type shows evidence of reworking of the phosphate and associated sediments, whereas the latter type is represented by undisturbed, normal deposition of phosphate oolites and associated dolomite.

INTRODUCTION

The Lower Cambrian rocks of the Hazara District of Northern Pakistan are host to important phosphate mineralization. The phosphorite deposits are currently being developed by Sarhad Development Authority. General geology of the area has been described by Latif (1970) and Calkins et al. (1975).

The Lagarban phosphorite is the part of the upper Abbottabad Formation i.e. the upper dolomite member of the Sarban formation of Latif (1970). Similar phosphorites are found at Kakul, Lami Dogi, Sarban and Dalola (Ghaznavi *et al.* 1983) Phosphorite in the Lagarban area extends from Lagarban to Tarnwai. The area is about 27 km from Abbottabad connected by all weather to fair weather roads. Approach from the Tarnwai side is easy in almost all weather.

Topographically, the area being developed for phosphate is about 1650 to 2200 m above sea level. The hills are steep-sided and form cliffs at many places. Climate of the area is moderate mostly, but winter is comparatively cold, as snow remains on the phosphate hills for days.

Rocks of the area are Precambrian (Tanol Formation), Cambrian (Sarban and Hazira formations) and Jurassic (Samana Suk Formation) in age. The major unconformities bound the Cambrian strata above and below (Ashraf and Chaudhry, 1983). The geology is complicated by imbricate reverse faults which run approximately parallel to the regional strike, thus rendering it into a number of discrete structural blocks which are in turn disrupted by later minor transverse faults.(Fig. 1). These structural blocks are as follow:

i) Lagarban North and South phosphorite.
ii) Batkanala and Kaludi Bandi phosphorite.
iii) East phosphorite.
iv) South phosphorite.
v) Middle phosphorite.

The entire succession is overturned and the blocks are repeated by imbricate thrusts. Imbricate structures down to the micro scale are also visible. General strike of the upper Abbottabad Formation is nearly 210^0. General dip is between 45^0 and 70^0 due east. The variation in dip is due to structural complexity. The displacement along the imbricate faults appears to be large, because the rocks of different phosphate facies have been brought into juxtaposition. For example, the East phosphorite of shallow water marine facies is separated from the phosphorite of more calcareous open-marine facies to the west by a reverse fault (Ashraf and Malik, 1983).

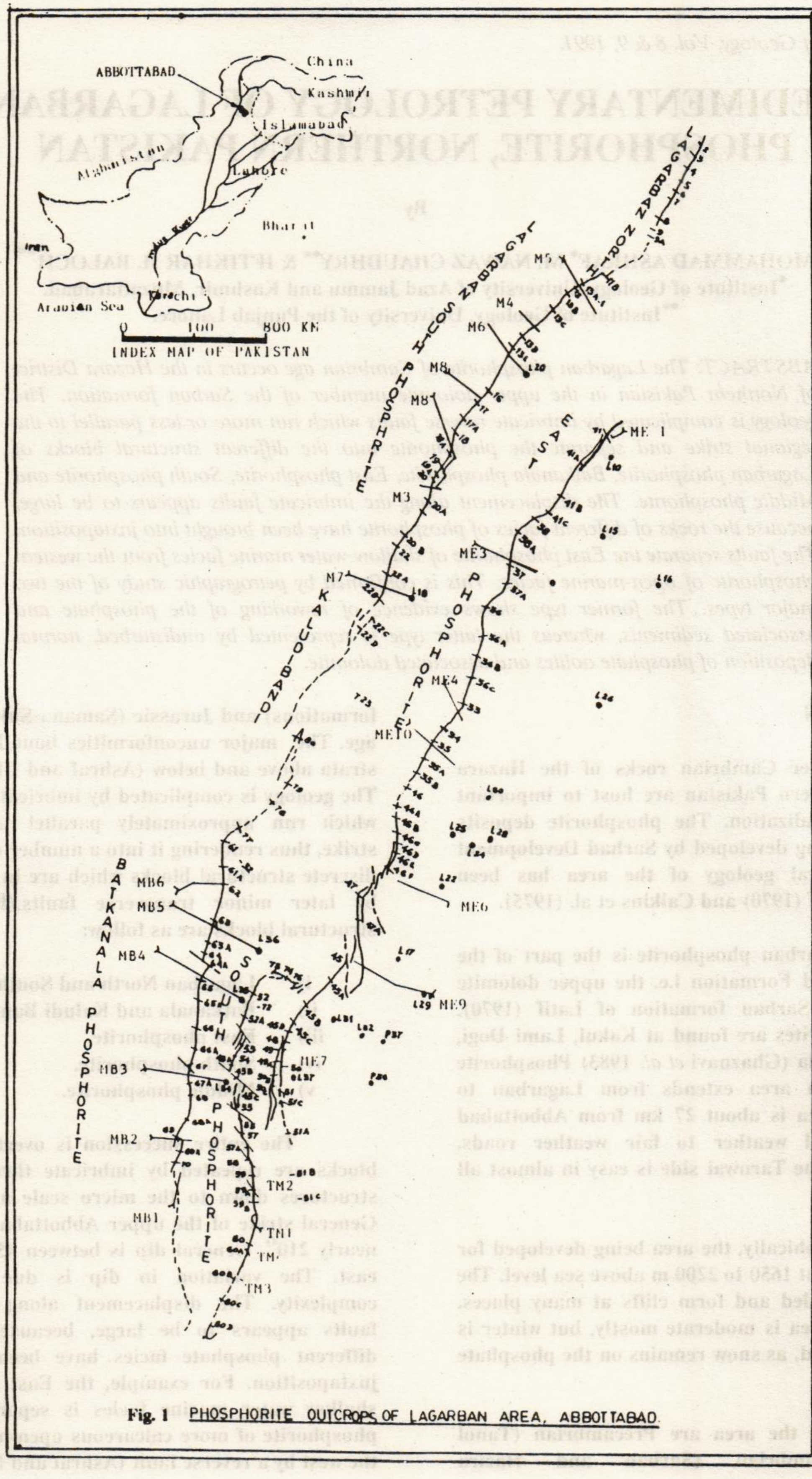

Fig. 1 PHOSPHORITE OUTCROPS OF LAGARBAN AREA, ABBOTTABAD.

Details of the geology of the Abbottabad area and the phosphorite deposits have been discussed earlier by Middlemiss (1896), Latif (1970), Calkins and Matin (1968), United Mines (1973), Ashraf (1974), Ali (1977), Bhatti (1977), Ghaznavi and Karim (1978), Hasan and Ghaznavi (1980), Ghaznavi *et al.* (1983), and Ashraf and Malik (1983). In this paper, detailed petrography of the phosphorite is described and its genesis is briefly discussed.

THE PHOSPHORITE

The phosphorite beds occur in the Cambrian Abbottabad Formation. The phosphorite member occurs in the upper part of the formation and is sub divided into four units; A, B, C and D (Fig. 2).

The A-unit consists of dolomite with numerous subordinate bands of phosphorite and chert. This marks the earliest deposition of phosphorite in the area. The phosphorite bands over the entire area are not continuous but occur as discontinuous bands.

The B-phosphorite consists of a basal pelletal sheared phosphorite, a non-pelletal dolomitic phosphorite and an upper interbedded phosphorite and cherty dolomite zone.It has a sharp contact with the dolomite of A-unit. The B-unit is the only consistent zone in thickness and lithology over the entire Lagarban-Tarnwai region. However, it does show thinning and thickening due to structural complexity. It comprises the main economic phosphorite deposit.

The C-unit makes a gradational zone between the B-unit and an upper gritty dolomite.

The D-unit indicates the end of phosphate bloom and is overlain conformably by siltstones and shales of the Hazira formation.

EAST PHOSPHORITE

Petrography

Petrographic studies of the Eastern phosphorite (Tables 1-4) show facies variation along and across the strike from its northern to southern end (Figs. 3, 4, 5 and 6). The facies to the north are from shallow water marine to possibly continental in nature. Whereas, the southern half shows a relatively deeper water facies. These facies variations have been also found in the subsurface by driving adits and drilling.

Texture and Structure:

In the northern area, the phosphate is in the form of irregular pieces of phosphate and chert embedded in a cherty matrix in the hanging wall where subsequent mobilization has redeposited some phosphate as well as chert obliterating former relationship by replacement. Below the hanging wall is phosphatic rock containing criss crossed chert veins 0.5 to 3 mm across. The phosphatic part is moderately pelletoidal with occasional pieces of chert. The footwall side is massive, brecciated phosphatic rock, where phosphate has been broken and recemented by chert. At places, pieces of massive phosphate show roughly rhombic partings which may be filled by carbonate and chalcedony.

In a drill hole at about 125 meters in the subsurface, the thin 0.6 m ore horizon at surface thickens to about 3 meters with the following textural features from the hanging wall downwards. The uppermost lithology is clastic grains of quartz embedded in collophane. Next there is a chert part showing salt and pepper structure. The phosphorite zone is a massive cherty phosphate (Fig. 7) containing veins, patches and disseminations of chalcedony. It also contains clastic grains of quartz. The phosphorite is fine-grained,massive and inequigr- anular containing some small recrystallized areas. In the higher zones, a few pellets 0.10 to 0.35 mm size are also embedded in the fine-grained groundmass.

In the central part of the Eastern phosphorite, the phosphatic rocks of various zones are inequigranular; bigger grains are of chert, quartz and collophane (Fig. 8). The reworked character of the rock is rather obvious, especially the rounding of the chert grains. The phosphate is pelletoidal to fine-grained. Towards the base of the phosphorite exhibits a poorly banded or streaked character. The streaked and banded nature is due to relative abundance of chert or phosphate in a particular area. The rock as a whole is fine-grained in this zone and chert seems to be a cementing material as well. The middle zone of the phosphorite is slightly reworked and contains a few bits and pieces of phosphate. Generally the rock is fine-grained and pelletoidal. The pellets are of phosphate minerals. In the upper beds, the rocks are highly inequigranular. The pieces of phosphate rock have been resedimented and recemented having the nature of a microbreccia bounded by chalcedony, dahllite and minor micaceous minerals.

In the southern-most end, the phosphorite

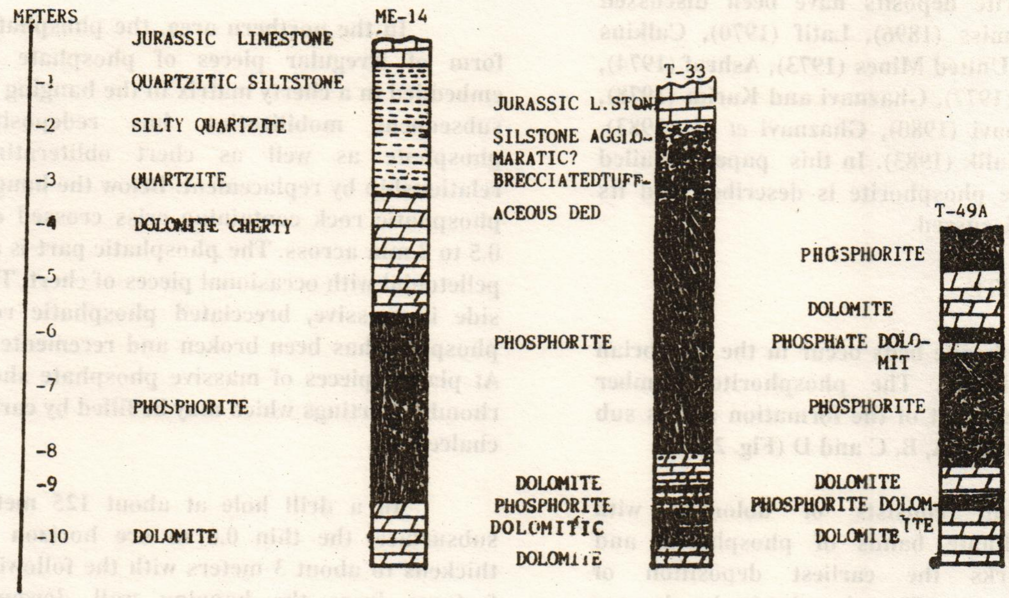

Fig. 2 PHOSPHATIC TRENCHES OF EAST PHOSPHORITE

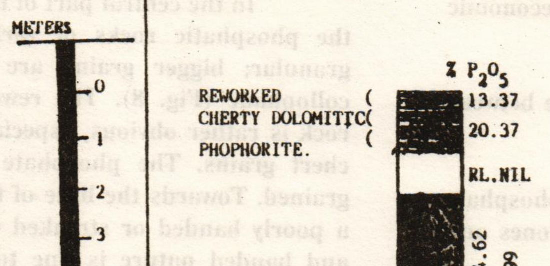

Fig. 3 DRILL HOLE L-19 PHOSPHORITE.

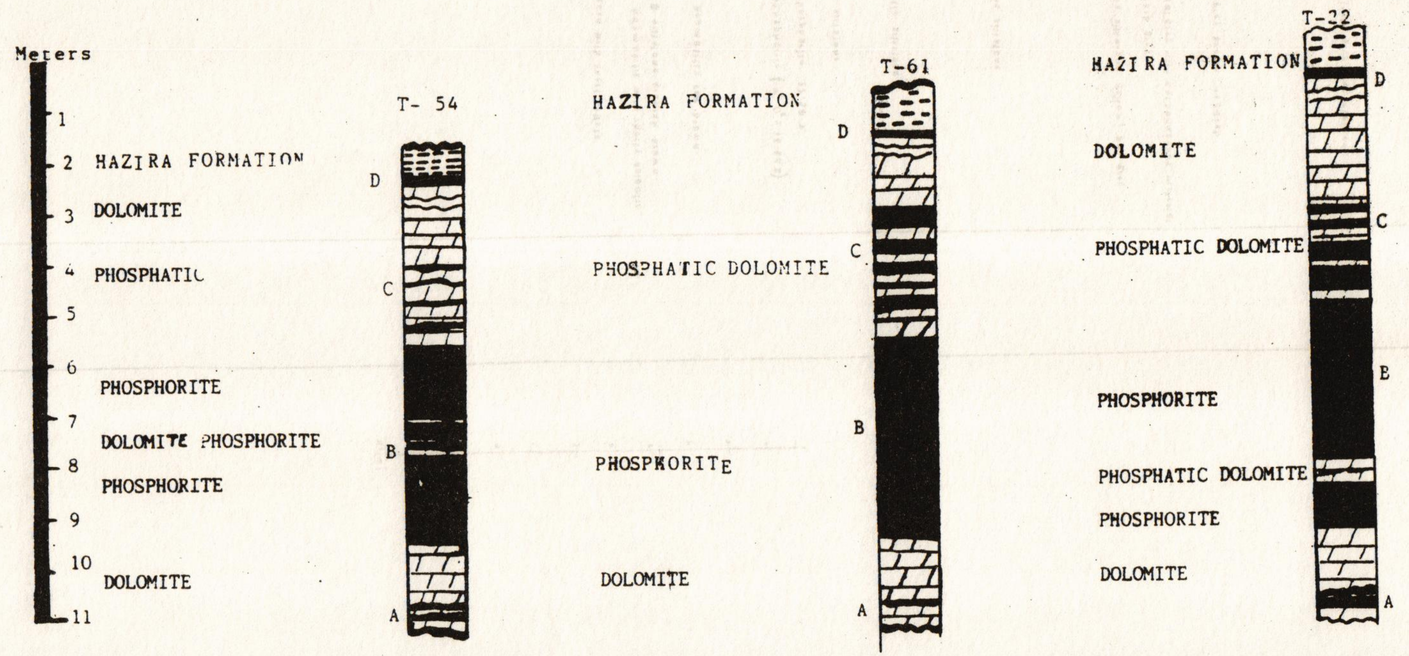

Fig. 4 TRENCHES SHOWING VARIOUS PHOSPHATIC ZONES AND YOUNGER HAZIRA SILTSTONE OF LAGARBAN BATKANALA & SOUTH PHOSPHORITES .

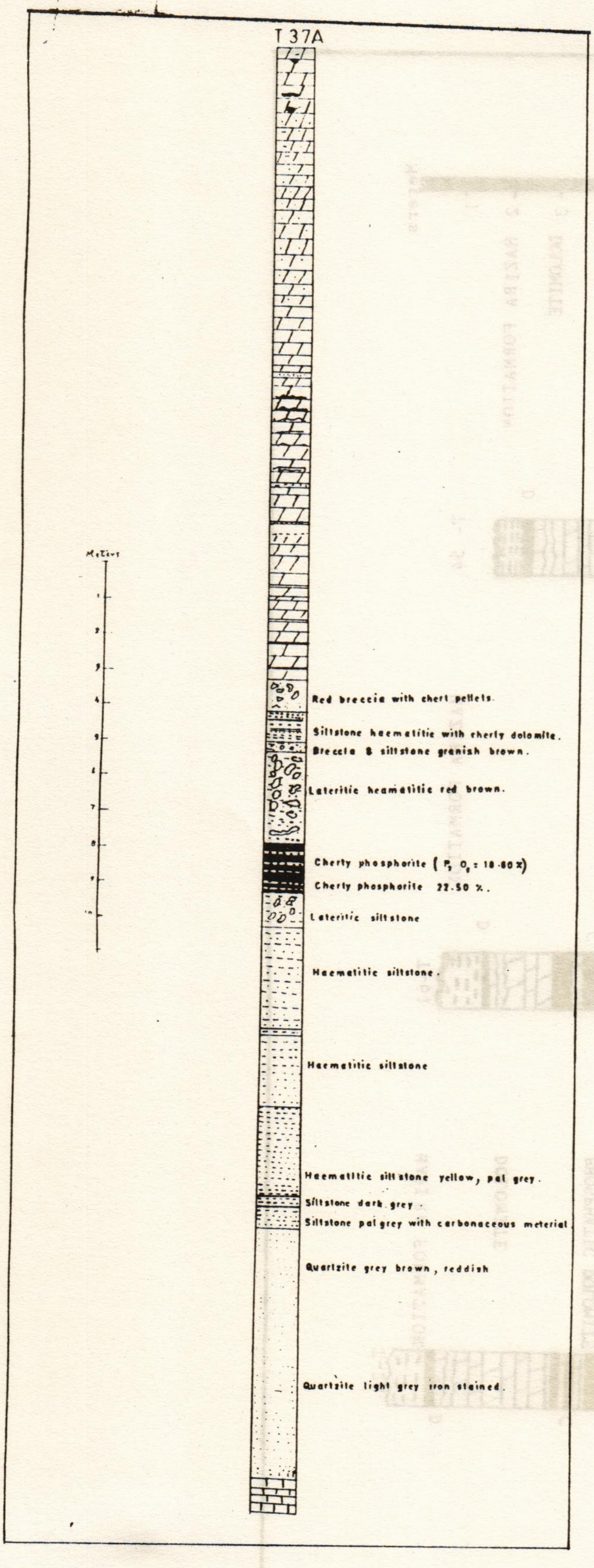

Fig. 6 TRENCH 37-A EAST PHOSPHORITE

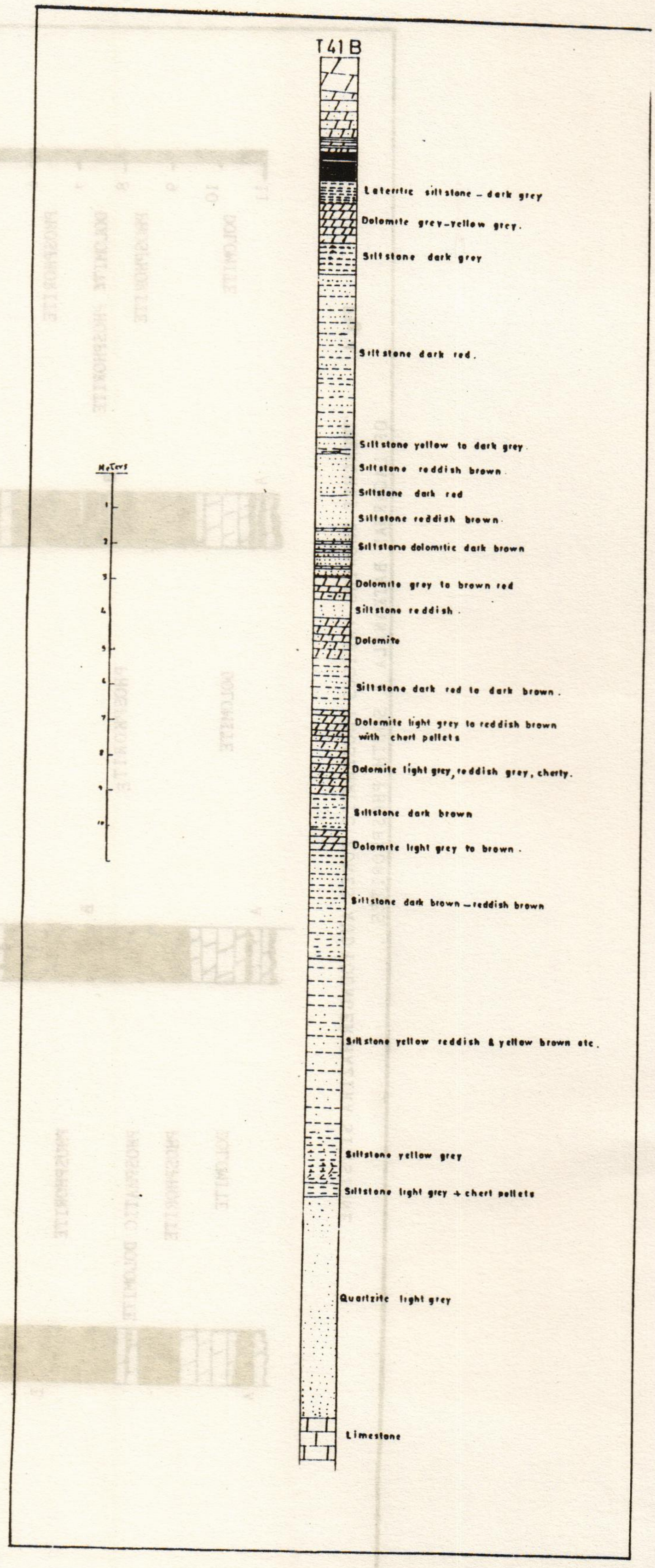

Fig. 5 TRENCH 41-B FAST PHOSPHORITE

Table - 1 Petrographic Composition of Sample of Trench 37A East Phosphorite

	37A/1	37A/2	37A/3	37A/4	37A/6	37A/7	37A/7A	37A/8	37A/9	37A/10	37A/11	37A/12	37A/13
Collophane	--	--	--	--	--	--	20.0	50.0	75.0	--	--	--	--
Dahllite	--	--	--	--	--	--	1.0	10.0	2.0	--	--	--	--
Carbonate	98.0	60.0	--	--	--	--	--	--	1.0	--	--	--	--
Chalcedony	--	5.0	60.0	62.0	65.0	--	60.0	30.0	20.0	--	--	--	--
Opal	--	--	3.0	5.0									
Quartz	0.5	--	12.0	15.0	15.0	35.0	--	6.0	2.0	20.0	35.0	30.0	94.0
Hematite	--	--	7.0	3.0	--	5.0	--	1.0	--	7.0	12.0	2.0	--
Limonite Goethite					1.0	10.0	1.0						1.5
Clay	1.5	--	12.0	--	4.0	30.0	--	--	--	20.0	45.0	30.0	3.5
Carbonaceous matter	--	--	--	--	--	--	--	--	--	--	±Sericite	--	±Sericite
Pyrite	--	--	--	--	--	--	--	--	--	--	--	--	--
Biotite	--	--	--	--	--	--	--	--	--	--	--	1.0	--
Muscovite/Sericite	--	--	6.0	--	--	15.0	--	--	--	50.0	--	33.0	--
Chlorite	--	--	--	15.0	15.0	2.0	18.0	3.0	--	2.0	3.0	1.5	--
K-Feldspar	--	--	--	--	--	1.0	--	--	--	--	2.0	1.0	--
Albite	--	--	--	--	--	1.0	--	--	--	0.5	2.0	1.0	--
Tourmaline	--	--	--	--	--	0.5	--	--	--	--	0.5	0.5	0.75
Rutile	--	--	--	--	--	0.5	--	--	--	0.5	0.5	--	--
Siltstone matrix		35.0											

Table - 2 Petrographic Composition of Sample of Drill Hole L-19 East Phosphorite

	L-19/1	L-19/2	L-19/3	L-19/4	L-19/5	L-19/6	L-19/7	L-19/8	L-19/9	L-19/10	L-19/11	L-19/12	L-19/13	L-19/14	L-19/15	L-19/16	L-19/17
Collophane	--	75.0	6.0	65.0	70.0	60.0	65.0	65.0	75.0	--	--	--	--	--	--	--	--
Dahllite	--	2.0	--	1.0	8.0	5.0	25.0	25.0	20.0	--	--	--	--	--	--	--	--
Carbonate	5.0	--	--	--	--	--	--	--	--	4.0	5.0	12.0	2.0	--	--	--	--
Chalcedony	60.0	3.0	45.0	20.0	7.0	20.0	--	7.0	3.0	--	10.0	60.0	--	--	4.0	--	--
Quartz	--	13.0	48.0	10.0	15.0	12.0	7.0	--	--	55.0	50.0	5.0	20.0	10.0	--	2.0	5.0
Hematite	2.0	3.0	--	1.0	--	1.0	3.0	2.0	1.0	24.0	26.0	12.0	5.0	14.0	1.0	1.0	--
Limonite Goethite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Clay	20.0	4.0	1.0	1.0	--	1.0	--	--	--	12.0	8.0	10.0	50.0	55.0	70.0	75.0	75.0
Carbonaceous matter	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.0	--
Pyrite	--	--	--	--	--	--	--	1.0	--	--	--	--	--	--	--	--	4.0
Biotite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Muscovite/Sericite	3.0	--	--	--	--	--	--	--	--	--	--	--	20.0	20.0	--	5.0	--
Chlorite	10.0	--	--	2.0	--	1.0	--	--	1.0	4.0	--	--	--	--	--	--	--
K-Feldspar	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Albite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tourmaline	--	--	--	--	--	--	--	--	--	--	--	0.5	1.0	--	0.5	0.5	--
Rutile	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.5	--	2.0
Sphene	--	--	--	--	--	--	--	--	--	0.5	0.5	--	--	0.5	0.5	--	--
Zircon	--	--	--	--	--	--	--	--	--	0.5	0.5	--	2.0	0.5	0.5	0.5	1.0
Epidote	--	--	--	--	--	--	--	--	--	--	--	0.5	--	--	--	--	--
Boehmite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	15.0	10.0	10.0
Gibbsite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	8.0	5.0	3.0

Table - 3 Petrographic Composition of Samples of East Phosphorite

	TRENCH 368 EAST PHOSPHORITE			TRENCH 33 EAST PHOSPHORITE			T-47A	TRENCH 49A EAST PHOSPHORITE				
	36B/1	36/B2	36B/2	33/1	33/2	33/2	47A	49A	49B/1	49B/2	49B/3	49B/4
Collophane	--	--	--	--	10.0	--	--	70.0	75.0	39.0	56.0	73.0
Dahllite	--	--	--	--	--	--	--	11.0	10.0	4.0	5.0	10.0
Carbonate	--	--	--	--	--	--	--	1.5	2.0	48.0	--	7.0
Chalcedony	25.0	6.0	--	70.0	75.0	75.0	50.0	7.5	3.0	3.0	32.0	3.0
Quartz	10.0	85.0	10.0	10.0	--	7.0	5.0	8.0	2.0	3.0	6.0	2.0
Hematite/Limonite/Geothite	10.0	--	--	15.0	6.0	10.0	3.5	1.5	4.0	3.0	1.0	5.0
Clay	55.0	7.0	80.0	--	7.0	--	35.0	--	--	--	--	--
Organic Matter	1.0	--	--	--	2.0	--	--	--	--	--	--	--
Pyrite	--	--	--	--	--	--	--	0.5	--	--	--	--
Biotite	--	--	--	--	--	--	--	--	--	--	--	--
Muscovite/Sericite	8.0	--	5.0	--	--	--	5.0	--	2.7	--	--	--
Chlorite	--	--	3.0	5.0	--	8.0	1.0	--	--	--	--	--
Tourmaline	--	2.0	1.0	--	--	--	0.5	--	0.2	--	--	--
Sphene	--	--	0.5	--	--	--	--	--	--	--	--	--
Rutile	--	--	0.5	--	--	--	--	--	0.1	--	--	--

Table - 4 Petrographic Composition of Samples of Mine ME10

	ME10/1	ME10/2	ME10/3	ME10/4	ME10/5	ME10/6	ME10/7	ME10/8	ME10/10	ME10/11
Collophane	11.0	45.0	60.0	65.0	70.0	60.0	22.0	--	--	--
Dahllite	--	5.0	3.0	4.0	8.0	9.0	2.0	--	--	--
Carbonate	62.0	--	--	--	--	--	--	55.0	--	--
Chalcedony	13.0	20.0	32.0	7.0	7.0	20.0	70.0	35.0	5.0	6.0
Quartz	12.0	7.0	5.0	15.0	7.0	6.0	3.0	--	35.0	35.0
Hematite/ Limonite/Goethite	0.5 1.5	-- 4.0	-- --	-- 5.0	2.0 2.0	-- 0.4	-- 2.0	-- 2.0	-- 3.0	-- 3.0
Clay	--	--	--	--	2.0	3.0	--	--	25.0	30.0
Organic Matter	--	1.0	--	--	--	--	1.0	--	--	--
Pyrite	--	--	--	--	--	0.1	--	--	--	--
Biotite	--	--	--	--	--	--	--	--	3.0	--
Muscovite/Sericite	--	--	--	1.0	--	--	--	--	20.0	20.0
Chlorite	--	18.0	--	3.0	2.0	1.0	--	8.0	8.0	5.0
Tourmaline	--	--	--	--	--	--	--	--	0.5	1.0
Rutile	--	--	--	--	--	--	--	--	0.5	--

Table - 5 Petrographic Composition of Samples of South Batkanala and Lagarban Phosphorite

		TRENCH-54 SOUTH PHOSPHORITE					TRENCH 61 BATKANALA PHOSPHORITE					TRENCH 22 IAGARBAN PHOSPHORITE				
	54A	54/1	54/2	54/3	54/4	54/5	61/1	61/2	61/3	61/4	61/5	22/1	22/2	22/3	22/4	22/5
Collophane	35.0	55.0	46.0	70.0	70.0	55.0	37.0	40.0	26.0	68.0	22.0	65.0	60.0	13.0	45.0	80.0
Dahllite	11.0	11.0	6.0	5.0	8.0	10.0	20.0	20.0	5.0	5.0	5.0	10.0	1.0	1.0	--	1.0
Carbonate	3.0	20.0	34.0	16.0	14.0	25.0	34.0	31.0	62.0	--	62.0	3.0	--	80.0	45.0	10.0
Chacedony	35.0	--	2.0	2.0	3.0	4.0	4.0	4.0	2.0	16.0	6.0	10.0	10.0	2.0	--	8.0
Quartz	15.0	4.0	2.0	1.0	--	3.0	2.0	2.0	3.0	5.0	5.0	10.0	--	--	6.0	--
Hematite/ Limonite/ Goethite	1.0 -- --	5.0 2.0 --	10.0 -- --	6.0 -- --	5.0 -- --	3.0 -- --	3.0 -- --	3.0 -- --	2.0 -- --	2.0 4.0 --	-- -- --	2.0 -- --	5.0 1.0 13.0	4.0 -- --	3.0 -- --	1.0 -- --
Clay	--	2.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Carbonaceous matter	--	1.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pyrite	--	--	--	--	--	--	--	--	--	--	--	--	10.0	--	--	--

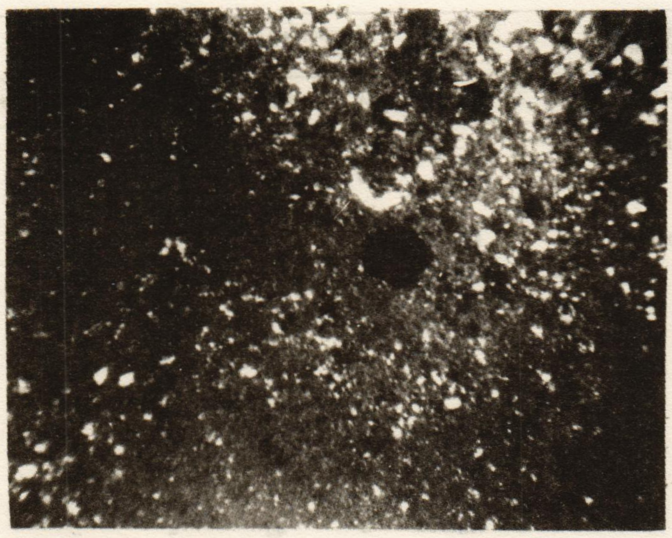

Fig. 7.

Fig. 8.

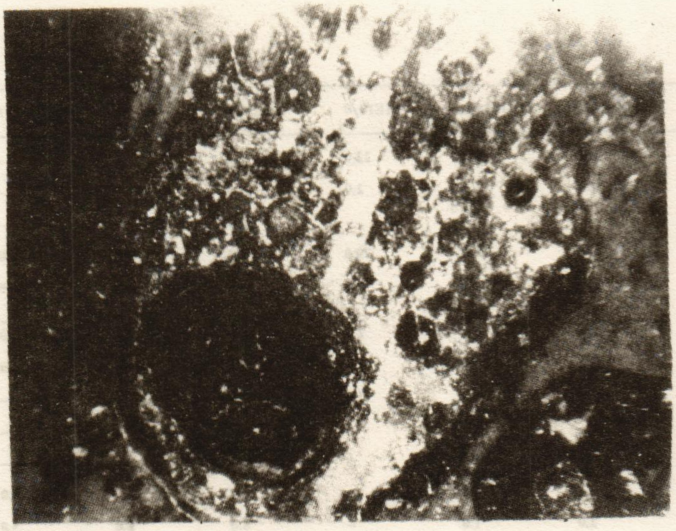

Fig. 9.

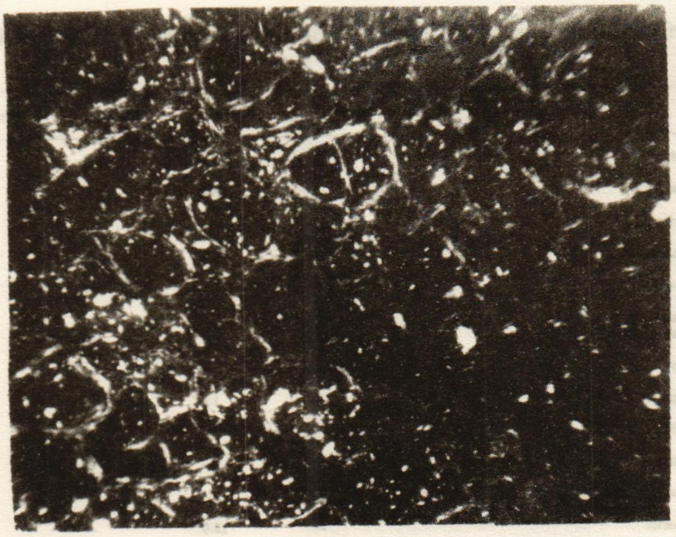

Fig. 10.

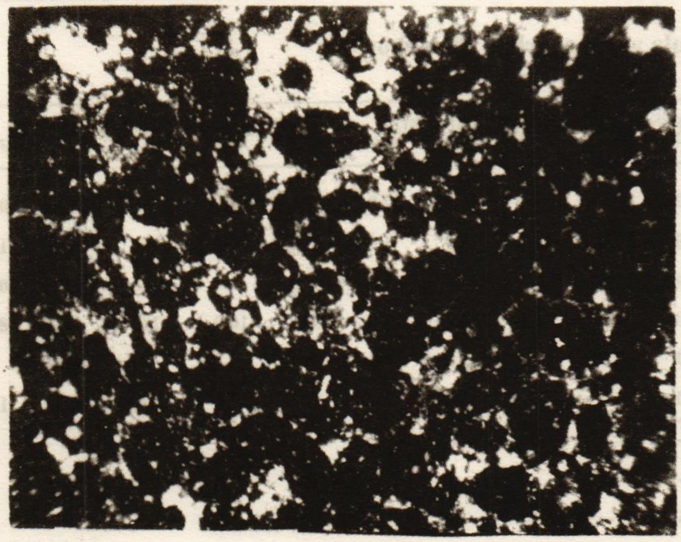

Fig. 11.

Fig. 7. Massive, Non-oolithic Phosphorite Containig Occasional Ooliths (black rounded) in Drill Hole L-19.X20, X-nicols

Fig. 8. Rounded Cherty Grains Embedded in Collophane. X20, X-Nicols

Fig. 9. Reworked Phosphorite,a Rounded Fragment of Phosphorite Containing Ooliths of Collophane of Variable Size. X20, X-nicols.

Fig. 10. Oolith of Collophane Surrounded by Rings of Dahllite. X20, X-nicols.

Fig. 11. Ooliths of Collophane (Black) Embedded in Dolomite. The Ooliths Themselves Contain Small Grains of Dolomite and Quartz (White Specks in Ooliths). X-20, X-Nicols.

bears the texture and structure of the pelletoidal and irregularly banded form. The phosphate pellets are embedded and cemented by amorphous-looking phosphatic matter (Fig. 9). Some stringers of carbonate and streaks of limonite/hematite also occur. In some zones the phosphatic rock is cut by veinlets of carbonate, chert and dahllite.

Mineralogy

Mineral composition of the phosphorite zones in general exhibits the following characters (Tables 1-4).

Collophane: It occurs as irregular bits and pieces embedded in chert, pelletoidal masses embedded in chert, fine-grained collophane and non-pelletoidal massive phosphatic material. The collophane pellets may have marginal rings of dahllite or alternating marginal rings of collophane/dahllite. The pellets generally range in size from less than 0.20 to 0.25 mm. Collophane is light brown to rusty brown sometimes greenish brown and non-pleochroic. In crossed nicols it is extremely weakly birefringent to almost isotropic.

Dahllite: It occurs mostly as an alteration product of collophane. Sometime distinct dispersed grains and patches also occur. The alteration is mostly on the margin of collophane pellets as fibers and flakes (Fig. 10). It also resembles apatite very much. It is colorless and birefringent. The grain size is usually finer than 0.01 mm but coarser grains up to 0.20 mm are also sometimes present. It is usually 1 to 10% of the rock but up to 25% is also found in some rocks.

Chert: It occurs as a few pellet-like and irregular pieces, patches, veinlets, thin bands and disseminated matter. It shows a well developed salt and pepper structure. Subrounded to rounded grains may occur embedded in collophane. Sheaf-like and sub-radial growths are rare. At places it recrystallizes to quartz. The general size of fragments ranges from 0.5 to 3.0 mm.

Quartz: Quartz is found as tiny silt-sized, randomly distributed angular to subangular grains 0.05 to 0.20 mm. The grains are sometimes embedded in a collophane matrix. Quartz grains sometimes show diffused boundaries.

Carbonate: Carbonate minerals are not present in the phosphatic zones of the northern part of the East phosphorite. However, carbonate is found in the southern part. It occurs as fine streaks and small grains. Their size ranges from 0.05 to 0.20 mm. In the dolomitic phosphate zone of T-49A, carbonate occurs as grains, veins, streaks, patches and rock fragments. It also forms small pellets. The grain size is as follows: Big crystals 0.5 to 2.5 mm one band about 0.5 mm thick, veins 0.05 to 0.25 mm and pellets 0.05 to 0.30 mm mostly.

Hematite/Limonite: Hematite occurs as fine grains (0.05 to 0.15 mm) randomly distributed and also as aggregates (0.02 to 0.3 mm). In reflected light it is dull red to blood red in color. Limonite occurs as colorations, specks, amorphous-looking aggregates and as cement.

Chlorite: It occurs associated with phosphate and chert phases. It formed along with the embedding chert as well as during the subsequent replacement phase. It is medium grained and distinctly pleochroic. It also occurs with iron minerals. As subradial to sheaf-like chlorite occurs in 0.08 to 0.15 mm aggregates. It is nearly ubiquitous mineral of the middle and northeastern phosphorite. The presence of chlorite and pyrophillite in these rocks have been also reported by Ghaznavi *et al.* (1983). This indicates low-grade metamorphism in this area (Ghaznavi *et al.*, 1983).

Accessory Minerals: Accessory minerals in the phosphatic zones are clay, organic matter, pyrite, biotite, muscovite/sericite, tourmaline and rutile. Their occurrence is volumetrically insignificant and they are not present in each case (Table-1).

LAGARBAN, BATKANALA AND SOUTH PHOSPHORITE

Petrography

Petrography of three phosphorite ore bodies (Table-5) is presented here as a single population because these represent almost the same facies of deeper water phosphate deposition based on the abundance of carbonate mineral (dolomite) and the smaller amount of chert and quartz compared to the East phosphorite (Fig. 11).

Texture and Structure

Texture and structure varies from zone to zone but general features can be given. On the hanging wall side, the rock is crushed and sheared pieces of phosphate, chert and quartz cemented by chalcedonic and phosphatic matter, sometimes showing replacement of phosphate by carbonate. In T-54 (Table-5) a mixed phosphate-dolomite groundmass contains pellets of collophane. In the subsequent zone the phosphate is either amorphous, strongly pelletoidal (oolitic) or both. Oolites of collophane and carbonate sometimes occur together (Fig. 12). In some cases alternate bands of phosphate and carbonate occur. The carbonate part is mainly fine-grained while the phosphate part is mainly pelletoidal. The pellets in most cases are rounded to sub-rounded. In the amorphous phosphatic zones collophane is micro-to cryptocrystalline. In such cases chert occurs either as microconcretions or as small aggregates and is crisscrossed by veinlets of carbonate.

Mineralogy

The mineralogy of the Lagarban, Batkanala and South phosphorite is as follows:

Collophane: It occurs as cryptocrystalline (amorphous) aggregate to pelletoidal material. The latter is rounded to subrounded as well as from irregular to fairly irregular shaped. The pellets contain some bits of carbonate, quartz and chert. Pellets range in size from 0.10 to 1.75 mm and occasionally up to 4.25 mm. It is light rusty brown to brown colored and isotopic to very weakly birefringent. It alters to dahllite.

Dahllite: It occurs closely associated with collophane. It occurs as tiny prismatic crystals, small granular areas and grains, and in some cases as anisotropic flaky and sheaf-like rings around pellets. The grains and their aggregates range in size from 0.01 to 0.08 mm. It is colorless to light brown and non pleochroic.

Carbonate: It occurs as highly unequal grains. It forms veins, patches, bands, streaks, and diffuse replacements. Individual grains are anhedral to subhedral. A few rounded oolitic grains also occur. It is very irregular in grains and aggregate size. Streaks are from 0.01 to 0.05 mm thick, veins are from 0.01 to 0.15 mm thick and bands up to 5 mm. It also forms a cement for collophane.

Chert: It occurs as a few pieces and as dispersed matter showing salt and pepper structure. Subradial structure is less common. It also occurs as thin veins and a binding matter to the phosphate pellets and fragments. The aggregates are very small to 1.5 mm in size.

Accessory Minerals: Some of the ubiquitous accessory minerals are quartz and hematite/limonite. The later are about 1.0 to 6.0% commonly while 10.0 to 18.0% are also present. Quartz is generally 2.0 to 5.0 in the rocks. Accessory minerals are pyrite, clay and carbonaceous matter, while chlorite is absent.

DISCUSSION

The geologic and petrographic studies in the Lagarban-Tarnwai area show that at the end of Early Cambrian the deposition became shallower to continental. First the A-unit was deposited, consisting of alternate thin phosphorite and thicker dolomite bands. The phosphate was deposited in a relatively calm sea in the Lagarban North, Lagarban South, and Batkanala and to some extent the South Phosphorite. The East phosphorite, in contrast, was deposited in a sort of undulating very shallow sea with abundant wave activity. This is evident by the presence of reworked dolomite having an undulating base and also recemented and brecciated phosphorite at many places. The phosphorite contains insignificant carbonate minerals while chert is dominant along with collophane. Chert can be formed in such conditions very easily and has no relation to depth for its formation. In the Eastern phosphorite area, the units overlying the B-unit are also reworked, consisting of typical continental lateritic material having oolitic bauxite as a minor constituent. In the depressions between two paleohighs quartzitic and silty Hazira formation is overlying the Abbottabad Formation, whereas on their slopes reworked reddish siltstone is formed. This sort of lithology is in contrast to the C-unit upper gritty dolomite, D-phosphorite and Hazira formation. The continental to shallow water environments are indicated by East phosphorite, mostly in middle northern portions, whereas the Lagarban, Batkanala and South phosphorite represent the normal deep water environments. This relationship show that the so-called Galdanian facies is an equivalent of the phosphorite while Hazira is a younger stratigraphic unit. It also indicates that the Galdanian culminates the Abbottabad time. These relationships are shown schematically in Fig. 13.

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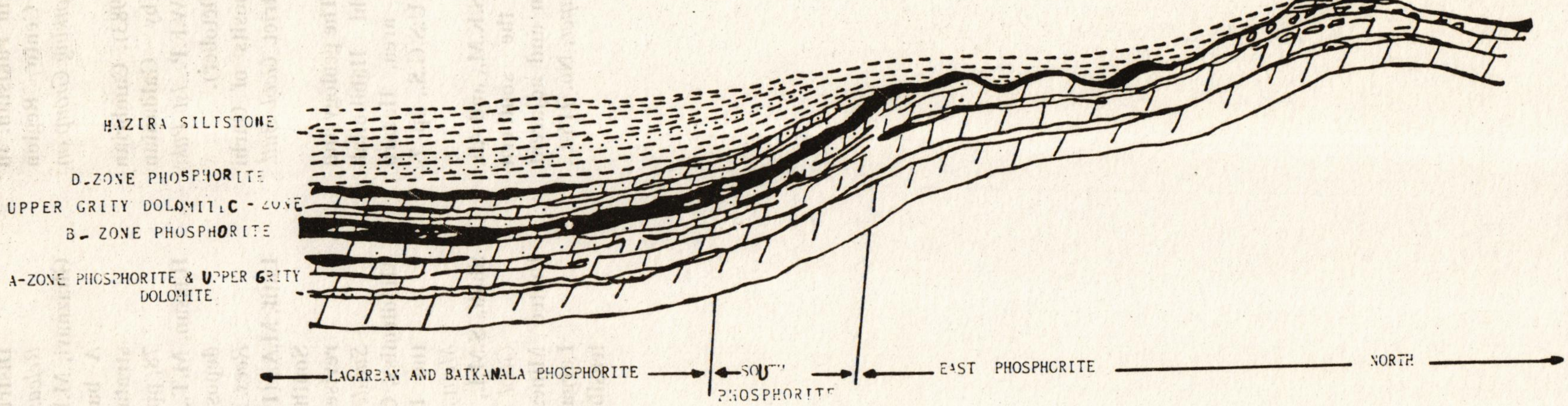

Fig. 12 IDEALIZED DEPOSITIONAL ENVIRONMENTS OF PHOSPHORITE AND GALDANIAN UNCONFORMITY IN LAGARBAN TARNWAI AREA ABBOTTABAD N.W.F.P.

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STRATIGRAPHY, METAMORPHISM AND TECTONICS OF THE HAZARA-KASHMIR SYNTAXIS AREA

By

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ABSTRACT: The stratigraphical and metamorphic features of the rocks belonging to the Hazara-Kashmir Syntaxis are described. A large-scale subdivision of the area in the classical Sub-, Lesser and Higher Himalayan tectonic elements is proposed. A model for the tectonic evolution of the area, based on a coherent and continuous development of the observed small-and large-scale structural and metamorphic features, is suggested.

INTRODUCTION

In the past years a group of geologists of the Geological Institute, ETH-Zurich has intensively investigated parts of the Himalayan ranges in NE-Pakistan (Kaghan Valley and Azad Kashmir). The results have been reported in several Ph.D. thesis, diploma thesis and publications. The aim of these works has been to investigate stratigrpahical aspects, to correlate large-and small-scale tectonic structures, to detect the complex structural geometry and to study the relationships between the deformational and metamorphic histories of the investigated areas.

This work reassume the stratigraphic, metamorphic and tectonic features of the Hazara Kashmir Syntaxis exposed in the accessible parts of Azad Kashmir (Muzaffarabad area, Neelum and Jhelum Valleys) and of the Kaghan Valley, and proposes a model for the tectonic evolution.

DESCRIPTION AND AGE OF THE ROCK SEQUENCES

The composition, age and distribution of the rocks of the investigated area is complicated by the development of different structural elements which contain repeatedly deformed and metamorphosed parts of the stratigraphical sequence. Despite these difficulties, in the last century several authors have produced maps and stratigraphical columns of the Hazara-Kashmir Syntaxis (HKS) area (Wadia 1931 and 1934, Calkins *et al.*, 1975 Bossart, 1986 and Ottiger, 1986). Figure 1 compares the stratigraphical columns compiled by these authors with those used in the present work, whereas the compilation map of Figure 2 shows the distribution of the rock sequences which are grouped into tectonic units.

1. The Salkhala Formation

The older rocks exposed in the investigated area are low metamorphic, unfossiliferous, crystalline pelitic-argillaceous schists alternated with carbonates and basic and granitic intrusions. This sequence has been subdivided by Wadia (1931) into a predominantly carbonaceous Salkhala series of Precambrian age and an argillaceous Dogra slates series, both corresponding to the "slates series" of Middlemnis (1896), and in the associated basic and acid "igenous intrusives: of post-Cambrian age. The definition given by Calkins *et al.*, (1975, from Offield and Abdullah, 1960, unpubl.) to the Salkhala formation seem to be much comprehensive because it associates the whole range of the metasediments (quartzitic schists, marbles, graphitic schists, ...) with the granitic gneisses.

In the present work the name Salkhala formation has been used to group all the graphitic, chloritic, porphyroblastic and quartzitic micaschists, often interbedded with marbles (*i.e.* groups together the Salkhala series and Dogra slates series of Wadia, 1931), sandwiched between the Panjal and the Main Central Thrusts, and which extend from the axial zone of the syntaxis towards to southeast (Figure 2). The

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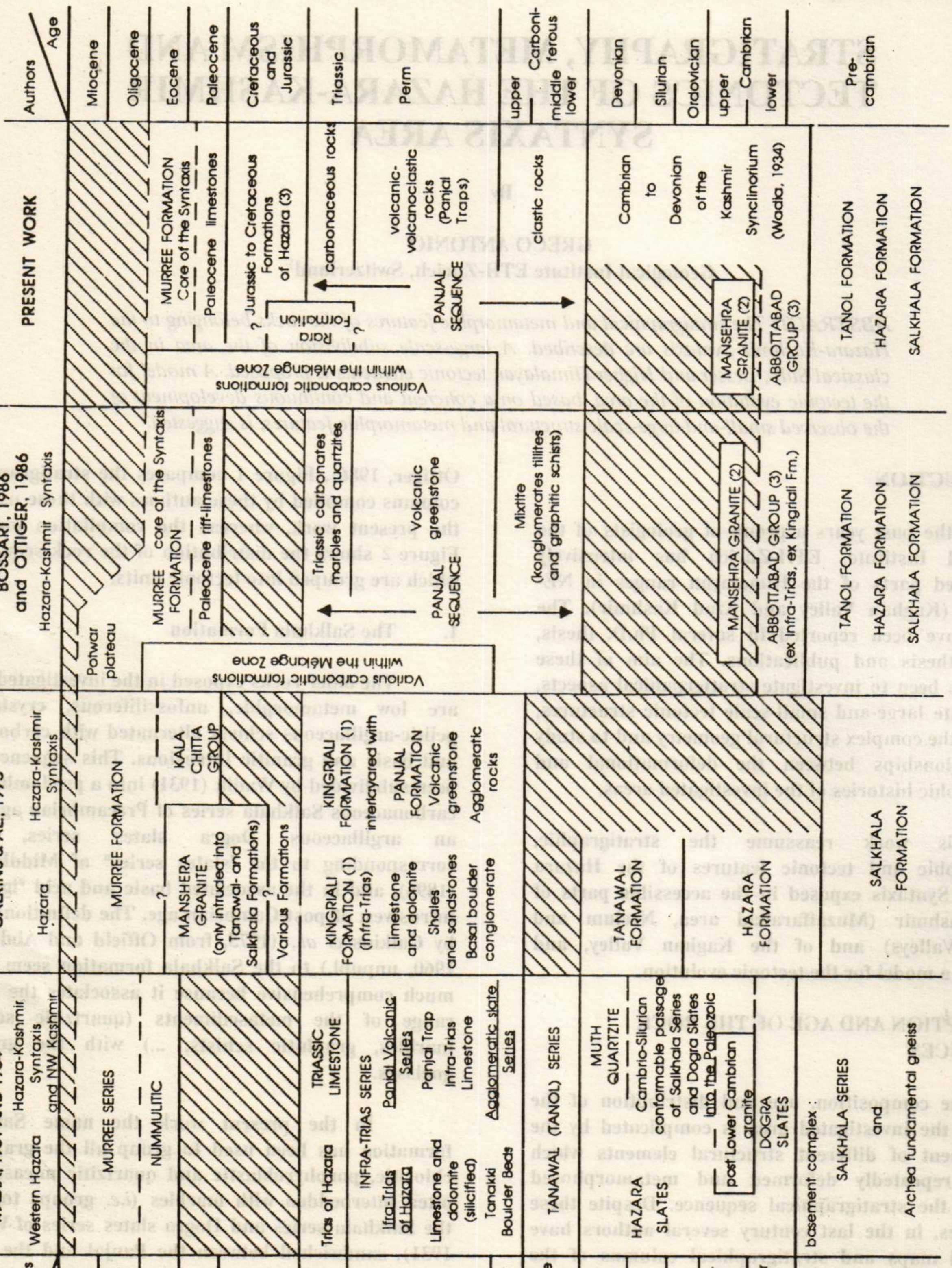


(1): Stratigraphic Committee of Pakistan; (2): Le Fort et al., 1980; (3): Latif, 1974

Figure 1: Stratigraphy of the investigated area: a comparison between different authors.

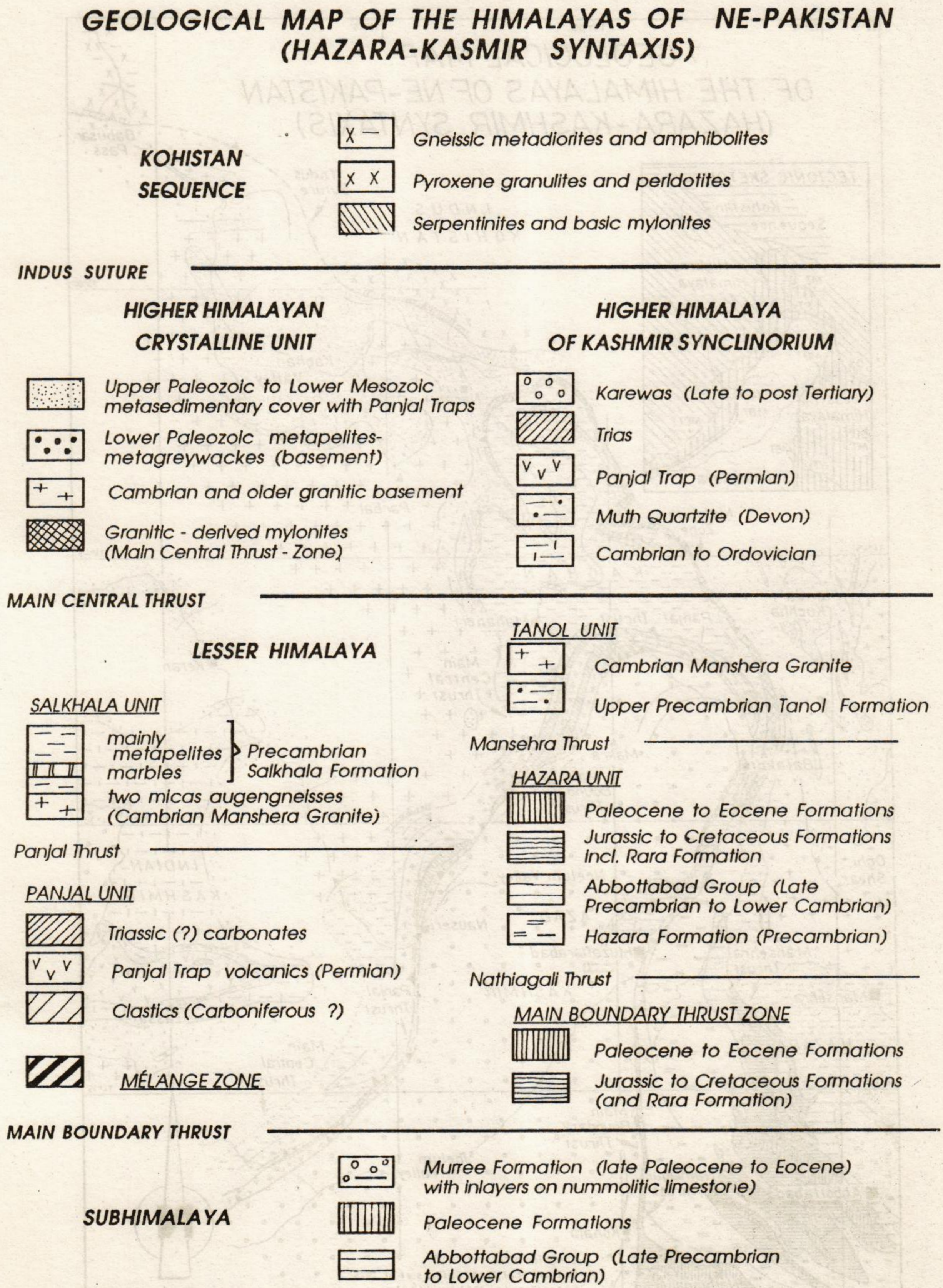
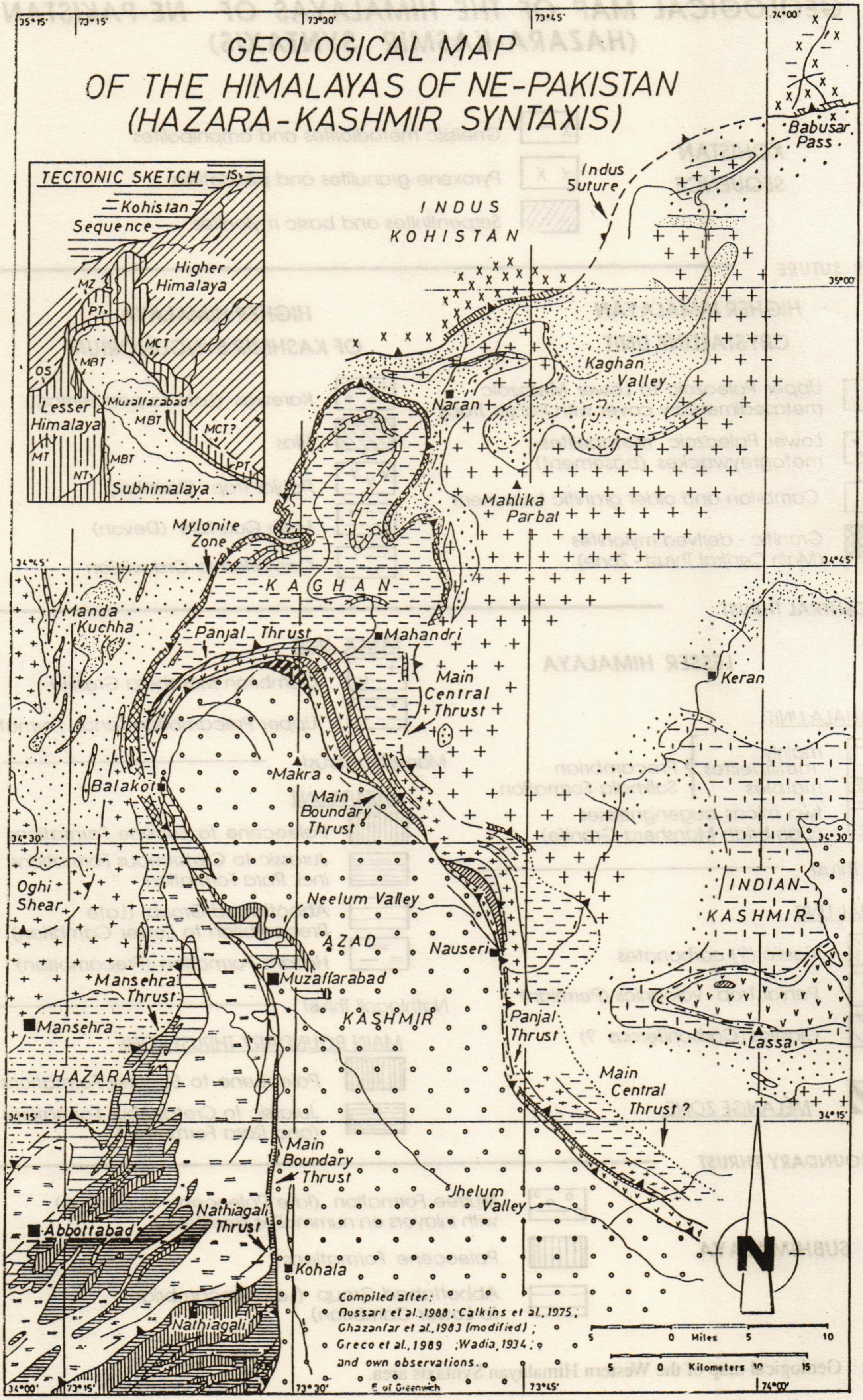


Figure 2: Geological map of the Western Himalayan Syntaxis area.


GEOLOGICAL MAP
OF THE HIMALAYAS OF NE-PAKISTAN
(HAZARA-KASHMIR SYNTAXIS)
TECTONIC SKETCH
IS
Kohistan
Sequence
Higher
Himalaya
MZ
PT
MCT
MBT
OS
Lesser
Himalaya
Muzaffarabad
MBT
MCT?
MT
NT
MBT
PT
Subhimalaya
INDUS
KOHISTAN
Indus
Suture
Babusar
Pass
Kaghan
Valley
Naran
Mahlika
Parbat
Mylonite
Zone
KAGHAN
Manda
Kuchha
Panjal Thrust
Mahandri
Main
Central
Thrust
Makra
Balakot
Main
Boundary
Thrust
Oghi
Shear
Neelum Valley
AZAD
Nauseri
Keran
INDIAN
KASHMIR
Mansehra
Thrust
Muzaffarabad
KASHMIR
Mansehra
Panjal
Thrust
Lassa
HAZARA
Main
Central
Thrust ?
Main
Boundary
Thrust
Jhelum
Valley
Abbottabad
Nathiagali
Thrust
Kohala
Nathiagali
Compiled after:
Dossari et al.,1988; Calkins et al.,1975;
Ghazanfar et al.,1983 (modified);
Greco et al.,1989 ;Wadia,1934;
and own observations.
Miles
Kilometers
E. of Greenwich
35°15'
73°15'
73°30'
73°45'
74°00'
35°00'
34°45'
34°30'
34°15'
34°00'

most common rock type is a fine-grained micaschist showing alternations of quartz-rich and mica-rich layers. This layering is best interpreted as relic sedimentary banding. Despite the severe deformation, primary sedimentary structures such as cross-bedding and current lamination are preserved in quartz-rich layers in the upper Kaghan Valley (Greco *et al.*, 1989), and are similar to those observed in the Tanol Formation (Fuchs, 1975).

As already suggested by Tahirkheli and Jan (1979), a Cambrian age is assigned to the porphyroblastic, two mica granitic gneisses because of their lithological similarity with the Manshra granite.

The basic intercalations could also be separated from the Salkhala schists because petrographic observations and geochemical analysis indicate their magmatic origin as hypabyssal equivalents of the Permian Panjal traps (Papritz and Rey, 1989).

Precambrian crystalline rocks, perhaps belonging to the Salkhala formation, form parts of the Higher Himalayan basement complex in both the Indian Kashmir (Wadia, 1934; Fuchs, 1975, Honegger *et al.*, 1982) and the Kaghan Valley (Greco *et al.*, 1989). At present, a distinction between Cambrian orthogneiss and older paragneiss has not been made in the investigated area.

2. The Hazara Formation

In the Hazara area of NE-Pakistan, the argillaceous, non-metamorphic equivalent of the Dogra slates have been called Hazara slates by Waagen and Wynne (1872) and by Wadia (1934), and more recently Hazara slates formation by Marks and Ali 1961). In the area between Nathiagali and Abbottabad, Gardezi (1968) was able to distinguish several lithological zones within the formation ("pelitic zone", "psammitic zone", "Miranjani and Langrial limestones"). Later, the whole sequence was renamed by Latif (1970) Hazara group of Hazara formation by Calkins *et al.*, (1975). A Late Precambrian age has been assigned (Gardezi, 1968; Latif, 1974; Crawford and Davies, 1975).

In the investigated area, Hazara formation occurs along the western limb of the Hazara-Kashmir Syntaxis (Muzaffarabad area). It is predominantly composed of slightly metamorphosed but strongly deformed argillaceous rocks (slates) accompanied by two distinct intercalations of carbonaceous and sulphate rocks respectively (Figure 3). The easternmost limestone band consists of thinly bedded, laminated limestones exposed along the Murree and the Nathiagali faults. These limestones become thicker bedded and intercalated with slates towards the west. The western band is characteristically composed of gypsum-bearing limestone and greenish, pyritic carbonaceous slates. The contact with the surrounding slates is sharp, probably tectonic, but some isolated thin limestone beds occur within the slates around Muzaffarabad. These non-argillaceous intercalations are considered to belong stratigrpahically to the Hazara formation and are supposed to extend southwestwards into the Miranjani and Langrial limestones. The strong deformational overprint makes hard to observe (if these have not been originally absent) sedimentary structures in the slates which result into very monotonous aspect except for the characteristic very fine-grained and graded lamination.

In the southwestern road section between Abbottabad and Nathiagali, a lesser degree of deformational overprint and the occurrence of coarse-grained intercalations allow the recognition of several primary sedimentary features. The cyclical aspect of the clastic facies is very characteristic. On a metric scale, a fine and gradually repeated variation from very fine-grained sandstone to argillite is observed. At small, millimeter scale, the argillaceous rocks repeat these gradation containing a continuous alternation of graded laminae ("graded laminated beds" Piper, 1972). This cyclical aspect of sedimentation is ubiquitous in the entire formation, and is even observed to the north where the superposition of tectonic and metamorphic overprinting could have obliterated other sedimentary structures. This observation confirms the supposition that the fine-grained, graded laminations observed in the Muzaffarabad area actually represent the bedding trace and their gradation indicates the stratigraphic younging direction.

The sedimentary cycles of the Hazara formation are best interpreted as Bouma cycles, which lack the coarser subdivisions and have poorly developed tractive-current structures. These features, accompanied by primary and compactional structures are typical for flyschoid, turbidite-like sedimentation (see also Marks and Ali, 1961 and Gardezi, 1968). On the other side, the sedimentological features of the Miranjani limestone (Figure 4) suggest a shallow sea with important tidal and wave activity. Stromatolites and the cherty limestones which pass laterally into gypsum and dolomite indicate an evaporitic milieu, accompanied by terrigeneous input. The rock sequence

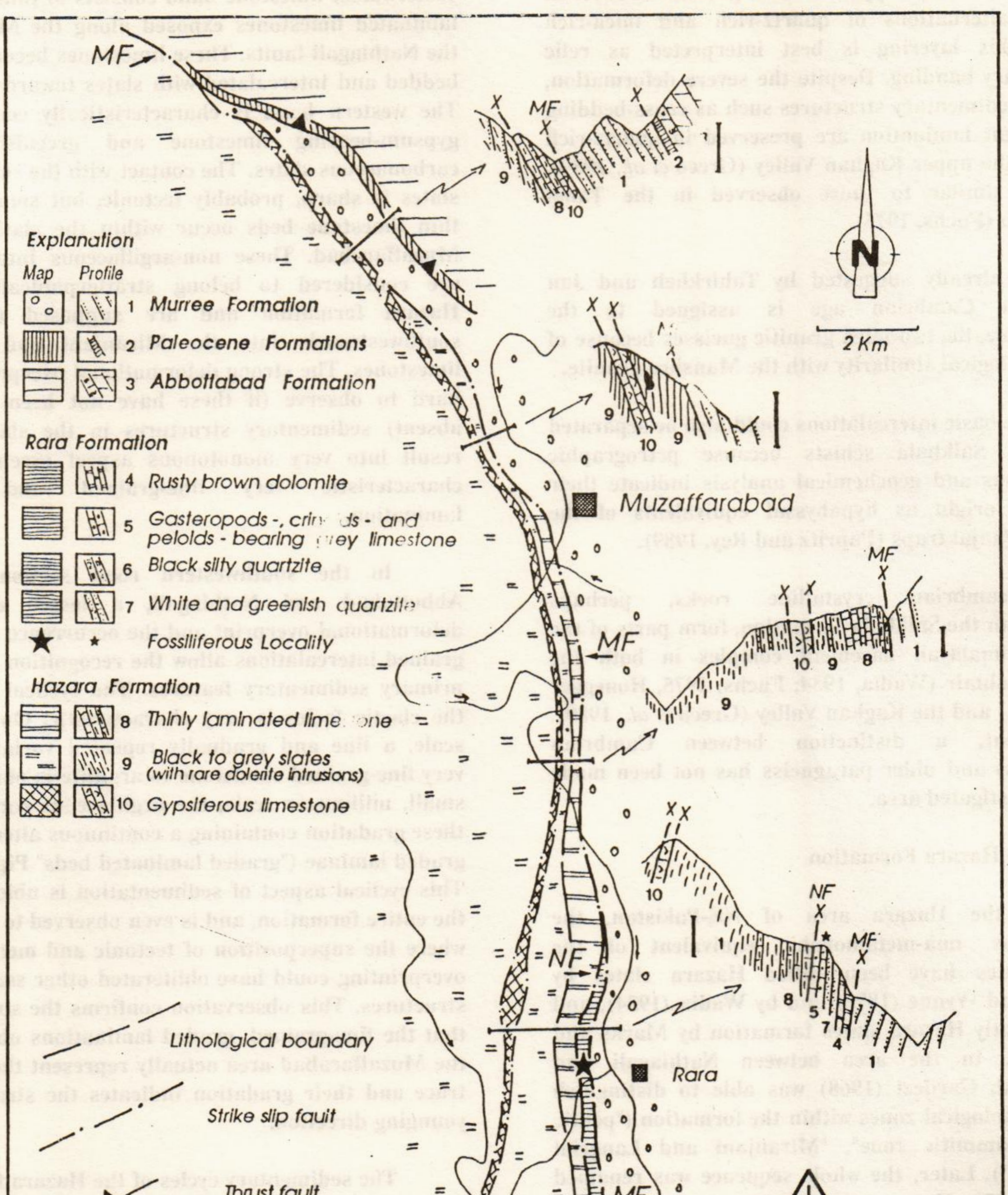


Figure 3: Geological map and profiles along the Main Boundary Thrust in the Muzaffarabad area.

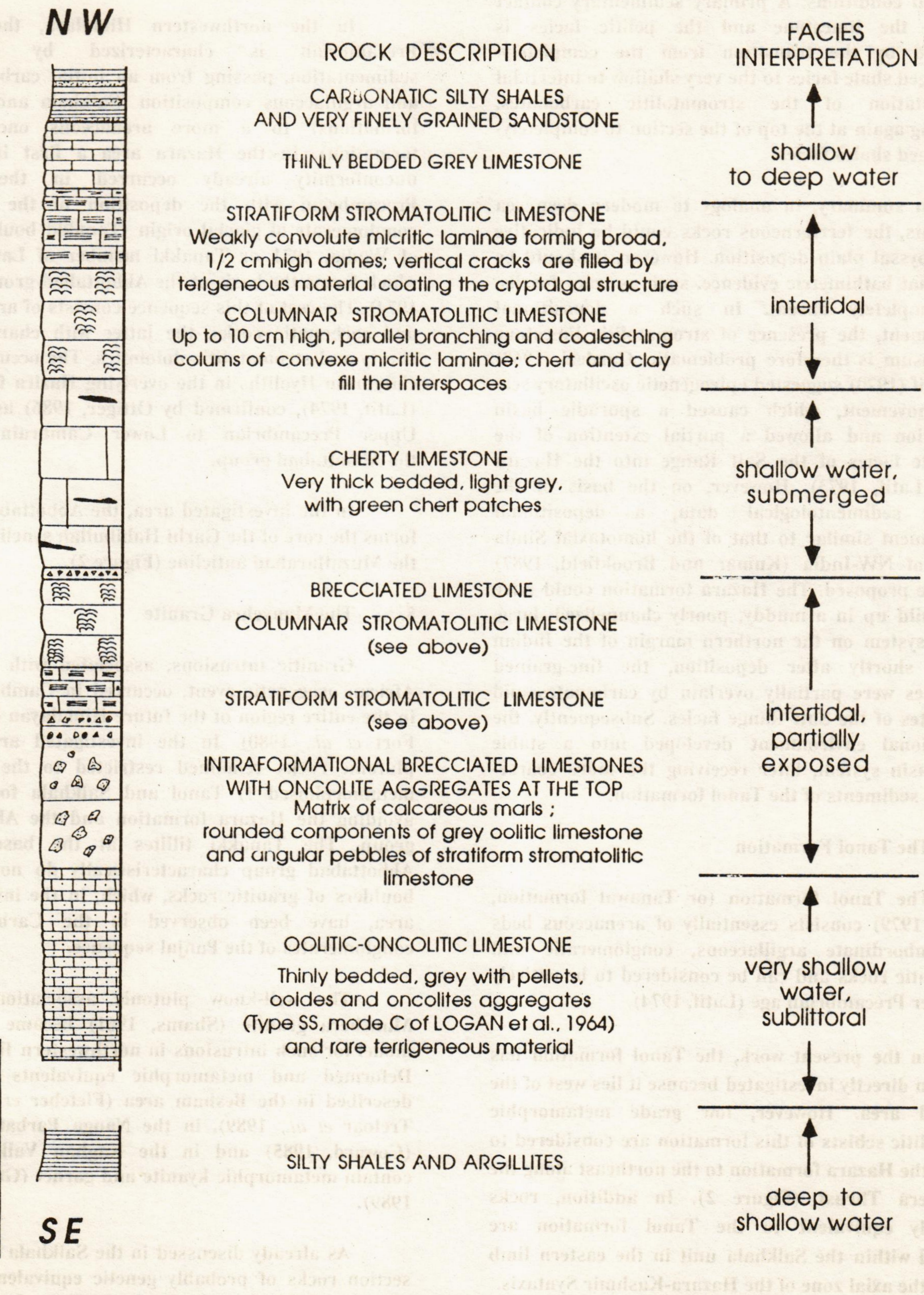


Figure 4: Detailed profile of the "Miranjani Limestone" exposed on the forest road between Kalabagh and Baragali (grid ref. 4095/0526 of the topographical map 43 F/7).

shown in (Figure 4) indicates a depositional environment of alternating completely-submerged and intertidal conditions. A primary sedimentary contact between the limestone and the pelitic facies is indicated by the transition from the completely-submerged shale facies to the very shallow to intertidal sedimentation of the stromatolitic carbonates, returning again at the top of the section to completely-submerged shales facies.

In summary, in analogy to modern deep sea sediments, the terrigeneous rocks could be indicative of an abyssal plain deposition. However, it should be noted that bathimetric evidence, such as trace fossils, are completely absent. In such a depositional environment, the presence of stromatolitic limestone and gypsum is therefore problematic. Gardezi (1968) and Latif (1970) suggested epirogenetic oscillatory sea-floor movement, which caused a sporadic basin dessication and allowed a partial extention of the evaporite facies of the Salt Range into the Hazara slates (Latif, 1973). However, on the basis of the present sedimentological data, a depositional environment similar to that of the homotaxial Simla Group of NW-India (Kumar and Brookfield, 1987) could be proposed. The Hazara formation could have been build up in a muddy, poorly channelized, large deltaic system on the northern margin of the Indian Shield. shortly after deposition, the fine-grained turbidites were partially overlain by carbonates and evaporites of the Salt Range facies. Subsequently, the depositional environment developed into a stable slope-basin system, later receiving the more coarse-grained sediments of the Tanol formation.

3. The Tanol Formation

The Tanol formation (or Tanawal formation, Wynne 1979) consists essentially of arenaceous beds with subordinate argillaceous, conglomeratic and carbonatic rocks and can be considered to be entirely of Upper Precambrian age (Latif, 1974).

In the present work, the Tanol formation has not been directly investigated because it lies west of the mapped area. However, low grade metamorphic metapelitic schists of this formation are considered to bound the Hazara formation to the northeast along the Manshera Thrust (Figure 2). In addition, rocks probably equivalent to the Tanol formation are exposed within the Salkhala unit in the eastern limb and in the axial zone of the Hazara-Kashmir Syntaxis.

4. The Abbotabad Group

In the northwestern Himalaya, the Upper Precambrian is characterized by flyschoid sedimentation, passing from an initial carbonaceous and argillaceous composition (Salkhala and Hazara formations) to a more arenaceous one (Tanol formation). In the Hazara area a first important unconformity already occurred in the Upper Precambrian with the deposition of the Tanakki conglomerate of glacial origin (Tanakki boulder beds of Wadia, 1931 or Tanakki member of Latif, 1970) which forms the basis of the Abbottabad group (Latif, 1974). The rest of this sequence consists of arenaceous and carbonatic rocks, the latter with characteristic cherty and stromatolitic dolomites. The occurrence of Cambrian Hyoliths in the overlying Hazira formation (Latif, 1974), confirmed by Ottiger, 1986) assigns an Upper Precambrian to Lower Cambrain age to the Abbottabad group.

In the investigated area, the Abbottabad group forms the core of the Garhi Habibullah syncline and of the Muzaffarabad anticline (Figure 2).

5. The Mansehra Granite

Granitic intrusions, associated with the Pan-African orogenetic event, occurred in Cambrian time in the entire region of the future Himalayan chain (Le Fort *et al.*, 1980). In the investigated area, these plutonic rocks remained restricted to the (already metamorphosed ?) Tanol and Salkhala formations, avoiding the Hazara formation and the Abbottabad group. The Tanakki tillites at the base of the Abbottabad group characteristically do not contain boulders of granitic rocks, which, in the investigated area, have been observed in the Carboniferous conglomerates of the Panjal sequence.

The well-know plutonic association of the Manshera granite (Shams, 1961) became the type model for such intrusions in northwestern Himalayas. Deformed and metamorphic equivalents are also described in the Besham area (Fletcher *et al.*, 1986; Treloar *et al.*, 1989), in the Nanga Parbat Syntaxis (Coward, 1985) and in the Kaghan Valley, which contain metamorphic kyanite and garnet (Greco *et al.*, 1989).

As already discussed in the Salkhala formation section rocks of probably genetic equivalence to the Manshera granite are exposed within the Salkhala formation in the eastern limb of the HKS (Neelum and Jhelum Valleys). These gneisses are coarse-grained with augen structure. They are quartzofeldspathic in composition and contain muscovite, biotite, rutile, sphene, epidote and tourmaline as secondary minerals. Apatite and zircon are important mineral accessories. Together with xenolithic inclusions and micaschists, dm-thick tourmaline-rich quartz ribbons (deformed tourmaline-pegmatite ?) have been observed in strongly deformed gneisses.

6. The Panjal Sequence

The so-called Panjal sequence includes a continuous stratigraphic sequence of Carboniferous to Triassic, clastic, volcanic and carbonatic rocks. This sequence is exposed in the investigated area between the molasse core and the crystalline rocks of the outer northern and eastern rim of the KHS (Figure 2). Recent investigations in the upper parts of the Kaghan Valley suggest - similar to the Ladakh area - that these rocks are also present in the Higher Himalayan nappes (Greco *et al.*, 1989).

In the Indian held Kashmir, based on well-developed lithologies and abundant well-preserved fossils, this sequence was described by Wadia (1934) as consisting of slates of pyroclastic origin, sandstones and conglomerates of Lower Carboniferous age (Agglomeratic slates series) at the base. These are overlain by lava flows and interbedded limestones of Upper Carboniferous to Lower Triassic age (Panjal trap), and are capped by Upper Triassic fossiliferous limestones, black shales and quartzites. Calkins *et al.*, (1975) grouped the Carboniferous to Permian volcanic and volcanoclastic rocks of the Kaghan Valley under the name Panjal formation. The recrystallised carbonates, have been assigned to the Carboniferous to Triassic Kingriali Formation. Furthermore, detailed investigations in the Kaghan Valley allowed Ottiger (1986) and Bossart (1986) to better identify the sedimentological origin and stratigraphic position of this rock sequence, which has been defined again (Figure 1). A detailed mapping indicates that the lithotypes extend into the Neelum and Jhelum Valleys (Figure 2).

The Clastic Rocks of the Panjal Sequence: A wide range of metapelitic to metapsephitic rocks are associated with the Panjal volcanics. The observed lithologies are: pyrite-bearing graphitic phyllites, sericite-chlorite schists, chlorite-sericite quartzite, and metapsammitic to metapelitic rocks with a fine-grained matrix of sericite, chlorite and graphite. The microscopic as well as the macroscopic detrital components indicate metamorphic and granitic origin of the source-rocks. No signs of volcanic components have been observed. The pebbles of the metaconglomerates are mainly fragments of quartzitic and granitic rocks with less carbonates and slates. Typically, the metaconglomerates are poorly packed and the components "swim" in a dark matrix. These clastic rocks are the southeastwards continuation of the *Panjal Mixtites* of the Kaghan Valley consisting of black graphitic schists, conglomerates, sandstones, and which have been interpreted as tillites of glacial origin (Ottiger, 1986).

It is impossible to directly correlate these clastic rocks with the Carboniferous Agglomeratic slates series of Kashmir because, contrary to the observations of Wadia (1931) and Calkins *et al.*, (1975), no sign of volcanic origin has been identified. However, because of its close association with the volcanics, a (Silurian to) Upper Carboniferous age for the pelite-psammitic sequence is suggested.

The Volcanic Rocks of The Panjal Sequence: The volcanic rocks outcropping in the investigated area are directly comparable with the Upper Carboniferous to Permian volcanic sequence of the Panjal Trap of the Kashmir Himalayas (Wadia, 1931).

In the investigated area the Panjal volcanics could be subdivided at the outcrop scale into dm to m thick basaltic lava flows alternating with dm-thick (locally reaching several 10's of meters) tuffaceous layers.

The basalts are metamorphosed into an epidote- and chlorite-rich, weakly schistose groundmass, containing amygdules filled by epidote, quartz and plagioclase aggregates. Microscopically, the presence of rare pyroxene and amphibole minerals as well as the idiomporphic texture of the saussuritic plagioclase indicate a magmatic origin of these layers. Locally, isolated subspherial occurrences of massive, epidote-rich rocks, half-meter in size, with quartz-filled amygdules and surrounded by very schistose rocks could be interpreted as deformed and transformed pillow structures (Ghazanfar and Chaudry, 1984). However, the field relations and the mineralogies do not directly support this conclusion. Other observed magmatic features are flow banding and degassing structures.

Fine-grained, very schistose rocks of green, violet and red colours are associated with the massive, amygdaloidal lavas and represent the volcanoclastic (tuffaceous) layers. These schistose rocks are predominantly composed of chlorite, actinolite and epidote, but lack the above described mineral aggregates. A spotted appearance is given by the concentration of Fe-rich chlorite in very flattended blebs. These structures may represent chips of glassy material which was deposited in the pyroclastic sediment (ingnimbrite ?) and subsequently flattened during the collapse of the porous rock under the load of the overlying sediments. The tectonic overprint has further increased their oblate shape.

Geochemical analysis of Papritz and Rey (1989) indicate a tholeiitic-subalkalic composition of the Panjal volcanics of the Hazara-Kashmir Syntaxis. Consequently, these rocks could be considered as equivalents of the Panjal trap of Kashmir (Bhat and Zainuddin, 1979, Honegger *et al.,* 1982). Macroscopic features (pillows, amygdules, interlayered tuffaceous levels) as well as conformable alternation with crinoidal limestone exclude an oceanic origin (as suggested by Ghazanfar and Chaudry, 1984) and indicate a continental, marine depositional environment of alternating shallow water and subareal episodes.

The Carbonatic Rocks of the Panjal Sequence:- A wide range of (meta) carbonates and few quartzites are associated with the volcanic and clastic rocks. These carbonates have undergone a more or less pronounced recrystallisation, especially in the neigbourhood of thrust planes or in the uppermost tectonic levels of the Panjal unit. However, fossils remains have been found and allow a correlation between these rocks and the similar lithologies in the Kaghan Valley described by Bossart (1986).

Mica-and chlorite-bearing marbles grading into carbonate schists are widespread and are characterized by a strong tectonic lamination and mineral lineation. In places these rocks alternate with volcanic and graphitic schists. Less transformed rocks include pyrite-, quartz- and sericite-bearing dark grey limestones, which rarely contain cross lamination, and fractured, fine-grained, thickly bedded and grey dolomites.

Of great interest are the fossils-bearing carbonates found in the road section above Balgiran (Neelum Valley, grid. ref. 7250/55175 and 7280/5190), 2.5 km northeast of Hariala (Jhelum Valley, grid ref. 7750/3110) and at Lamnian (Jhelum Valley, grid ref. 8100/2730). Poorly preserved segments of crinoids, as well as remains of undeterminable echinoderms, shells, gastropods and bryozoa have been observed n sparitic, cross-bedded limestone as well as in microsparitic to micritic laminated limestone. In the deformed marbles, remains of crinoids are outlined by big, single calcite crystals with a central channel of differently composed calcite. These grains have been completely rounded and distorted by deformation so that their origin can only be assumed to be similar to the crinoids in the neigbouring, lesser deformed fossiliferous carbonates. Above Balgiran (Khetar, Neelum Valley) a strong convolute lamination of macroscopic rusty brown colour is observed in medium-grained dolomite. for the first time in this formation, these observations, together with the presence of vertical pockets of terrigeneous material (quartz and micas) between the convolute columns, suggest a stromatolitic origin for these laminated structures. The stratigraphic top indicated by the stromatolitic shape is consistent with the local stratigraphic setting.

Wadia (1934) already discussed the "contemporary interstratification" of Panjal volcanics with fossiliferous (Triassic) and unfossiliferous (Infra-Trias) carbonates. Although some of these intercalations are of tectonic origin, the close relationships between Upper Carboniferous to Lower Triassic Panjal volcanics and the crinoidal limestones suggest an Upper Paleozoic to Lower Mesozoic age for the carbonates. In addition, fossil associations which include relics of reptile bones (found in the Kaghan valley, Bossart *et al.*, 1984) indicate a Lower Triassic to Middle Jurassic age.

7. The Rara Formation

South of Muzaffarabad, along the Murree Fault, a rock sequence composed of dolomites, quartzites and limestones is sandwiched between the Murree Formation and the Hazara formation (Figure 2 and 3). Blocks of bioclasts-bearing limestone have been found on the truck road from the Rara bridge to Pattan Kurd (grid ref. 5055/5053). More careful observations in the section exposed along the northern bank of the Kunhar River (Figure 5), between the bridge on the Jhelum River and the village of Ril, revealed the presence of in situ fossiliferous limestone associated with dolomites, quartzites and carbonaceous slates. Consequently this rock sequence of about 100 m in thickness could be distinguished from the carbonates belonging to the Hazara formation and it is provisionally called Rara formation (Rara is the village lying on the junction

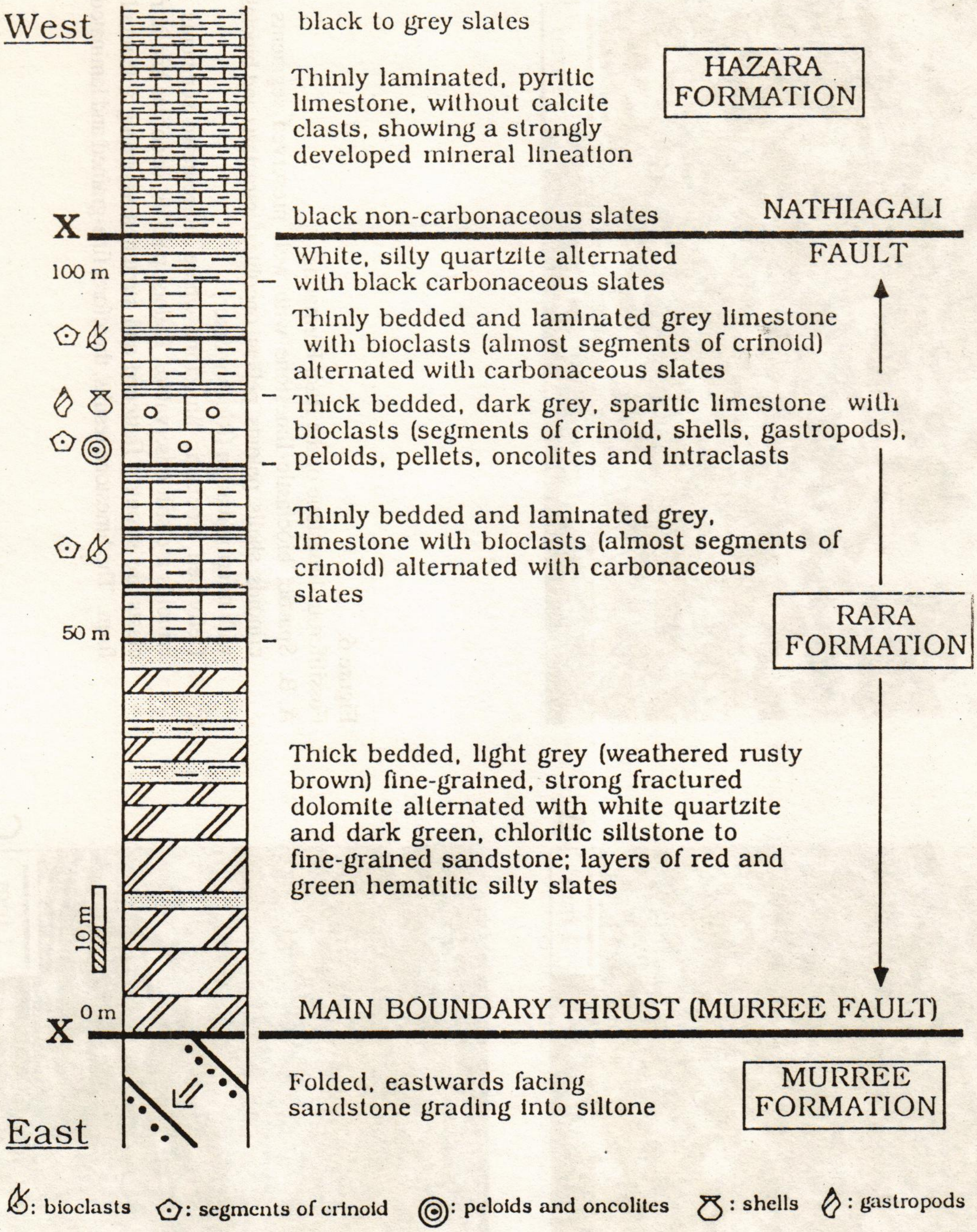
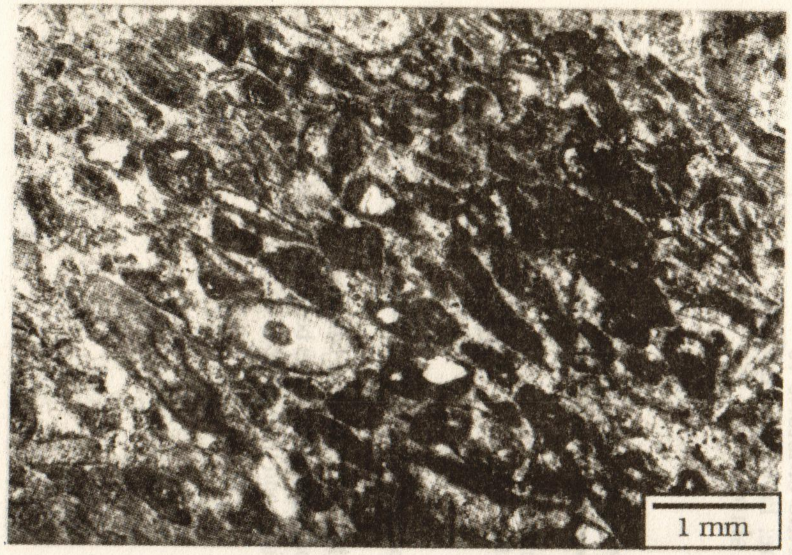
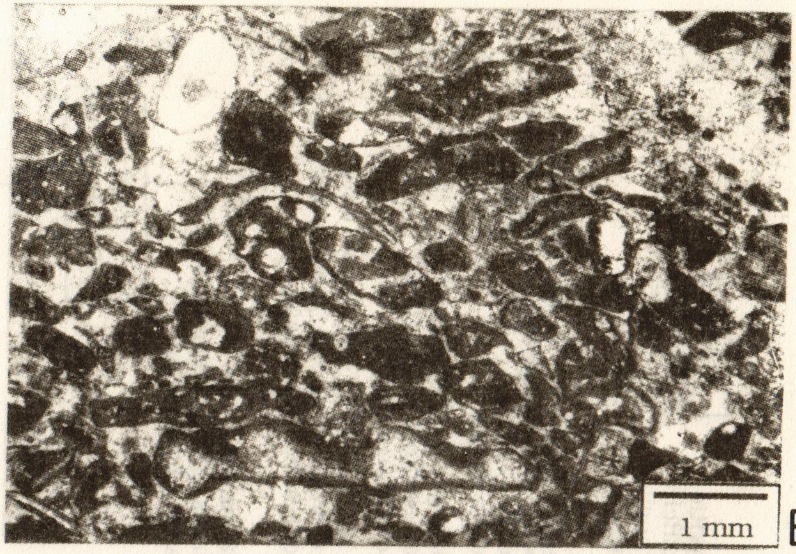


Figure 5: Section across the Rara Formation exposed at the confluence between the Kunhar and the Jhelum Rivers, 8 Km south of Muzaffarabad (this section has been measured on the northern bank of the Kunhar River, between the bridge and the village of Ril).



A.



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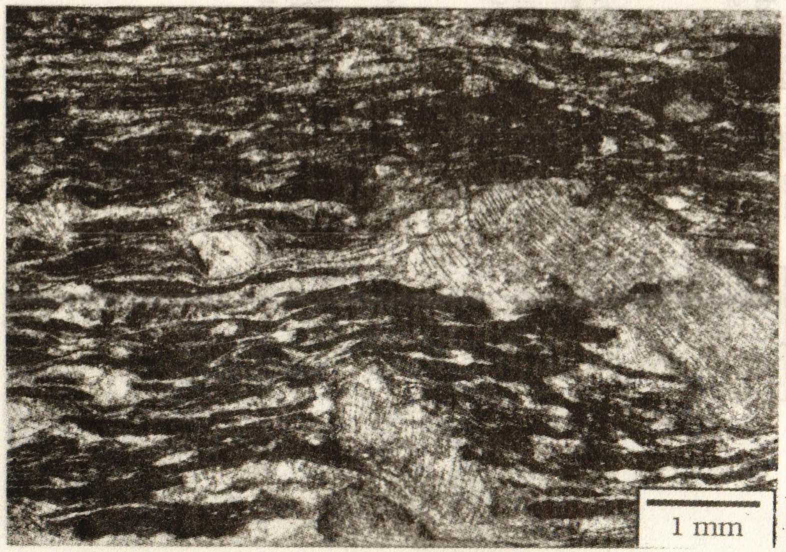


C.

Figure 6:
Fossiliferous limestone of the Rara Formation.

A, B: Spartic, bioclastic limestone with well preserved segments of crinoids, shells, peloids, pellets, oncolites, intraclasts and bioclasts with micritic margin (Rindenkörner).

C: Deformed bioclastic limestone where subrounded segments of crinoids are still observable. Pellets, peloids, oncolites and intra-clasts are strongly flattened and stretched assuming a lenticular form. The limestone results, therefore, fine-grained and laminated.

between the Kunhar and the Jhelum River, about 8 Km south of Muzaffarabad).

Along the section exposed on the northern slopes of the Kunhar River (Figure 5) the Rara formation begins, at the contact with the Murree Formation (Main Boundary Thrust or Murree Fault), with approximately 50 meters of thickly bedded, light grey, fine-to medium-grained dolomite, which exhibits a typical rusty brown weathering colour. Widespread fractures in the dolomite are filled by a lithified breccia composed of original rock fragments. Layers of white, pure quartzite with silt-silt-sized grains are intercalated with the dolomite. Green - dark green, clasts, poorly sorted siltstone to fine sandstone beds are also observed, and contain mainly angular quartz-clasts in a matrix of recrystallised chlorite and sericite. Red, green and voilet slates are present as dm-thick intercalations within the quartzites and are composed of multi-coloured argillaceous matrix.

The overlying 50 m of the section are composed of thinly bedded, tectonically laminated, bioclasts-bearing, grey limestone alternating with carbonaceous, black slates. Intercalations of thicker bedded, dark grey limestone, with well preserved bioclasts are found. These limestones (Figure 6A,B) are sparitic, dark grey with macroscopically identifiable segments of crinoids (columnals) and remains of shells (lamellibranchia, brachipoda ?) and gastropods. Microscopically, these limestones are composed of peloids, small pellets oncolites where micritic have grown concentrically around grains of quartz, dolomite, bioclasts and groups of smaller peloides, intraclasts and bioclasts with micritic margin (Rindenkorner).

The deformed carbonates (Figure 6C) are laminated and contain macroscopically identifiable mm-sized calcite crystals. Microscopically evidence for an organic origin of most of the components is still seen: the peloids and oncolites have been strongly flattened, but a concentric, laminated, micritic structure is still observable. Subrounded, big calcite crystals maintain the crinoidal structure with a typical central channel filled by calcite of different compostion. The rock matrix is recrystallized to a very fine-grained calcite. With increasing deformation the peloids are transformed into dark, micritic laminate alternating with lighter ones, which probably correspond to the original, but now recrystallised, sparitic matrix. Only a few segments of crinoids have survived deformation, whereas the majority of the bioclasts and intraclasts are completely obliterated. These features are very important because they allow the carbonates of the Rara formation to be distinguished from those of the Hazara formation. The latter are also laminated, but contain euhedral pyrite crystals and lack single big calcite crystals.

The formation is capped at the west by black, carbonaceous slates and white quartzites. The contact with the Hazara formation (Nathiagali fault) is defined by the first occurrence of non-carbonaceous slates and by thinly laminated, pyrite-bearing limestones.

The strong tectonic overprint and the poorly preserved bioclasts do not allow a direct age identification of the Rara formation, which probably represents a Mesozoic sequence pinched in between the Tertiary Murree Formation and the Precambrian Hazara formation.

The lithological association of the Rara formation (peloidal, bioclastic limestones, quartzites, shales and dolomites) and the fossil contents suggest a very shallow, high energy marine depositional environment, typical for several Triassic formations exposed in the southeastern parts of the Hazara district: the Lower Triassic Mianwali Formation (Tahirkheli, 1982), the Liassic Maira formation (Latif, 1970), the Early Jurassic Datta Formation (Latif, 1970), and the Upper Jurassic Samana Suk Limestone (Calkins *et al.*, 1975).

On the basis of lithological character and fauna contents, the Rara formation does not exactly correspond to one of the above mentioned formations, but shows commonly developed features. On the basis of its tectonic position, the Rara formation correlates better with the Thandiani group, which according to the map of Latif (1970), outcrops between the Hazara and the Murree Formations southwest of the Kohala bridge, and forms the stratigraphical base of a Jurassic to Eocene rock sequence (Figure 2). A Jurassic age is therefore suggested for the Rara formation, but further decisive evidence (well-preserved, determinable fossils) needs to be found.

8. The Tertiary (Paleocene and Murree Formation)

In the investigated area, Tertiary rocks are exposed in the core of the Hazara Kashmir Syntaxis as Paleocene limestones and marls gradationally overlain by the red clastic rocks of the Murree Formation (late Paleocene to Eocene).

On the northeastern limb of the Muzaffarabad anticline, a good section across the Lower Tertiary is exposed along the road of the Neelum Valley. A similar section, exposed east of Balakot (Beran Katha), has been studied in detail by Bossart (1986). In the Neelum Valley, the stratigraphical gap between the Lower Cambrian Abbottabad groups and the Paleocene is filled by 4 meters of black, graphitic, coal beds accompanied by bauxite soils (Jurassic ?). The Paleocene is represented by about 200 m of alternating silty marls and limestones, the latter occurring as bedded and nodular strata. The rich macrofossil fauna (foraminifera, lamellibranchia, gastropoda, corallia, bryozoa etc.) allowed Bossart (1986) to date these reefal sequences as Illerdian (Upper Paleocene) and to compare these rocks with the southern exposed Lockhart Limestone and Patala Formation of the Kala Chitta zone (Tahirkheli, 1982). Towards the top (northeast), the Paleocene reefal sequence grade into the basic conglomerates and sandstone of the Murree Formation, as evident by an increase of detrital material in the Paleocene marls and by the presence of calcareous clasts in the Murree conglomerates.

The Murree Formation is characterized by a cyclic sedimentation of sandstone and conglomerate grading into siltstone, with a few intercalations of marls and limestone containing a reworked fauna of Late Paleocene to Middle Eocene, subtropical foraminifera (Bossart and Ottiger, 1989). These authors suggest that the Murree Formation was deposited in an intertidal environment (clastic rocks), episodically transgressed by shallow marine conditions (Nummulitic limestone), and filing the southwards migrating Tertiary foreland basin of the Himalayan chain (see also Lillie *et al.*, 1987). This hypothesis is based on sedimentological features (e.g. cyclicity), on the detritus type and on the age of the formation. The age of the Murree Formation becomes younger away from the axis of the Muzaffarabad anticline towards the northeast, where it reaches the Middle Eocene along the Main Boundary Thrust and towards the south (Potwar Plateau), where it reaches and Early Miocene age.

STURCTURAL STYLE AND TECTONIC SUBDIVISIONS

The Hazara-Kashmir syntaxis area is tectonically divisible into three main elements: the Subhimalaya, the Lesser Himalaya and the Higher Himalaya. In detail, the rock distribution in the Kaghan valley and in Azad Kashmir indicates that each element is composed of one or more tectonic units, each having a particular stratigraphic sequence and a local name. The lateral continuity of such units, which could extend for several hundred of kilometers, is one of the most impressive features of the Himalayan range. A correlation with the tectonic equivalents in the Indian Kashmir and in the Hazara, Kohistan and Potwar areas of north Pakistan, based on data from the literature is schematically summarized in the Figure 7. Figure 2 shows the distribution of the tectonic units in the investigated area.

1. General Features of the Tectonic Elements

A subdivision of the Himalayas of Nepal and Northern India into Sub-, Lesser- and Higher tectonic elements (Gansser, 1964, 1981) was first assigned on a stratigraphic and paleogeographic basis. In northwestern Himalaya, the paleogeographic subdivision into the Tethys or Tibetan realm and the continental-influenced sequences deposited on the northern margin of the Indian Shield no longer seems to be not more applicable: the Lower Paleozoic as well as the Mesozoic of both the Lesser and the Higher Himalayas is carbonatic, suggesting a southwards extention of the Tethys facies (Fuchs, 1975). It is therefore difficult to apply the classical tectonic subdivision to the Himalayan range, which has been possible for Nepal and north India. The metamorphic state as well as the deformational features of the rocks must be considered for such subdivision.

In fact, in contrast to paleogeography and stratigraphy, the deformational and metamorphic features seem to be much more constant along the entire Himalayan range. The Himalayan tectonics emphazise the age and facies differences between the different elements. The thrusted units generally becomes older in stratigraphic age towards the uppermost tectonic elements, because the thrust planes reached deeper levels of the Indian crust. The deepest crustal level is represented by the Main Central thrust, which brought the Higher Himalayan crystalline basement, with its Phanerozoic predominantly carbonatic cover, over the Lesser Himalayan detrital formations.

The deformational style is very ductile at the base of the Higher Himalaya. Polyphase folding, associated penetrative schistosity and ductile shearing affect the nappes structure composed of basement and cover rocks. Characteristic for the Lesser Himalaya is the imbrication and folding of the stratigraphical sequence, which is in part or completely detached from its basement substratum. schistosity developed more

MAIN SUBDIVISIONS (7)	INDUS KOHISTAN - HAZARA and POTWAR PLATEAU	HAZARA-KASHMIR SYNTAXIS and UPPER KAGHAN VALLEY	KASHMIR - LADAKH and ZANSKAR
	Kohistan Sequence (12)	**Kohistan Sequence** (12)	**Indus - Tsangpo Suture Zone** (9)
IS	*Indus Suture*	*Indus Suture*	*Indus Suture*
HIGHER HIMALAYA	**Basement and Cover Imbrications** (14) Tertiary granitoids (14) Paleozoic to Mesozoic (2) Cambrian: granitoids and Karora Group (5) Proterozoic:gneiss (14), Besham and Pazang Gps. (5)	**Crystalline Unit** (8) Cover of Permian and Mesozoic with "Panjal affinities" Pre-Permian basement of detritic Lower to Middle Paleozoic, Lower Paleozoic granite (Mansehra Type) and Precambrian paragneisses	**Tibetan Zone** Tethys platform sediments of Zanskar-Spiti area (6,9) **Upper Crystalline Nappe** (6) Suru: Zanskar Crystalline (Precambrian to Lower Paleozoic) and Paleozoic to Lower Mesozoic metasedimentary cover (9)
MCT	*Oghi Shear Thrust* *(4)*	*Mylonite Zone (1)*	Kashmir - Chamba Syncline: Late PC to Trias (13) **Lower Crystalline Nappe** Precambrian schists around the Kistwar Window (6)
internal unit	**Tanol Unit** (1) Cambrian: Mansehra Granite Upper Precambrian to Lower Cambrian: Abottabad Group. Upper Precambrian: Tanol Fm.	**Salkhala Unit**(1,8) Permian (?): dolerites Lower Paleozoic: granite gneiss Possible remains of Upper Precambrian: Tanol Formation Precambrian: metasedimentary rocks (Salkhala Series)	**Chail Nappe** Late Precambrian to Middle Paleozoic (6)
	Mansehra Thrust (3)	*Panjal Thrust (15)*	*Panjal Thrust (15)*
LESSER HIMALAYA	**Hazara Unit** (1) Paleo-Eocene: Gali Groups. Mesozoic: Thandiani and Hotla Groups. Upper Precamrian to Lower Cambrian: Abottabad Group. Precambrian Hazara Fm.(10)	**Panjal Unit** Panjal Imbricate Zone Triassic (Jurassic ?): Limestone and Dolomite Permian: Panjal Volcanics Upper Carboniferous: tilloides (1)	**Parautochtonous Unit** (6) "Schuppen" of Late Precambrian to Cambrian, Paleomesozoic and Eocene Formations (13)
external units	*Nathiagali Thrust (11)* **Main Boundary Thrust Zone** (3) Paleo-Eocene: Gali Gp. Mesozoic: Thandiani and Hotla Groups (10)	Mélange Zone Permian to Eocene (1)	
MBT	*Murree Thrust (15)*	*Murree Thrust (15)*	*Murree Thrust (15)*
SUB-HIMALAYA	**Murree Unit** **Siwalik Unit** Cambrian to Pleistocene (16)	**Murree Unit** Late Paleocene to Middle Eocene: Murree Fm. Paleocene formations Upper Precamrian to Lower Cambrian: Abottabad Group.	**Tertiary Zone** (6) or **Outher Himalayan Zone** (13) Cambrian, Paleocene to Pleistocene
MFT	*Salt Range Thrust (16)*		
ACTUAL FORELAND	Holocene of the Indus and Jhelum alluvial plains (16)		

References :

(1): Bossart et al., 1988 ; (2): Coward et al., 1982 ; (3): Coward and Butler, 1985 ; (4): Coward et al., 1986;
(5): Fletcher et al., 1986 ; (6): Fuchs, 1975 ; (7): Gansser, 1964 and 1981 ; (8): Greco et al., 1989 ;
(9): Honegger et al., 1982 ; (10): Latif, 1970 ; (11): Latif, 1984 ; (12): Tahirkheli et al., 1979 ;
(13): Thakur and Gupta, 1983 ; (14): Treolar et al., 1989 ; (15): Wadia, 1931 ; (16): Yeats et al., 1984.

Figure 7: Table of the tectonic subdivision of the North-Western Himalayas.

selectively in the less competent rocks. The number of brittle thrust planes, which controlled the tectonic style, increase with respect to the Higher Hiamalaya. In the Subhimalaya, folding and internal thrusting is also developed.

The metamorphic development reflect this tectonic style and therefore the distribution of the metamorphic grades help to further understand the tectonic subdivision (see section 3).

2. The Subhimalaya

From the Indus river to the Chenab River, the Murree Formation occurs continuously along the southern margin of the Lesser Himalayan units, forming almost of the Subhimalayan unit. In the core of the Hazara-Kashmir Syntaxis folding and subsequent doming (Bossart *el al.,* 1988) are the principal structural features, resulting in the exposure of lower Cambrian and Paleocene rocks along the hinges of the Muzaffarabad and Kotli anticlines. Around the former anticiline, the metamorphism reaches the prehnite-pumpellyite facies.

To the north, *the Main Boundary Thrust*, locally called the Murree Fault, borders the Subhimalaya. Geometrically, the fault plane cuts the steep dipping molasse beds of its footwall, carrying northeast plunging Lesser Himalayan schists and gneisses on its hangingwall.

3. The Lesser Himalaya

The Lesser Himalaya is composed of folded and thrusted rock formations, ranging in age from Precambrian to Eocene. it is delimited to the south by the Tertiary molasse along the Main Boundary Thrust, and to the north by Higher Himalayan crystalline rocks along the Main Central Thrust. The metamorphism in this element is of very low-to low-grade. A further tectonic subdivision of the Lesser Himalaya into separate rock units is necessary because of the presence of several thrust slabs, which present only slight different stratigraphical sequence and metamorphic grade.

West of the Hazara-Kashmir Syntaxis, the *Main Boundary Thrust Zone* (Coward and Butler, 1985, or Islamabad zone of Fuchs, 1975, or Kala Chitta Zone of Tahirkheli, 1982) forms a complex mosaic of thrusts and folds consisting of Mesozoic and Paleogene formations. The northern boundary is represented by the *Nathiagali thrust* (Latif, 1984), which branches from the Main Boundary Thrust (or Murree Thrust) 5 Km south of Muzaffarabad, where probably Jurassic limestone of the Rara formation has been found (Figure 3). to the west, the Main Boundary Thrust Zone can be correlated with the Triassic to Paleocene sequence of the Kala Chitta Range near Attock, and the Nathiagali thrust can be equivalent to the Hissartang fault of Yeats and Hussain (1987).

North of the Nathiagali thrust, the *Hazara unit* contains a thick sequence of the Upper Precambrian Hazara formation at the base followed by the Lower Cambrian Abbottabad Group. Toward the south the Cambrian disappears and the Mesozoic rocks directly overlie the Hazara slates. The very low grade metamorphic and as well as the structural features are continuous from the southern frontal part of the unit (Gali area) towards the northern, internal one (Muzaffarabad area). The structures developed in the Precambrian slate formation can be inferred to be of Himalayan age because the associated folds contain Jurassic and Paleogene formations. The absence of Lower Paleozoic granite also suggests the lack of Panafrican events, In the Hazara unit the metamorphism reach anchi- to low epizonal facies.

The northern boundary of the Hazara unit is represented by the *Mansehra thrust* (Coward and Butler, 1985 , which is supposed to branch with the Murree Thrust south of Balakot under the alluvium of the Kunhar River. The interpretation of the Mansehra thrust as a continuation of the *Panjal Thrust* (Calkins *et al.,* 1975) suggests an equivalence between the Panjal- and the Hazara units. In contrast, the age, metamorphism and deformational character of the formations involved indicate that it is preferable to consider the Hazara unit as an individual sheet, which is missing in the apex of the Hazara-Kashmir Syntaxis. Therefore, it is suggested here that the term Panjal Thrust be abandoned to the west of the syntaxes bend and instead use the name Manshera thrust.

The Panjal unit is exposed in the apex and eastern limb of the Hazara-Kashmir Syntaxis (Figure 3.2). In the Kaghan Valleuy, this unit is composed of four different imbricate slices. The lowermost slice is formed by a tectonic melange of Permian to Eocene rocks (the melange zone), whereas the remaining three (the Pānjal imbricate zone) represent an Upper Paleozoic to Lower Mesozoic stratigraphic sequence of Carboniferous tilloids, Permian Panjal trap vocanics, and Triassic limestone (Bossart *et al.,* 1988). The metamorphic grade reached to the greenschist facies. Geometrically this unit shows a typical "duplex" configuration with the Main Boundary Thrust as floor-thrust and the Panjal Thrust as roof-thrust. With small changes in their geometry, this unit can be followed to the Indian Kashmir-Chamba area.

In the Hazara area, the *Tanol unit* consisting of the Tanol formation of Upper Precambrian age and of the Cambrian Mansehra granite represents the highest structural level of the Lesser Himalaya. The metamorphic grade of this Tanol unit is appreciably higher than the underlying Hazara units. The northern tectonic limit of the Tanol unit in Hazara is represented by the Oghi thrust (Coward et al.,1986) which should correspond to the mylonite zone of Kaghan Valley and to the Main Central Thrust.

In the apex and eastern limb of Hazara-Kashmir syntaxis, the uppermost Lesser Himalayan unit is mainly represented by the Precambrian metamorphic rocks of the *Salkhala* formation. The *unit* is mainly composed of metapelitic schists with characteristic graphite, quartzite and carbonate sediments and is intruded by pegmatite dykes and two mica augengneisses, which represent the deformed equivalent of the Lower Paleozoic Mansehra granites. The widespread basic dykes should belong to the Permian magmatic event because of their geochemical similarity with the Panjal volcanics (Papritz and Rey, 1989). The Salkhala sequences are folded, well foliated and thrusted. Similar to the Tanol unit, pre-Himalayan metamorphism could exists but is overprinted by the strong Himalayan event. The northern limit of the Salkhala unit is the mylonite zone or Main Central Thrust.

4. The Main Central Thrust

The Main Central Thrust occurs in the Kaghan Valley (Naran area) as a granite-derived mylonitic zone which divides the low metamorphic grade Salkhala schists from amphibolite-facies metamorphic carbonaceous schists belonging to the cover rock sequence of the Higher Himalaya (Greco *et al.*, 1989). The same discontinuity was first observed in the western part of the syntaxis near Balakot by Bossart (1986), who called it mylonite zone" or "Balakot discontinuity". In the eastern limb of the syntaxis, the Main Central Thrust could be mapped in the Kalasar area (Neelum Valley), where it forms an up to 500 m thick pile of metapelitic mylonites containing fibrolitic sillimanite (see Figure 9), and which pass upwards into paragneisses of the Higher Himalayan basement. Therefore, this main intracrustal discontinuity cuts across the basement-cover sequence of the Higher Himalayan crystalline. the petrological composition of the Main Central Thrust associated rocks emphasizes the extreme ductile deformation occurred under upper amphibolite facies metamorphic conditions.

5. The Higher Himalaya

The Higher Himalayan crystalline is exposed in the uppermost parts of the investigated area. Recent investigations in the Kaghan Valley (Greco *et al.*, 1989), allowed a basement and a cover sequence in the Higher Himalayan crystalline unit to be distinguished. The basement is composed of granitoid rocks, lithological similar to the Cambrian Mansehra granite, intruded into older paragneisses perhaps corresponding to the Precambrian Salkhala formation. A distinct, second lithotype of the basement is the metapelitic-metagreywacke gneiss, probably corresponding to Lower Paleozoic sediments of the Kashmir synclinorium (Cambrian to Ordovician in Figure 2) and the Zanskar area (see Garzanti *et al.*, 1986). All these rocks are the metamorphic, magmatic and sedimentary products of a Late Pan-African orogenic event and, therefore, form the (pre-Permian) basement on which rocks of the Alpine cycle were deposited. In fact, the cover sequence begins with thick amphibolitic layers, which, with the doleritic dykes of the basement, on the base of the petrographic, geochemical and filed evidence, have been correlated with the Permian Panjal Trap (Papritz and Rey, 1989). Towards the top, the cover is carbonatic and pelitic (Lower Mesozoic ?), and is always accompanied by interlayered basaltic flows. The tectonic limits of this sequence are represented by the mylonites of the Main Central Thrusts zone at the base, and by the mafic-ultramfic rocks of the Kohistan sequence at the top.

Recumbent folding and ductile thrusting, accompanied by imbrication, formed several nappes. Greco *et al.* (1989) have proposed the use of the term crystalline unit for this basal, metamorphic parts of the Higher Himalaya.

GRADE AND TYPE OF METAMORPHISM

The distribution of the metamorphic facies in the investigated are is shown in (Figure 8). Except for the Subhimalayan formations and the rock sequences forming the Kashmir synklinorium, the boundaries between the different metamorphic facies coincide almost with the main thrust faults. Because these structures do not represent reaction isogrades, the distribution of the metamorphic grade is a direct consequence of the tectonic evolution of the area (see section 4).

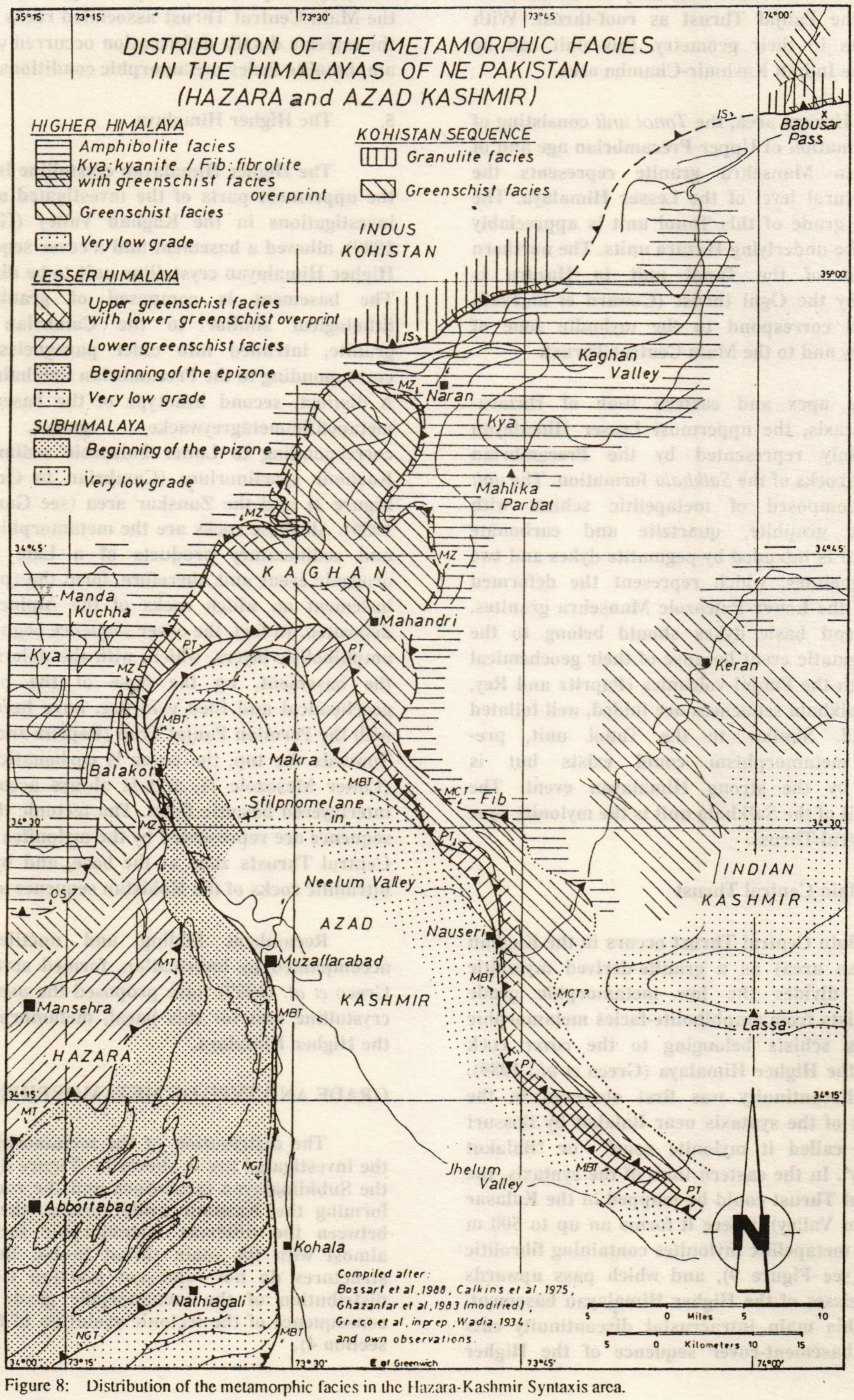


Figure 8: Distribution of the metamorphic facies in the Hazara-Kashmir Syntaxis area.

1. Pre-Himalayan Metamorphism

Evidence of pre-Himalayan metamorphism in the Lesser- and Higher Himalayan realms are scarce. Microstructural evidence indicates that the main metamorphic recrystallisation in the Precambrian rocks in both the Lesser and Higher Himalaya, is associated with the Himalayan deformation (Bossart *et al.*, 1988; Greco 1989). Because clear evidence for the presence of Precambrian events is at present lacking, it is reasonable to consider the metamorphism as mainly associated with Himalayan tectonism. Nevertheless, the presence of Cambrian intrusives (Manshera granite) and some sedimentary evidence in the North-West Himalayas (Garzanti *et al.*, 1986) support the existence of a Late-Pan African event in the Himalayan realm. In addition. records of a Precambrian orogenic event seem to have been found in the basement of the Indian Plate south of the Indus Suture in the Besham area (Northern Pakistan, Treloar *et al.* 1989).

2. Higher Himalaya

The highest tectonic element of the Indian Plate, the Higher Himalaya, consists of a basement with an originally overlying sedimentary cover sequence. In the Kaghan Valley, both basement and cover have suffered an intense common syn- to post-deformational medium grade of metamorphism. In addition, within this element a decrease in metamorphic grade, showing a Barrovian type gradient, is observed towards the sedimentary cover of the Kashmir syncline. As the metamorphism involves Mesozoic rocks, it is considered of Himalayan age, and to have originated from the continental collision along the Himalaya. Isotopic ages also point to a Miocene age for the metamorphic peak in the Central Himalaya (Le Fort, 1986).

3. Main Central Thrust

The southwest-directed transport of the Higher Himalayan basement-cover sequence took place along an important intracrustal shear zone, the Main Central Thrust.

Evidence that deformation along the Main Central Thrust started to develop under hangingwall metamorphic conditions are found in the mylonitic metapelites at the Kalasar area (Neelum Valley, see also Greco, 1989). As shown in Figure 9, these rocks are a product of shear deformation occurring during amphibolitic facies metamorphism, and have subsequently been overprinted by post-kinematic mineral growth without a change in metamorphic conditions. Because fibrolitic sillimanite is stable during the shear deformation, we conclude that the mylonitisation developed within the temperature-dominated metamorphism of this portion of Himalaya.

These features are rare, whereas rocks of the mylonite zone, South of Naran (Creco *et al.*, 1989) and around Balakot (Bossart *et al.*, 1988) indicate deformation occurring during upper greenschist facies conditions, similar to those of the upper Salkhala unit. In these mylonitized rocks, hornblende remains stable and only garnet has grown after the deformation.

Therefore, the Main Central Thrust did not developed after the metamorphism but represents a narrow zone of transition between two metamorphic realms, where the very ductile deformation developed from the metamorphic conditions in the hangingwall rocks up to the less metamorphic grade of the footwall sequences. After deformation and far from the Main Central Thrust, the two tectonic units maintained their original thermal conditions long enough to allow post-deformational mineral growth. A syn- to postkinematic metamorphic re-equilibration between the two units has only been reached along the mylonite zone. The Main Central Thrust at the Kalasar area records the entire tectonic throw (vertical displacement). From the petrologic features observed it is estimated that deformation along this thrust occurred between 550°C. and 650°C. In a Barrovian-type metamorphic gradient, these temperatures correspond to a lithostatic pressure of 6-9 Kbar (Depth of 20 - 30 Km) and record a tectonic throw (vertical displacement) between the Higher and the Lesser Himalaya of at least 10 Km.

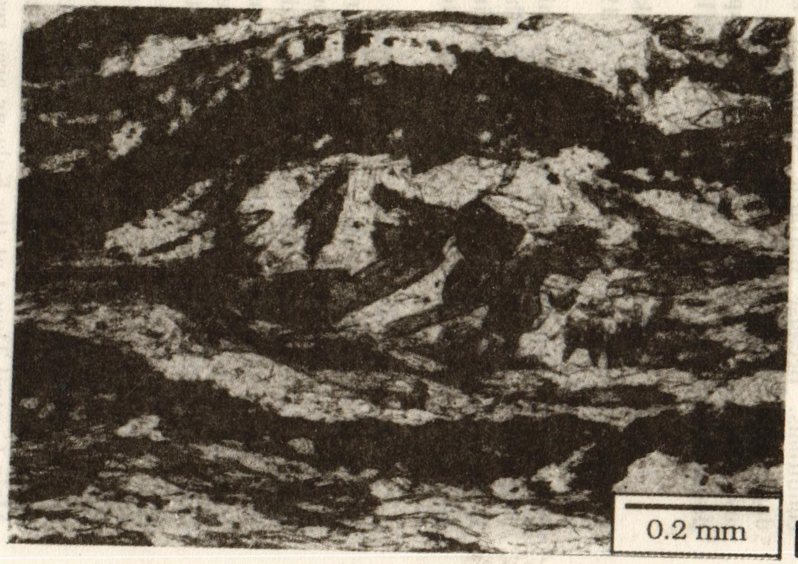
4. Lesser Himalaya

In the Himalaya, basement and cover have been in part completely detached, leading to the separation of different nappe units or imbricated sequences. The older thrust units lie more internally (and tectonically higher) in the tectonic system, and show higher metamorphic grades than the younger, tectonically lowest units. The series of metamorphic facies observed in the Lesser Himalaya belong to a medium presure, regional Barrovian metamorphism, as is evident by the presence of chloritoid- and almandine-bearing mineral assemblages.

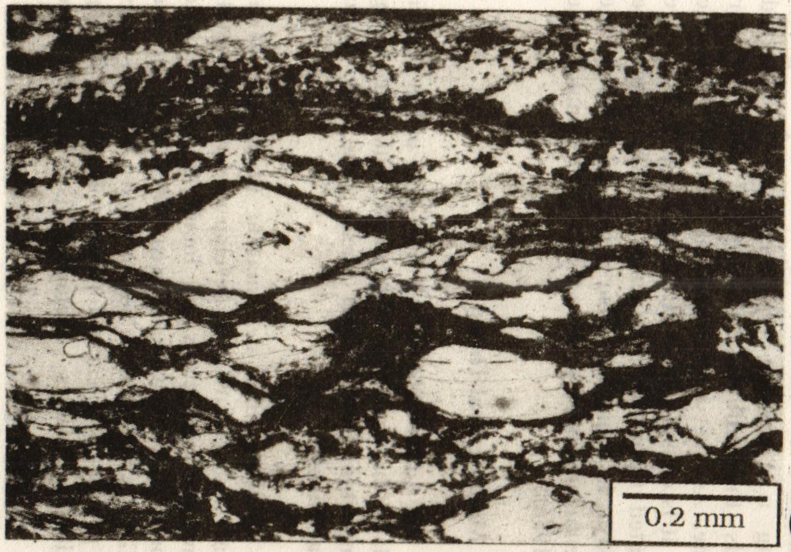
5. Inverse Metamorphism

An inverted distribution of the metamorphic

A.



B.



C

Figure 9:
Metapelites belonging to the Main Central Thrust (Kalasar, Neelum Valley).

A: Medium-grade mineral paragenesis from an undeformed rock (Garnet+Staurolite+Biotite+Muscovite+K-feldspar+Sillimanite+Quartz)

B: Idiomorphic, postkinematic individuals of staurolite growing on a white mica "fish" wrapped by brown biotite and fibrolitic sillimanite (Mylonitic rock).

C: Clasts of white mica sourrounded by broken needles of fibrolitic sillimanite which have been accumulated around the clasts during the shear deformation (Mylonitic rock).

facies is particularly well developed in the Lesser Himalaya, and its origin has been investigated with microstructural analysis in these rock units (Greco, 1989). Observations in both the Panjal and the Salkhala units indicate that peak metamorphic conditions reached during the main, thrust-related deformational phase. In addition, features related to the development of the Panjal Thrust indicate that the rocks at the base of the lower Salkhala unit have suffered a retrograde mineral transformation at lower greenschist conditions (see Figure 8, Neelum and Jhelum Valleys). The metamorphism across the Panjal Thrust also tended to re-equilibrate. This last observation leads us to conclude that the inverted distribution of Barrovian metamorphism of the Lesser Himalaya has been caused by continuous movements along the thrust planes (Greco, 1989).

6. Main Boundary Thrust

The Main Boundary Thrust cuts across several Lesser Himalayan units with different metamorphic grades, and also across the stilpnomelane isograde in the Subhimalayan Murree Formation (see Figure 8). As features of brittle-ductile deformation are present, and because postkinematic mineral growth is only rarely observed in the Panjal and Hazara units, the Main Boundary Thrust must have developed after the peak of regional metamorphism. An important vertical displacement less than 10 km, is recorded across this tectonic discontinuity. As a consequence, the development of the Main Boundary Thrust and the immediately subsequent doming of the Hazara-Kashmir Syntaxis (Bossart *et al.*, 1988) could be considered responsible for the rapid uplift of Lesser and Higher Himalayan units. This rapid uplift resulted only in an initial thermal re-equilibration across the Main Central Thrust, and in particular prevented retrograde recrystallisation of the prograde metamorphic assemblages.

7. Subhimalaya

As already emphasized, in the Subhimalaya rocks of the apex of the Hazara-Kashmir syntaxes, the metamorphic conditions reached the beginning of the epizone (lower greenschist facies) with the formation of stilpnomelane in the arenaceous beds. As suggested by Bossart (1986), the sedimentary thickening of the molasse formation caused the low to very low grade mineral assemblages in the stratigraphic base of these clastic rocks, which have subsequently been deformed by the thrust tectonics without metamorphic consequences. Therefore, the metamorphism in the foreland is of a different character from that seen in the Himalaya nappes.

TECTONIC EVOLUTION OF THE HAZARA-KASHMIR SYNTAXIS AREA

A tectonic evolution of the investigated area is based on detailed small-scale structures, rock distribution and textural and petrogrpahic studies. Summarizing the structural data elaborated by Bossart *et al.* (1984, 1988), and by Greco *et al.*(1989), two superimposed deformational phases could be observed in each tectonic unit of the Hazara-Kashmir syntaxes area on a macroscopic as well as on a microscopic scale. In all tectonic units, a first deformational phase produced the major recumbent fold nappes of the Higher Himalaya as well as the small scale isoclinal folds and the imbrications in the Lesser Himalaya. In the Subhimalaya, this phase is emphasized by the Muzaffarabad anticline and by the tilting of the Murree beds before the development of the Main Boundary Thrust. All these structures are not necessarily contemporaneous, but are the first to develop in each tectonic unit.

The well-established northeast to southwest directed thrust movements, signalized by the stretching lineations, probably are related to the initiation of folding and continued later deformation of these structures. The Main Central Thrust cross cuts these nappes, as different rocks types are found in its hangingwall. The overlapping of the mylonitization on the first phase structures is particularly clear in the western limb of the syntaxes, whereby the associated deformation produced the curved bend of the Panjal imbricate structures. The Muzaffarabad anticline and the Murree sediments are clearly cut by the Main Boundary Thrust in the lower Kaghan Valley, which indicates that movements on the most frontal thrust plane took place after the first deformational phase. The most likely explanation for these geometric features is that the deformation developed first in the higher tectonic units and propagated towards the Subhimalaya. The north-south trend of the mylonite zone near Balakot and the stretching lineations which become progressively north-south oriented in the lowermost tectonic elements (Greco, 1989), are the results of rotation of the initially formed northeast-southwest thrust during the later southeasterly-directed over thrusts.

A second regionally identified phase of folds is superimposed on both isoclinal folds and thrusts. It is possible to follow these structures through the different tectonic elements which suggests their contemporaneous development (Greco *et al.*, 1989). The crenulation cleavage remains fairly constantly oriented and cuts the previously formed penetrative schistosity and mylonitic foliation. Regionally, this deformation can be correlated with the northeast-southwest oriented structures which develop from the Hazara to the Indus Kohistan (Coward & Butler, 1985; Coward *et al.*, 1986; Bossart *et al.*, 1988). In the Kaghan Valley it is clear that this second set of structures is superimposed on the older set, producing an anticlockwise rotation of the earlier thrust lineations.

The last tectonic event led to a doming of the earlier structures, the bowing up of the Murree Formation into the core of the Hazara-Kashmir Syntaxis, and the domal arrangement of the dark phyllitic schists in the Salkhalas south of Naran. Between the domes, "basins" and regionally important synformal depressions have been observed. These cause the flexure of the mylonite zone around Kaghan village, while a major axial depression has led to the extensive area of surface outcrop of the Upper Paleozoic to Lower Mesozoic cover in the upper Kaghan Valley. In the Sub- and Lesser Himalaya discrete small-scale tectonic features related to the doming (minor folds, schistosity or shear structures) have not been observed. The domes are recognized only by the flexuring of the preexisting thrust planes, foliations and lineations. Consequently, it is suggested that the domes in the Subhimalayan and Lesser Himalayan units do not belong to a discrete third deformation, but are the product of the non-coaxial interference pattern of type 1 (->2) (Ramsay, 1967) of the two previous phases.

The observation that the deformational regime and the metamorphic development of the area are intimately associated allows the use of petrologic data to suggest a model for both the tectonic and metamorphic evolution of the area as schematized in Figures 10 to 12. A specific tectonic event, which is characteristic for a specific time span, led to metamorphic changes in the tectonic units. These changes are represented in qualitative P-T diagrams which are conceptually not new for the Himalayas, and the suggested time spans are also derived from other studies.

The model begins (Figures 10) with the Late Cretaceous granulitic facies metamorphism at the base of the Kohistan sequence representing the oldest, "Eo-Himalayan" event recorded in the investigated area. The exact age of the emplacement of the Kohistan sequence over the Indian Plate is questionable. Observations suggest that the formation of the Indus Suture occurred in the Early Tertiary and that the movements along this thrust plane ended after the penetrative deformation, in amphibolite facies, of the Higher Himalaya (Greco *et al.*, 1989), and therefore correspond to nappe formation in the Higher Himalaya, which developed under amphibolite facies conditions.

In a subsequent phase (Figure 11) the Main Central Thrust developed, and the inverse metamorphic zoning pattern started to form. The portion of Higher Himalaya which remained under the influence of the Kohistan sequence continued to develop kyanite, whereas southeastwards (Neelum Valley), in the more shallow parts, pressure could be released during the thrusting, and sillimanite formed. Rocks at the base of the Higher Himalaya cooled during this thrusting and reached upper greenschist facies conditions (the mylonite zone of the Kaghan Valley). Contemporaneously, the Lesser Himalaya became tectonically loaded and heated by the overriding Higher Himalaya and developed the imbricated structure. Consequently, rocks of the Salkhala and Panjal units underwent syn-deformational greenschist grade metamorphism. The internal thrusting within the Lesser Himalaya caused cooling at the base of the Salkhala unit (Panjal Thrust), where we observe the retrograde mineral transformations. The end of this tectono-metamorphic event, which also caused the folding of the Subhimalayan unit, is characterized by the progressive closure of the Indus Suture which produced the greenschist facies overprint of the granulites of the Kaghan Valley (Greco *et al.*, 1989).

In order to prevent the complete thermal re-equilibration of the tectonic pile, which would have obliterated the inverse metamorphic pattern, a rapid uplift of the area is required (Figure 12). Zeitler (1985) has shown that this uplift occurred in the investigated area in the last 15 my. However, the isostatic re-equilbriation of the thickened Indian crust could not have solely produced the rate and the amount of required uplift. Consequently, the uplift must have had other important tectonic components. In the present model, uplift already began with the development of the Main Boundary Thrust in the apex and eastern limb of the Hazara-Kashmir Syntaxis. The anticlockwise rotation of the transport direction and therefore the development of the second deformational phase signalizes the shift of deformation to the limb of

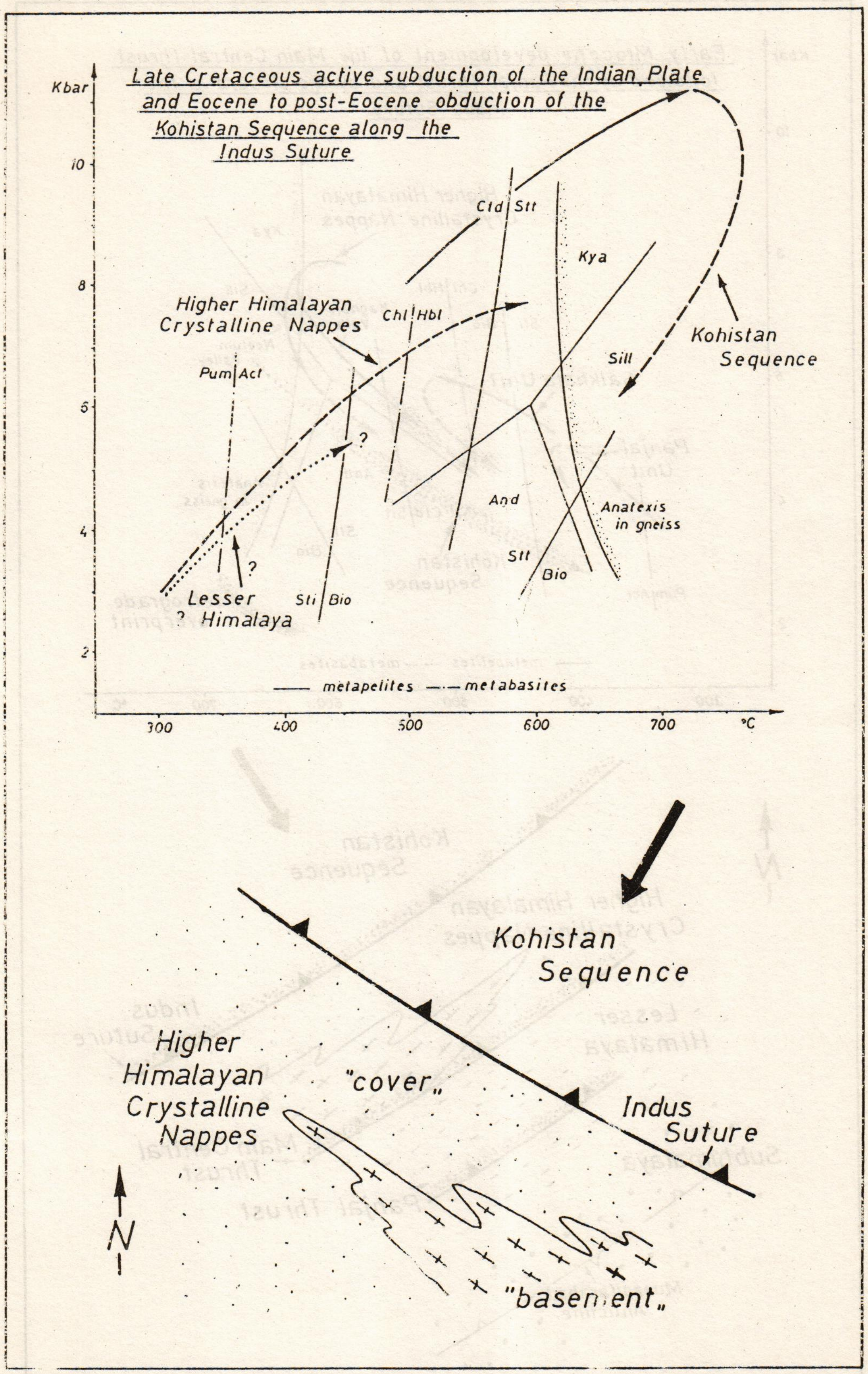


Figure 10: The first tectono-metamorphic event begans with the high pressure metamorphism at the base of the Kohistan Sequence. Much later, the emplacement of the Kohistan Sequence above the Indian Plate produced the recumbent folds structure in the Higher Himalaya under amphibolite facies conditions.

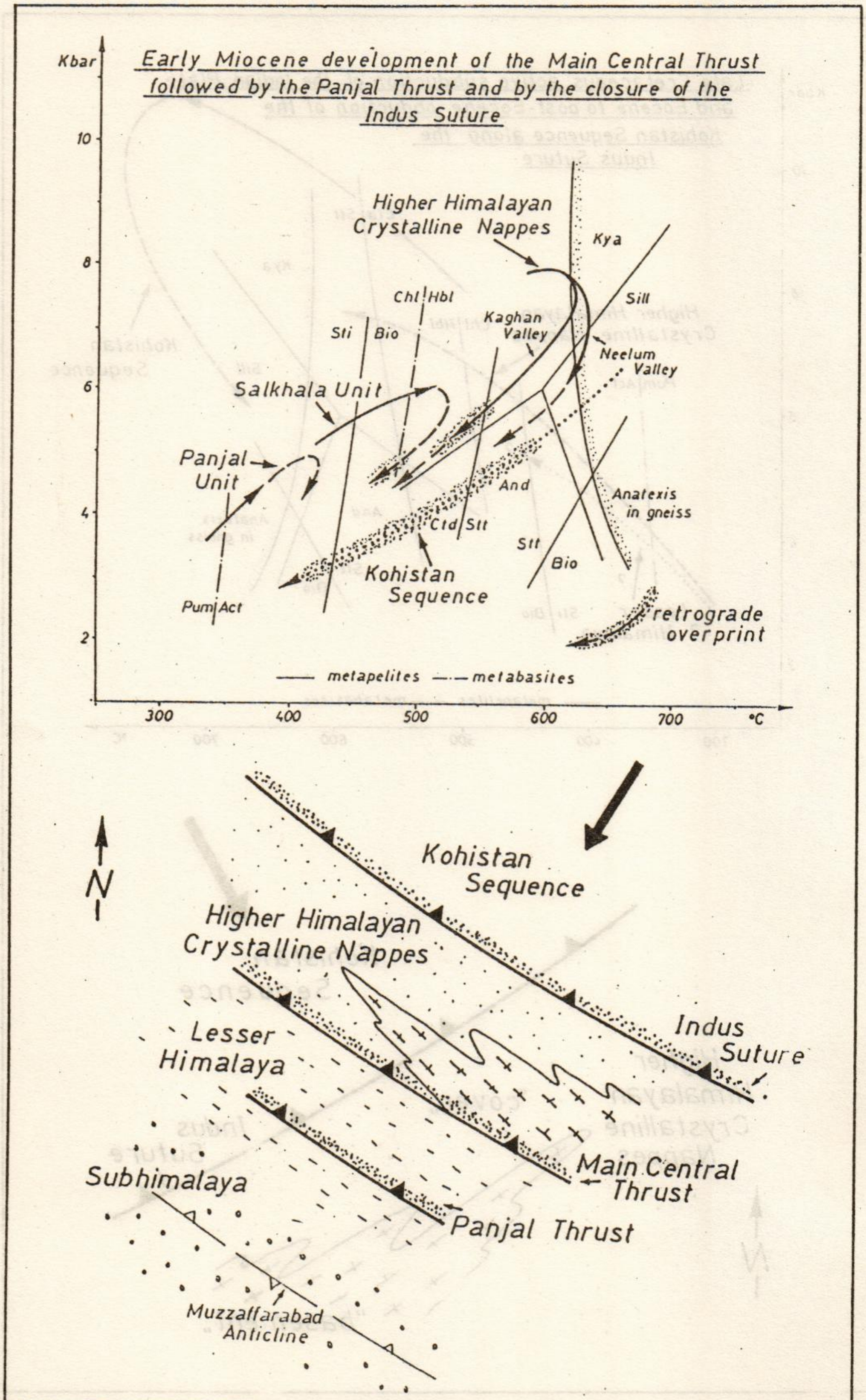


Figure 11: Development of the Main Central Thrust and of the consequent inverted metamorphic zoning pattern. Both are accompanied by deformation in the Lesser Himalayan realm. Development of the Muzaffarabad Anticline in the Subhimalya and absence of the Main Boundary Thrust should be noted.

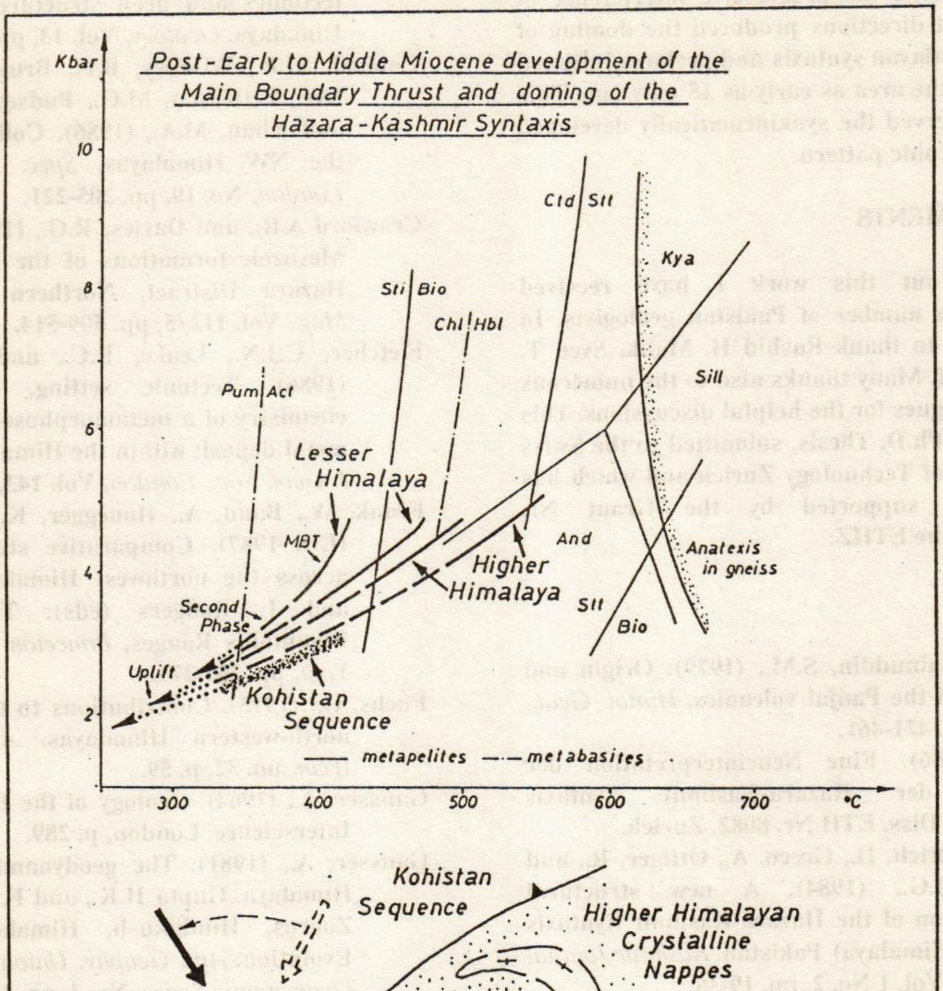


Figure 12: The last tectono-metamorphic phase comprises formation of the Main Boundary Thrust and anticlockwise rotation of the transport direction. The latter produced doming in the Western Himalayan Syntaxis and perhaps initiated a rapid uplift of the area as early as 15 my ago.

the syntaxis. Finally, the progressive interference of the two transport directions produced the doming of the Western Himalayan syntaxis and perhaps initiated a rapid uplift of the area as early as 15 may ago. This rapid uplift preserved the synkinematically developed inverted metamorphic pattern.

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GEOLOGY AND PETROTECTONICS OF SOUTHEAST KOHISTAN, NORTHWEST HIMALAYA, PAKISTAN

By

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ABSTRACT: About 2200 Km^2 of southeast Kohistan has been geologically mapped and the stratigraphy of the area established. A possible sequence of events has been listed. Detailed field relations and lithologic descriptions of many units have been reported for the first time. The rocks in main belong to arc and oceanic affinities. The predominantly plutonic arc set represents a relatively older much eroded terrane where the volcanic cover stands largely removed. The relatively smaller volcano-hypabyssal suite appears to be the latest magmatic event. Most of the amphibolite mass, tholeiitic greenstones and ultramafics represent obducted masses and shreds of oceanic affinities. The hanging wall sole rocks of MMT as well as foot wall rocks along minor syntaxis do contain deeper level obducted slices and shreds of eclogites and high pressure granulites.

The Chilas norite complex is sandwiched between northern and southern arc masses. The field and petrographic data suggest that the Chilas norite complex appears to have been formed under a spreading centre. The MMT suture zone ultramafics are divided into part cumulate and part mantle tectonite. The carbonaceous-argillaceous, argillaceous and calc-pelitic phyllites and associated low grade carbonates represent Tethyan shelf sediments, sandwiched between the Higher Himalaya and southern suture ophiolites.

Structurally the area is characterised by a number of northwest dipping high-angle imbricate thrusts which converge into and are terminated by the Raikot fault in the east. Polyphase folding is seen in the Kamila amphibolites while the norites appear to have been folded into a tight to isoclinal antiform.

INTRODUCTION

Geologically, Kohistan is considered to comprise the area between the two sutures i.e. the Main Karakoram thrust (MKT) in the north and the Main Mantle thrust (MMT) in the south (Fig. 1). In the east, it is abruptly juxtaposed against the Nanga-Parbat-Haramosh massif. In the west, the two sutures, MKT and MMT close in and meet outside Pakistan in Afghanistan (Fig. 1).

Thus defined, Kohistan would include not only the Indus valley between Jijal and Jaglot but also Gilgit, parts of Hunza, Yasin, Darel, Tangir and parts of Swat and Dir. Southeast Kohistan is the lower eastern corner of Kohistan island arc in contact with MMT or the active Raikot fault (Lawrence and Ghauri, 1983a). Geographically, it is the area around Chilas and includes the valleys of Thor, Buto Gah, Thurli, Huddar, Bunder and Gunar Farm.

Like many other petrotectonic features of the Himalayas, major lithologic units of southeast Kohistan are remarkable in their occurrence in the form of parallel E-W to NE-SW trending belts. This thrust stacked pile of major units narrows in the east where they are truncated against MMT/Raikot fault. Thus, the very thick units of the central part of Kohistan can be seen along a small section in southeast Kohistan.

Geographically and geologically, Kohistan is a very big area and a very big mass respectively. So far it has only been studied in isolated patches i.e. along certain sections in Dir (Chaudhry *et al.*, 1974, 1974a, 1974b, 1983a, 1984; Butt *et al.*, 1980; Jan *et al.*, 1983), along parts of Swat (Martin *et al.*, 1962; Jan, 1968, 1979a, 1979b, 1979c, 1983, 1985; Jan and Mian, 1971;

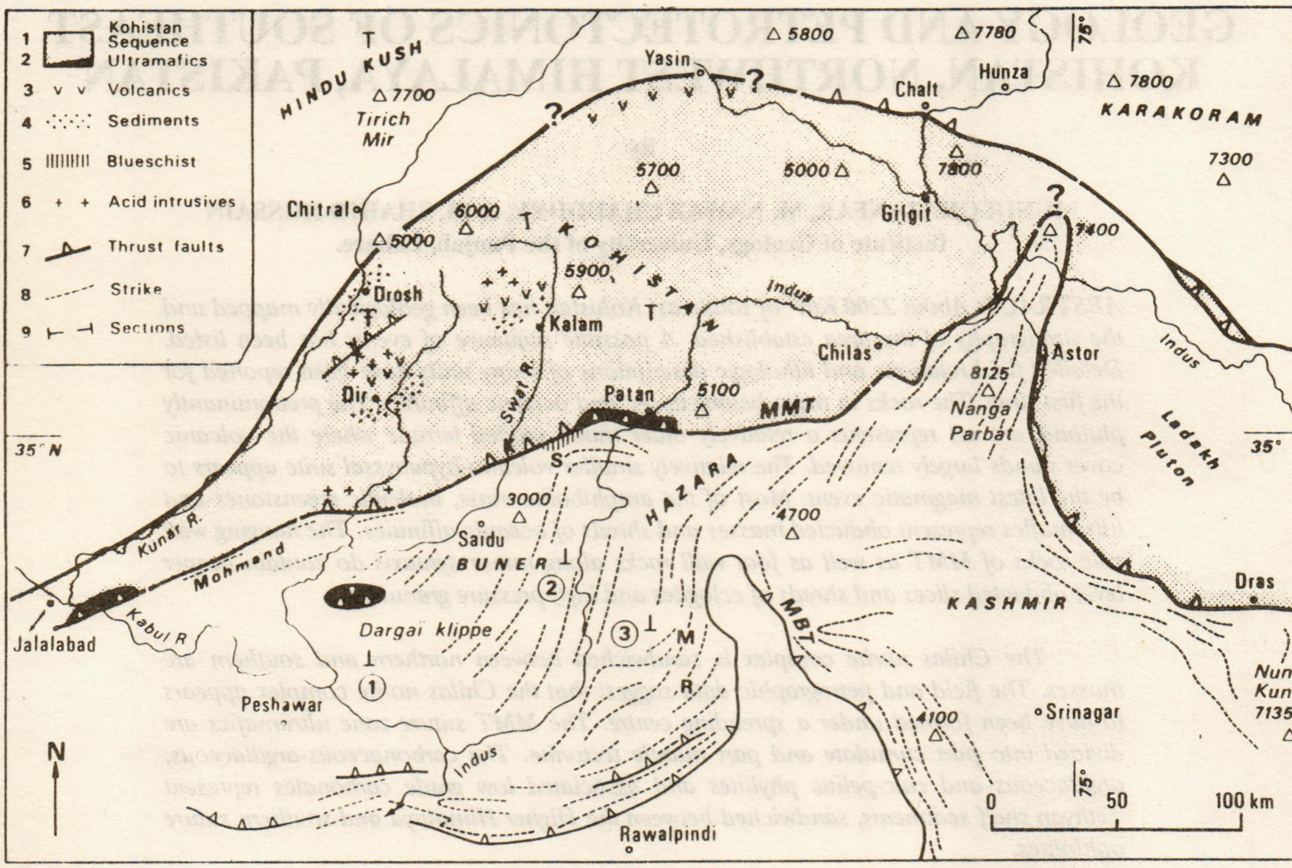

Figure 1. Sketch map of the India-Eurasia suture zone in Northern Pakistan and adjacent areas. 1: *Kohistan sequence* ("Kohistan basic complex" and associated metasediments and volcanics), *basic complex around Nanga Parbat*, and *Indus suture zone* (including post tectonic granitic plutons, and possible sialic remnants, undifferentiated). 2: Peridotites and other ultramafic or high density mafic rocks. 3: Volcanics of calcalkaline composition (Dir, Kalam, Yasin, Dras (perhaps partly tholeitic for the last two). 4: Sediments or metasediments, presumably of Late Cretaceous age. F: fossils. 5: Shang-La blueschists. 6: Granites and other acid post-tectonic intrusives. 7: Main thrust faults. 8: Tectonic trends in Buner (and Kashmir) series. 9:

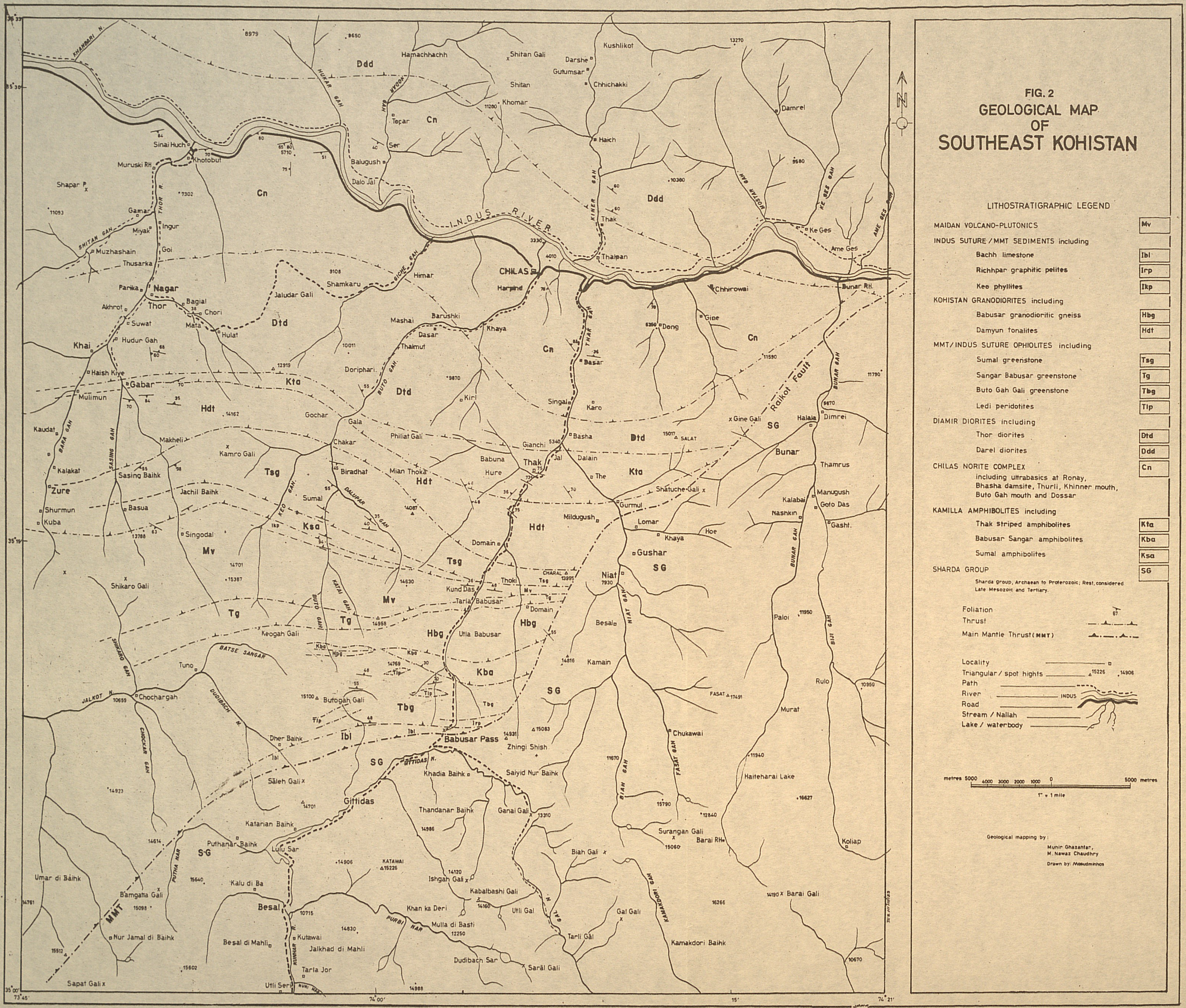

FIG. 2
GEOLOGICAL MAP OF SOUTHEAST KOHISTAN

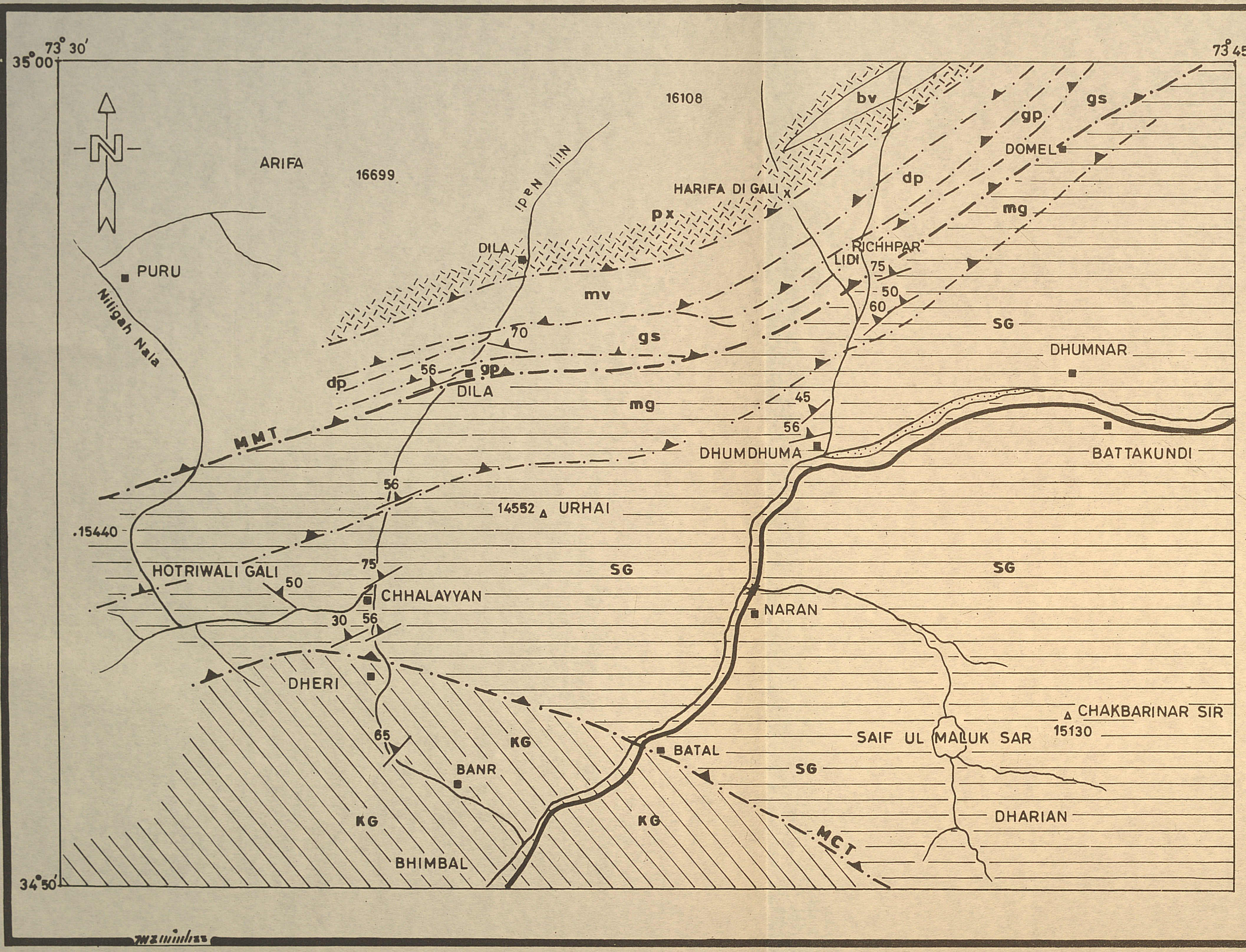

FIG. 3

GEOLOGY ALONG MMT NILI NADI, LEDI NAR SECTION UPPER KAGHAN

LEGEND

MMT Melange

Tertiary	mv	Maidan volcano-plutonics
Cretaceous	px	Pyroxenite
	dp	Dunite, Peridiotite
	gs	Greenstone
Paleozoic	gp	Graphitic phyllite
Precambrian	KG	Kaghan group
	SG	Sharda group including
	mg	Babusar mylonites (garnetiferous graphitic schist etc.)

Thrust, Foliation 50

0 1 2 3 km

River, stream, lake, Road, town

Geological mapping by : Munir Ghazanfar and M. Nawaz Chaudhry

Drawn by : Masudminhas

Jan and Kempe, 1973; Desio, 1977; Shams, 1972, 1980; Majid, 1979; Majid *et al.*, 1981; Chaudhry *et al.*, 1980; Chaudhry and Ashraf, 1986; Symes *et al.*, 1987) and along Karakorum Highway (Desio, 1973, 1983; Chaudhry *et al.*, 1983; Bard, 1983, 1983a; Bard *et al.*, 1980, 1981; Jan and Asif, 1981, 1983; Khan *et al.*, 1985; Hamidullah and Jan, 1986; Lawerence and Ghauri, 1983, 1983a; Majid and Shah, 1985; Petterson and Windley, 1985). Apart from Dir hardly other area has so far been mapped in detail. Obviously, therefore, a controversy rages on the interpretation of the rocks of Kohistan. The present mapping of the southeast Kohistan (Figs. 2 and 3) is very instructive in terms of the study of field relations of various rock units and their description for the purposes of interpretation.

In the broader context of Kohistan the reader is referred to the following important works.

Bard *et al.* (1980), Bard (1983 and 1983a) Butt *et al.* (1980) Chaudhry *et al.* (1974, 1974a, 1974b, 1980, 1983, 1983a, 1984, 1986), Chaudhry and Chaudhry (1974), Chaudhry and Ashraf (1986), Chaudhry and Ghazanfar (1987), Coward *et al.* (1982, 1986, 1987), Coward (1985), Desio (1973, 1977, 1983), Gansser (1980), Ghazanfar and Chaudhry (1985), Hamidullah and Jan (1986), Jan and Mian (1971), Jan and Kempe (1973), Jan and Howie (1980, 1981), Jan and Asif (1981, 1983), Jan (1977, 1979, 1979a, 1979b, 1979c, 1980, 1985) Jan *et al.* (1983), Kazmi *et al.* (1984), Khan *et al.* (1985), Lawrence and Ghauri (1983, 1983a, 1984), Lawrence *et al.* (1983), LeFort (1975), Majid (1979), Majid and Shah (1985), Majid *et al.* (1981), Petterson and Windley (1985), Powell and Conaghan (1973), Pudsey *et al.* (1986), Searle *et al.* (1987), Shah and Majid (1985), Shams (1972, 1980), Shams and Shafiq (1979), Spencer *et al.* (1989), Symes *et al.* (1987), Tahirkheli (1979),Tahirkheli *et al.* (1977, 1979), Verplanck (1987), Zeitler *et al.* (1982), Baig (1989).

The southeast Kohistan area is critical for stratigraphic, structural and tectonic studies. Four major tectonostratigraphic units are exposed in the area. The units from south to north are; the Tethyan shelf sediments, the Indus suture zone and the Kohistan island arc. All of these units are thrust bounded.

INDIAN PLATE MARGIN

Tectonically the Indian plate margin has been indentified as the Higher Himalaya Crystalline of Pakistan. The geology of this high grade old Indian shield slab has been described at length by Misch, 1947, Chaudhry and Ghazanfar 1987, 1990, Greco *et al.*, 1989 and Spencer *et al.*, 1990.

Tethyan Shelf Sediments: These are represented by only thin, discontinuous slices of low grade metasediments exposed between the high grade Indian plate margin and the Indus suture melange. The Bachh limestone, Richhpar graphitic pelite and Keo phyllite units ,are very distinct. These are very slightly metamorphosed and occur associated with Babusar thrust (southernmost thrust of MMTZ).

These rocks have been metamorphosed in lower greenschist facies. The exposures of these units may be seen at Bachh in Lohyalul and near Ledi in Ledi Katha. A few slices also occur near Babusar pass. The rocks just south of Babusar thrust (Spencer *et al.*, 1988) fall in upper amphibolite facies, while the rock units occurring to the north fall in the greenschist facies. Thus, there is a very big PT break across Babusar thrust of MMTZ (Chaudhry and Ghazanfar, 1987).

The Bachh limestone unit is thinly bedded and slightly argillaceous. It is dirty white to off white. The pelitic calcareous layers contain chlorite flakes. The weathering colour is pale white to dirty off white with rusty patches and stains.

The Richhpar graphitic pelite unit is a dull black phyllite. It is very fine grained. It weathers from dull black to rusty black. It is splintry. It contains tiny pyrite grains. It decomposes to earthy and splintry aggregates. At places contains quartz veins. It does not form cliffs or very steep slopes. The Keo phyllite is non graphitic pelite.

INDUS SUTURE ZONE

The Indus Suture Zone marks the collisional boundary between the Indo-Pakistan plate and Kohistan island arc. The Indus Suture zone constitutes the greenschist, blueschist and ophiolitic melange (Kazmi *et al.*, 1984; Chaudhray *et al.*, 1984; Baig, 1989). These malange units are thrust bounded.

KOHISTAN ARC COMPLEX

On the basis of field relations a partial stratigraphic sequence of the rocks of southeast Kohistan is as follows.

5. S-type minor intrusive bodies of tourmaline granite, aplite and pegmatite.
4. Maidan volcano-hypabyssals, Huddar and Babusar granodiorites and tonalite.
3. Thor and Darel diorites.

2. Chilas complex.

1. Kamila amphibolite, Thak striped amphibolite and Sumal, Sangar, Babusar and Buto Gali greenstones. This sequence also includes lenses and blocks of suture ultramafics.

Detailed study of field relations shows that the rock units of southeast Kohistan can be grouped into five broad groups listed above. The amphibolites, greenstones and ultramafics of the first group of rocks are intruded by granodiorite, tonalite and volcano-hypabyssals. The latter contain xenoliths and screens of amphibolites and greenstones. The xenoliths and screens have been assimilated to varying degrees leading to colour and compositional changes of the this group of rocks.

A very distinctive rock type is the norite of the Chilas complex. The age of this complex has been constrained at 80 Ma (Coward et al. 1987) from certain hornblende pegmatites that cut it. The field relations show that the norite is not intruded by diorites or granodiorites and, therefore, appears to be younger than diorites or granodiorites. In contrast, at some places norite complex has been deformed and at least tectonically emplaced along some undeformed to much less deformed diorites and, therefore, appears to be older than the latter. The youngest group of rocks are S-type granites and tourmaline- bearing aplites and pegmatites. This group of rocks intrude all the rock types.

A detailed description of the above listed rock units is given below.

Amphibolites, Greenstones and Suture Ultramafics

Kamila Amphibolite: Unlike the Kamilla outcrop this unit does not occur as a single extensive body in this area. At Kamila, this unit is very wide and continuous but in the area under study, this unit is dismembered and occurs as relatively thin linear outcrops, screens, patches and xenoliths. This unit has been dismembered and intruded by diorites, granodiorites, and tonalites etc. It has been extensively mixed and modified by the intruding/invading units.

South of Utla Babusar village (Fig. 2), this unit occurs as a thin linear belt which is terminated in the eastern part. The rock is strongly banded and foliated and is composed of amphibole, epidote, plagioclase and pink eumorphic garnet. Garnet occurs in certain bands whereas it is absent in other bands. Garnet is often fractured and shows alteration to chlorite.

Near Sumal, amphibolites occur associated with greenstones. Outcrop of amphibolites is also present near Lemat and Losh in Thak valley. Amphibolite is also present near Gutomal in Buto Gah. On the fresh surface it is dark grey to dark greenish grey with 1 to 3 mm white specks of plagioclase. It may be banded or foliated. At places, it contains hornblende pegmatites. On the weathered surface, it looks dark greenish brown. At Lemat in Thak valley the rock also shows small intrusions of granodiorites.

In Thor dismembered amphibolite, similar to the one which occurs in Thak and Buto Nalas, is also seen.

The amphibolite shows a lot of mineralogical, textural and structural variations. This is due to variable mineral composition, mixing and metamorphic differentiation.

Thak striped Amphibolite Mylonite: The Thak amphibolite mylonites, a part of Kamilla Amphibolites are a striking unit. Although they are far less extensive than Chilas norites or Thor diorites. Their outcrop occurs in the form of a generally E-W extending slice which is widest in Thak and Niat valleys, where it occurs between Khun and Jhal and Gurmil and Jhal respectively (Fig. 2). Westwards a very thin outcrop continues for a long distance, appearing at Gabar in Thor valley and then below Papoti Gali in Harban Nala.

The Thak striped amphibolite mylonites are striking mainly because of the leucocratic bands and granite pegmatite sill type bodies which are so common as to give the rock an intercalated appearance. Secondly, at many places, the dips are nearly vertical and the structure simple which make the long dark grey and pale white stripes especially distinctive and characteristic.

The amphibolite bands are fine grained, melanocratic and foliated. The amphibolite is specially dark or black on bedding planes where, at places, many criss-crossing crystals of hornblende can be seen. These are post-tectonic and developed when the rock was still hot. On the fresh surface the amphibolite is generally dark grey or dark greenish grey with small (1 to 3 mm) specks of white plagioclase. On the weathered surface, the amphibolite bands are dark greenish brown or dark brown and dark brownish grey and, at places, show desert polish.

The granite pegmatite bodies are generally in the form of one to three feet thick sills and some dykes. They also make ptygmatic veins and boudins in amphibolite. The leucocratic veins and granite pegmatites are white to light grey on fresh surface and on the weathered surface they become pale white to pale yellow. Small sills and dykes of diorite or tonalite may occur near the contacts of this amphibolite and enclosing diorite/tonalite.

At places the two rock types (leucocratic bodies and amphibolite mylonite) show greater degree of mixing leading to the formation of what looks like a tonalite or granodiorite. The colour on the fresh surface also becomes lighter shades of green and greenish grey and the rock is banded in the form of thin medium greenish grey and white layers.

In the Thak Valley, the striped amphibolite unit is markedly different from the upstream tonalites (which are more uniform and medium to light grey) and from the down-stream Thor diorite which begins at Jhal. The contact of Thak amphibolites with Thor diorites is abrupt.

The mylonised amphibolitic part is composed of black hornblende and plagioclase with rare garnet. This part may also contain a little quartz. Sphene and magnetite are the accessories.

The pegmatite bodies are coarse grained and composed mainly of feldspar and quartz but biotite, muscovite, vermiculite and chlorite may also occur. A few simple tourmaline mica pegmatites were also encountered in this unit. Many of these tourmaline mica pegmatites which also contain garnet are S-type and have been derived from melting of the Indian Shield. S-type granite pegmatites and aplites are also found in the amphibolites around Kamila.

Sumal Greenstones: A fairly wide and distinctive zone of greenstones with subordinate amphibolites on the southern margin (near Gutomal) occurs in Buto Gah between the villages Chakar and Gutomal. Eastwards this zone thins and outcrops between the villages of Lemat and Losh in Thak valley. Westwards these greenstones extend as a wide zone extending into Jalkot Nala.

The greenstones are dark to medium green on the fresh surface, foliated and generally fine grained but may contain porphyroblasts of chlorite and yellowish green shades of epidote can also be seen at places. At other places, the rock shows some admixture with granodiorites/tonalite and at such places its colour index decreases and it may become light greenish grey. In addition, sills, veins and lenses of granodiorite can be seen intruding the rock at some places which may show the effects of chilling at times. The rock is greenish brown to dark greenish brown and dark greenish grey on the weathered surface. Generally its weathered surface is distinctive and even greenstone patches in adjacent tonalites or granodiorite can be recognised from far off.

The amphibolite associated with the greenstones to the south appears at Gutomal in Buto Gah and at Lemat in Thak Gah. On the fresh surface it is dark grey to dark greenish grey with 1 to 3 mm white specks of plagioclase and is foliatead and may be banded. At places, the rock is pegmatitic. On the weathered surface the amphibolite looks dark greenish brown. At Lemat in Thak the rock also shows small intrusions of granodiorite.

Sangar Babusar Greenstone: Around Sangar especially to its south there is over a kilometre wide zone of greenstones and some amphibolites. This zone narrows and extends to the east appearing at Tarla Babusar in Thak valley (Fig. 2). Further east, it is pinched out and truncated by the Raikot fault. Towards west it continues across the watershed of Buto Gah and Thor into the drainage of Jalkot Nala.

The greenstone is medium greenish grey on fresh surface. It is generally fine grained and is foliated. The foliation planes show greater enrichment of chlorite and, therefore, appear dark green. Thin quartz partings give the rock a laminated appearance at places. On the weathered surface from far off the rock appears dark greenish grey and, at places, dark brown. The greenstones show small intrusive patches and lenses of leucocratic coarse grained granodiorite representing intruded arc material. Depending on the level of mixing the colour index of greenstones may decrease. The greenstones show a weathering colour contrast with the foliated granodiorite underlying and overlying them. The granodiorite is light brown to light greenish brown generally, whereas the greenstones show a darker shade of greenish grey or greenish brown from far off.

Downstream of Sangar some amphibolites are also associated with the greenstone. These are dark greenish grey with thin white streaks on the fresh surface and dark grey on the weathered surface. This zone is more or less eliminated in Thak Gah.

Buto Gah Gali Greenstones: Nearly a mile wide outcrop of greenstones trending NE-SW occurs on both sides of Buto Gah Gali (Fig. 2). These greenstones have contacts with porphyroblastic granodiorite both on Kaghan side (Lohy Lul) and on Kohistan side (Buto Gah). Eastwards this outcrop extends to the north of the Babusar Pass where these greenstones alongwith amphibolites are present just north of the MMT. Further east the Raikot fault truncates the outcrop. Westwards these greenstones extend into the drainage of Jalkot Nala.

The greenstones at Buto Gah Gali are dark greenish grey to medium greenish grey on fresh surface and show a fair amount of mixing with granodioritic intrusive sills, bands and dyke. The mixing is especially more towards contact of the unit with granodiorite and veins of quartz are also present.

In Thak valley the greenstones occur close to MMT and a much wider zone of dark grey amphibolites occurs northwards towards Utla Babusar village. This zone of amphibolites is fairly extensively intruded and mixed with grandoioritic intrusions. Small lensoid slices of ultramafic rocks, generally peridotite, have been mapped within these greenstones/amphibolites in upper Thak valley (Ahmad and Chaudhry, 1976).

Maidan Gali Pyroxenites: A very thick slice of pyroxenite is seen trending NE-SW and lying in the northernmost highest reaches of Ledi Katha (north of Maidan) and Nili Nadi (north of Dila as shown on toposheet). The outcrop is at least two to three miles wide, though the northern limit could not be visited for lack of time. Perhaps it is the thickest and largest slice of pyroxenites reported so far from anywhere in Pakistan. The pyroxenites, however, were not seen among the ultramafics in Lohy Lul or at Babusar. Obviously the pyroxenite slice petered/pinched out somewhere to the north east of Ledi Katha or Maidan Gali.

The pyroxenite is a coarse grained to pegmatitic rock with a randomly interlocking crystalline texture. The finer parts may have 3 to 4 mm crystals but the larger crystals are up to 10 cm long. The colour on the fresh surface is patches of light greenish grey and medium grey and on the weathered surface the rock is dark grey, dark greyish brown and greenish grey and orange brown.

The Maidan Gali pyroxenites are more pure but still contain subordinate dunite, peridotite and pyroxene hornblendite. In addition they have minor zones of intermediate to basic volcanics and amphibolite. At least two minor granodiorite bodies were seen to intrude them.

The pyroxenite outcrop in Nili Nadi shows a lot of mixing with granodiorite. Arc type rocks with pieces and patches of pyroxene hornblendites are common; and at places, the greenish pyroxene crystals show reaction rims of black hornblende. Dioritic rock with green porphyroblasts shows frequent intermixed relation with pyroxenite.

Ledi Peridotites: Peridotite with subordinate dunite outcrops north of Ledi in Ledi Katha (trending SW-NE), north of Lohy Lul in Lohy Lul Katha and as small lensoid slices in amphibolites and greenstones between Babusar pass and Utla Babusar village (Fig. 2). On the fresh surface the peridotite is medium to dark grey sometimes with a purplish tinge. Some specks of light greenish grey can also be seen on the fresh surface. It is coarse grained, compact and very tough rock. The weathered surface from close up shows interplay of a number of colours, light brown, white, purple and green being the most common. The weathered surface may be white or brown with a network of thin purple lines or it may be purple with green, turquoise and brown patches. This few millimetre thick lining of bright light green smooth serpentine altered from dunite/peridotite is common along joints and on the joint blocks it frequently shows slickenside marks or growth fibres. This serpentinization is ubiquitous and characteristic. Alteration in the form of magnesite is also common along joints and is generally seen as a white veneer along some joint block sides. At some places small black metallic specks of chromite can also be seen standing out on the brown and greenish weathered surface of dunite.

The Chilas Complex

Chilas Norite: The norite occurs in the form of a belt extending in a general E-W direction on both sides of River Indus between Kandia River and Chilas (Fig -2). This belt which is apparently over 10 miles wide extends on both sides of the Indus; however, being much wider on the southern slopes than on the northern slopes. Towards west the belt continues across Indus into Swat, Dir and finally into Afghanistan. Towards east it is truncated by the Khe shear zone and the Raikot shear zone just before Bunar east of Chilas.

The norite is a tough massive medium to coarse grained rock, medium grey on fresh surface and brown to dark brown on the weathered surface. Patches showing desert polish are still darker shade of brown. On the fresh surface the rock is white and black mottled or coarsely speckled. Parts of Chilas norite have flesh coloured plagioclase which imparts a flesh colour to the rock. Pyroxene is both olive coloured and black in a white background of plagioclase. Orthopyroxene is generally olive green while the clinopyroxene is black. The pyroxenes may often be partially rimmed by dark green to black amphibole. Resinous, transluscent, light greenish to pale yellow crystals of olivine can also be seen in norites near the central part of the outcrop away from the contacts, as near Chilas. On a larger scale, too, there are light coloured coarser patches in a darker finer grained rock. Both are norite but the type of pyroxene varies. Some, however, are dioritic patches. In addition, there are darker aplitic veins of norite as well as veins of hornblende pyroxenite.

Near Chilas, as elsewhere, norite contains small bodies of dunite and peridotite. The dunite is both dark grey and green. It weathers in orange shades of brown. Some of these outcrops can be seen on roadside close to Chilas on way to Thak as well as on the Karakoram Highway near Chilas. The ultrabasic bodies have been discussed in more detail below.

Although both contacts of norite are faulted, the faulting is not everywhere apparent since hornblende pegmatites and hornblendites have developed on both contacts. At places, however, as in Thak Valley and Buto Gah, faulting has led to the formation of a norite mylonite which is generally a very tough dark coloured rock with streaks of white or pale white colour.

The norites are composed mainly of plagioclase and pyroxene. Both orthopyroxene and clinopyroxene are present. But the two types of pyroxenes occur in fairly variable quantities in different parts of the outcrop. Amphibole may form partial rims around some pyroxene grains. Quartz and iron ores are ubiquitous accessory minerals. Plagioclase is generally white but, at places, it may be light flesh in colour. The norite may either be massive or layered. The layers are marked by pyroxene and plagioclase.

Ronay Dunite: This unit occurs in the Ronay part of Chilas city as well as on the mouth of Thak Nala (Fig. 2). The rock is hard and compact. Its colour on fresh surface in Ronay part of the outcrop is from green to pale green. The lustre is resinous. Its weathering colours are bright orange to orange brown. However, desert polished parts are clearly dark brown to shining grey or black. Forsterite olivine makes up more than 98% of this rock. The rest is pyroxene, serpentine and magnesite. The Ronay outcrop shows deep weathering.

At the mouth of Thak Nala along K.K.H. the dunite is massive. It is black to pale greenish grey or dark greenish grey in colour. Rarely it may be dark green. The weathering colours are orange to rusty orangish dark brown. The desert polished surfaces are dark brown to grey. Along some joints serpent green serpentine has developed. Magnesite films may coat some joints. Pyroxene may also occur along some planes. Olivine makes up more than 95% of the rock in this outcrop. The rest is pyroxene, serpentine and magnesite.

Basha Damsite Ultrabasics: This body is only a few meters thick. It is composed of variable proportions of olivine, pyroxene and amphibole. It is multicoloured, pale green, light green and black. The pale green colour is due to olivine, the light green colour is due to amphibole. This body is texturally heterogeneous. The parts rich in olivine are generally fine to medium grained while the parts composed of pyroxene are medium to coarse grained and the parts composed of hornblende are coarse grained. This body is cut by, at least, two (30 cm. thick) amphibole plagioclase pegmatite veins. It weathers to shades of brown and orange.

Thurli Ultrabasics: This ultrabasic body occurs near Thurli Nala (Fig. 2). It covers an area of 2.7 sq. kilometres. It is basically a dunite-peridotite body with patches of hornblendite and hornblende plagioclase pegmatites. The fresh colour of the body is from yellow green to grey. Hornblendite patches are black. The weathering colour of this body is generally orange to orange brown. The desert polished parts of the outcrop are shining buff to brownish grey. The joint surfaces are often lined with magnesite. For details, see Khan et al. (1985).

Khinner Mouth Ultramafics: A few small peridotite pods and veins occur near the mouth of Khinner Nala. These bodies range in size from a few cms to about 1 m. They are composed mainly of olivine with small quantities of pyroxene.

Buto Gah Mouth Ultramafics: Near the Buto Gah bridge behind Chilas city occur a few small peridotite pods and veins.

Dossar Ultramafics: Two bodies of ultrabasic cumulates occur near Dossar. These bodies are mainly dunites and peridotites. They are composed mainly of olivine with variable quantities of pyroxene. Both orthopyroxene as well as clinopyroxene occur in these bodies. Magnetite, chromite, magnesite and serpentine occur as accessories.

Thor and Darel Diorites

Thor Diorites: Parallel and to the south of norite an outcrop of diorite extends in a general E-W direction from Thor to Bunar (Fig. 2). This outcrop band is thinner than the norite outcrop and narrows further towards east until it is pinched out and truncated between the Khe thrust and Raikot fault across Bunar on the Karakoram Highway. In Thor River the diorite outcrop is nearly 8 miles wide and occurs around Nagar, Thor and Khai. In Buto Gah, its wide outcrop occurs in the area of Chichh, Barushk, Dudifaree and Bassakal. In Thak Gah, the outcrop narrows and occurs between Kali and Jhal. A much thinner slice is present near the mouth of Bunar Gah before the outcrop terminates on the Karakoram Highway. Westward a wide outcrop of Thor diorites continues across the Harban Nala between Harban Kot and Papoti Gali to the Karakoram Highway and further west.

The Thor diorite is a hard, compact and massive rock unit which is light brown to dark brown on the weathered surface, at places with dark steel desert polish. On the fresh surface, the rock is generally medium grey but sometimes greenish grey. In the hand specimen, the black or sometimes dark green amphibole in white plagioclase makes a coarse stippled pattern.

The diorite contains numerous patches and xenoliths of finer grained melanocratic amphibolite and also patches of leucocratic granodiorite. There are also dark grey aplitic veins and few veins of vermiculite/biotite pegmatite. Much more numerous, and in fact characteristic are the hornblende pegmatites and associated hornblendites. The pegmatites contain hornblende crystals in plagioclase. The crystals may be less than one centimetre but can attain upto 10 cm size. These dark grey pgmatites are common but they make especially thick zones near Barushk in Buto Gah. However, their frequency decreases towards Thak Valley. Here they are intimately associated with hornblendites.

The Thor diorite can sometimes be difficult to distinguish from the Chilas norite. However, the diorite is characterized by black amphibole as against the generally olive coloured pyroxene of norites. They are also characterized by hornblende pegmatite veins and hornblendites and a relatively more heterogeneous nature compared to norite. The latter towards Chilas also contains pale green olivine.

The northern contact of Thor diorite with Chilas norites is faulted and sheared. Upstream of Khe, hornblende pegmatites present near the contact have also been mylonitized.

These diorites are composed essentially of amphibole and plagioclase. Biotite, vermiculite and quartz mostly occur as accessories. Amphibole is generally black in colour but, at places, may be medium to dark green. Rarely the diorite may contain small patches with chalcopyrite altering to azurite/malachite.

The pegmatite and pegmatitic hornblendite zones are intimately associated. The pegmatites are generally from mesocratic to melanocratic. They are composed essentially of hornblende and plagioclase. Quartz and biotite/vermiculite may occur from accessory to subordinate minerals. The associated hornblendites are also pegmatitic and composed essentially of black amphibole with accessory plagioclase. Very often the pegmatites and hornblendites grade into each other.

Darel Diorite: This diorite body varies in composition from diorite to quartz diorite to tonalite. It is speckled black and white but sometimes speckled dark green and white. The rock is generally medium grained, massive and well jointed. Its weathering colour is rusty brown to dark brown. At places, the weathering colour is pale grey. The outcrop at many places exhibits a dark brown desert polish.

The diorite body is composed mainly of black to dark green amphibole and white (rarely light pink) feldspar. Black to bronze black biotite and quartz occur as accessories. With increase in quartz (and biotite) the rock changes to quartz diorite and even tonalite. This unit is generally medium grained, massive and well jointed.

Its contact with norite is sheared and faulted. But here also develops a discontinuous and erratic zone of amphibole plagioclase pegmatites and hornblendites. In Khinner Nala this zone is very wide and may be hundreds of metres thick. The pegmatites are composed mainly of black amphibole and white plagioclase. Many areas within this zone also contain abundant grey to dark grey K-feldspar. Quartz, biotite and vermiculite may occur as accessories.

The hornblendites do not occur as separate bodies. But with the increase in amphibole, the intermediate pegmatites change into basic hornblende pegmatites which in turn may change to plagioclase hornblendites and hornblendites. The individual crystals vary widely in size, some of them may reach a size of 10 cm. Within this zone a few thin muscovite bearing quartz-o-feldspathic pegmatites are also present. The dioritic matter though present in this zone is subordinate.

Tonalites, Granodiorites and Volcanohypabyssals

Damyun Tonalite: Upstream of Thak striped amphibolites, an outcrop of quartz diorite/tonalite extends in a general E-W direction (Fig. 2). The outcrop is thickest (about 4 miles wide) in Thak Gah where it extends between Losh and Khun. Towards east a thin slice is met with between Gurmil and Nagaran but is truncated soon after by the Raikot shear zone before it can reach Bunar Gah. Westward a nearly 2 mile wide outcrop is also present in Buto Gah between Chakar and Gochhar. The outcrop widens again in Thor valley where it occurs between Gabar and Makheeli. In Harban Nala, the same unit outcrops between Papoti Gali and Puskhari pass. The outcrop then continues further west towards the Karakoram Highway.

The unit, named after village in Thak Gah is generally a foliated to partly non-foilated quartz doiorite-tonalite which shows a lot of mixing with greenstone which it has presumably intruded and assimilated to varying degrees leading to corresponding changes in the composition of the rock. Xenoliths and patches of greenstone are ubiquitous. Large screens of greenstone can be seen within the tonalites near their contact with greenstones at Chakar in Buto Gah. Elsewhere, too, the colour of the rock can vary according to the degree of assimilation. At places, therefore, the rock may be described as meladiorite as near Kumal upstream of Thak Kot where the rock shows numerous patches of amphibolite and even hornblendite and as hybrid near where it is again dark and shows numerous patches and xenoliths of amphibolite.

Generally speaking the Tonalite is light to medium greenish grey or grey on the fresh surface where black and/or dark green amphibole, variable amount of minor biotite and some transluscent quartz can be seen along with white plagioclase. The dark greenish grey or black amphibole in white plagioclase gives the coarse grained rock a stippled appearance. At places, the biotite and hornblende show alteration to chlorite. The chlorite occurs as green porphyroblasts on the outcrops.

Huddar Tonalite-Granodiorite: This unit is located to the north just outside the mapped area. This tonalite/granodiorite body is rather heterogeneous. It is generally medium to coarse grained, and leucocratic and with colour index of about 20-25%. It is speckled black and white. It is lighter coloured and often somewhat coarser than the diorite. It weathers to light brown and rusty light brown colours. It is composed of plagioclase, hornblende and biotite. Quartz is ubiquitous. The colour of feldspar is generally white but may also be light flesh. Both black and bronze biotite may be present. Biotite may sometimes form porphyritic crystals. Quartz is conspicuous and may be easily identified.

In Huddar Gah, xenoliths of basic gneiss (amphibolite) are present in this unit. Intermediate pegmatites are rare while simple granite pegmatites and aplites are often present. The simple pegmatite veins are generally composed of white feldspar, muscovite, quartz and sometimes tourmaline.

Babusar Granodiorite Gneiss: This leucocratic granodiorite gneiss which extends in Thak valley from south of Utla Babusar village to Lemat down-stream of Tarla Babusar has a wedge shaped outcrop which pinches out rapidly to the east and is truncated by the MMT east of Damyun Gah (Fig. 2). Within this unit a nearly half mile wide slice of greenstone is present at Tarla Babusar. Westward in Buto Gah, the granodiorite becomes thicker and so does this slice of greenstone. The greenstone also includes a thick volcanic suite between Sangar and Dadar (in Buto Gah). Thus in Buto Gah the Babusar granodiorite gneiss has one outcrop north of the greenstone suite around the area of the junction of Buto Gah and Katai Gah including Gutomal village and another outcrop extending between Shay Dheri to close to Butō Gah Gali. Further west this expanded unit continues into the drainage of Jalkot Nala.

At Utla Babusar, the granodiorite gneiss is coarse grained and light greenish grey on fresh surface. White plagioclase (occasionally pink) with variable amount of chlorite porphyroblasts or biotite and even hornblende give the rock a foliated and spotted/coarse stippled appearance. Quartz can also be seen in the hand specimen. Foliation is characteristic and, at places, leads to slab type joint blocks. The rock is brownish to brownish grey on the weathered surface. At places, algal growths can give the weathered surface an orange tinge.

In Buto Gah, the unit occurs between Gutomal to Dadar and Shay Dheri to close to Buto Gah Gali. These two outcrops can further be subdivided into a number of bands depending upon the degree of mixing with greenstones/amphibolites. At least three bands, one north of Gutomal (and south of volcanics), one at Shay Dheri and one south of the last cirque lake below Buto Gah Gali are quite leucocratic. These whitish granodiorite intrusions are characterized by the presence of green chlorite and dark brown biotite porphyroblasts. The chlorite is the product of alteration of mostly biotite and sometimes hornblende. The biotite is generally black but also bronze. At places, the granodiorite has developed small porphyroblasts of grey feldspar. In such a case the size of biotite porphyroblasts apparently decreases. The leucocratic body north of Buto Gah Gali also shows some hornblende-biotite pegmatites. The leucocratic varieties are white with green or dark grey porphyroblasts but varieties which have assimilated greenstones to a greater degree are greenish grey. In these cases xenoliths, pieces and patches of greenstone/ amphibolite in granodiorite are common. Fairly wide zones of dark greenish grey and light greenish grey or whitish banded rocks are common. Granodiorite bands intruding and mixing with the basic rock and enclosing and assimilating basic rock pieces clearly indicate a younger age for the granodiorite.

Below Buto Gah Gali or closer to MMT a few S-type tourmaline-mica pegmatites were also noticed.

In Buto Gah, the Babusar granodiorite gneisses on the weathered surfaces are generally light brown or light grey where leucocratic. A shade of green is added to the weathered surface either due to mixing with greenstone or due to green algal growth on the higher slopes and the brown colour may become greenish brown.

Near Dadar in Buto Gah, porphyritic granodiorite shows mixing with volcanics and a single boulder may have volcanic, plutonic and hypabyssal textures. This phenomenon is also to be noticed north of Dila in Nili Nadi and north of Maidan in Ledi katha (both locations in Kaghan Valley) where mixing of granodiorite and hornblende pegmatites is common not only with volcanic flows and tuffs but also with (ultramafic) pyroxenites. This field relation indicates a younger age for the Babusar granodiorites than even the ultramafics.

The granodiorite gneiss is coarse grained, gneissic and porphyroblastic. The porphyroblasts are mainly of biotite and chlorite. It is composed mainly of feldspar, quartz, biotite and chlorite. At places, pale yellow epidote patches are also visible. Hornblende is randomly distributed in this unit and is not ubiquitous.

Maidan Volcano-Hypabyssals: Outcrops of meta-volcanics, thin hypabyssal equivalents and mixed rocks have been mapped in the higher reaches of Buto Gah (between Dadar and Sangar villages) in uppermost Thak Valley near Babusar pass and in Thor Nala (all three locations in Kohistan, Fig. 2) while in Kaghan they were mapped in the two valleys of Ledi and Nili Nadi (Fig. 3). In Ledi Katha, they occur at Maidan north of Ledi village as two outcrops between slices of ultramafics. In Nili Nadi, they occur to the north of Dila (actual Dila village and not the one shown on toposheet) and to the south of pyroxenite body (Fig. 3).

Generally speaking the volcanics and equivalents are light to medium greenish grey with white specks or white grey specks in white matrix or thin white lines forming various types of patterns and textures in light greenish grey matrix on the fresh surface. They are commonly intermingled with related greenish grey coarse grained rocks. Light greenish grey greenstone type material or greyish tuffs are also found. The coarse grained material is foliated at places and occurs at places as light green laminated rock. On the weathered surface the outcrop appears light grey or light greenish grey.

At Maidan north of Ledi, the outcrop is more than one mile wide and is sandwiched between a peridotite slice to the south and a pyroxenite slice to the north (Fig. 3).

The volcanics and their hypabyssal equivalents extend in Nili Nadi north of Dila. The peridotite-slice coming from Ledi is mostly pinched out before reaching Nili Nadi, so the meta-volcanic outcrop is sandwiched here between greenstones and pyroxenites. The rocks are generally light greenish grey or light grey with white or black specks. The weathering colour is greyish brown to greenish grey. The relationship of metavolcanics and equivalents with pyroxenites in Nili Nadi is interesting. Both fine grained and coarse grained material appears to be intruding, reacting with and, at places, enclosing the pyroxenite pieces. At places these rocks surround and enclose pieces and parts of pyroxenite where reaction rims of hornblende can be seen around pyroxene. Light greenish grey pyroxene crystals are seen surrounded by dark greenish grey rims of hornblende showing that these rocks are younger and while coming out reacted with and picked up pieces of pyroxenite. At other places, this basic to intermediate material is seen intruded and folded in more basic materials.

The area between Dadar and Sangar in Buto Gah is ideal to see a variety of volcanic textures and types. There are tuffs with white granule size felsic pieces in fine grey matrix. There are pillow type structures in greenstone. At places, flow lined metavolcanics surround pieces of amphibolite. These are amygdaloidal types, tuffaceous types and hybrids. The weathered surface as seen from far off is generally greenish brown and the fresh surface most commonly is a shade of greenish grey.

The metavolcanic material appears to be mostly basaltic to andesitic in nature, however, the associated intrusives are metagabbro and metadiorite.

S-type Instrusives

Most of these bodies occur to the north of the mapped area and, therefore, are not discussed here in detail. However, a few are met with in Buto Gah close to the MMT within the mapped area. These comprises tourmaline granites, pegmatites and aphlites with very close affinities to the acid intrusives of Higher Himalaya Crystalliane to the south.

PETROGRAPHY

Below a petrographic description of various rock units of the area is presented. In order to avoid unnecessary repetition the very similar Thor and Darel diorites have been grouped together for petrographic description below.

Amphibolites

Kamila Amphibolite: Kamila amphibolite does not occur as a thick intact unit in the area under consideration. It occurs as a highly dismembered unit. It occurs as relatively thin linear outcrops, screens, patches and xenoliths. The unit has been dismembered and intruded as well as worked into by diorite, tonalite, granodiorite, greenstone and arc rocks.

In the Babusar area this unit occurs as a linear outcrop. It is very distinctly banded at many places. At places, prominent lineation is also seen due to the development of nematoblastic amphibole (Ahmed and Chaudhry, 1976). Alternate leucocratic and melanocratic bands and layers are often present. Hypidioblastic and porphyroblastic textures with poikiloblastic porphyroblasts are common.

Porphyroblastic and poikiloblastic pink garnets show an erratic distribution. Inclusions of quartz and iron oxides are common. Hornblende is bluish green and strongly pleochroic from light pale green to bluish green. It appears to be an aluminous hornblende. Relics of plagioclase are often of high andesine. But it may be replaced by epidote and albite. Due to mixing with younger and more acidic rocks, the hybrid zones may contain albite or oligoclase.

Clinozoisite is secondary and may occur either as individual grains or as aggregates. Quartz is anhedral and shows strong strain effects. Sphene, biotite, magnetite or ilmenite are common accessories.

The rock shows clear cut effects of retrogression. The retrogressive effects are manifested by the development of chlorite and epidote. These changes which belong to greenschist facies are superimposed on garnet-amphibolite facies.

Amphibole and garnet both show alteration to chlorite. Plagioclase alters to epidote and albite.

The occurrences of amphibolite near Sumal, Lemat and Losh are similar. These rocks are from layered to distinctly banded. Texturally, these rocks are highly heterogeneous. The sheared rocks are hypidioblastic, hypidioblastic porphyroblastic, nematoblastic and even xenoblastic. Pegmatitic amphibolite also occurs at places. The white to pale coloured layers are rich in plagioclase/albite, epidote and quartz while the darker layers are rich in amphibole, biotite, sphene, magnetite/ilmenite and at places, chlorite. Unlike Babusar occurrence, garnet is not very widespread.

Amphibole may occur as needles or stout prisms. The bigger crystals are distinctly poikiloblastic. It is a pleochroic aluminous hornblende. However, due to retrogression some actinolite may occur along certain planes.

Plagioclase is generally a well twinned high andesine. It occurs as subidioblastic crystals. At places, porphyroblasts (poikiloblastic) upto 5 mm are also present. It often shows alteration to epidote (mainly clinozoisite) and albite.

Quartz occurs as highly strained discrete grains as well as aggregates. Rarely anhedral and fractured porphyroblasts of quartz are also seen. Chlorite (with inky blue to tobacco green interference colours) is secondary mineral and develops after amphibole and rarely biotite.

Pink, fractured and inclusion rich garnet is present at few places. Sphene and iron oxides occur as common accessories. Chalcopyrite, pyrite and chalcocite occur but rarely. Retrogression and mixing with more acidic younger types is seen at places.

Amphibolite occurs as a number of outcrops along Darel and Tangir Rivers. In these occurrences amphibolite is again banded and layered. It is often intermixed with diorite and tonalite. It is basically a plagioclase amphibole rock which has been strongly epidotised along some zones. It may show augen like structure at a few places.

Plagioclase is well twinned and from high andesine to rarely labradorite. It is generally subidioblastic. Hornblende is pleochroic and from light to dark green. The porphyroblasts of amphibole may contain inclusions of quartz and plagioclase.

Epidote generally occurs as an accessory but along some mylonised portions it assumes the status of an essential mineral. Here plagioclase is replaced by epidote plus albite. Biotite, chlorite, sphene, K-feldspar and iron ores occur as accessories.

The almandine amphibolite facies amphibolites have been subjected by widespread greenschist facies retrogressive metamorphism. The modal composition of this unit is given in Table-1.

Table - 1 Modal Analyses of Amphibolites from Southeast Kohistan

	Babusar Ampibolites				Lemat - Sumal Losh				Thor - Darel Amphibolites									Thak Striped Amphibolites							
	N24C	N24A	N24	N24B	N37E	N26	N25	N24D	N38	N378	20448	20461	20462	20442	20464	20435	N104	K66	K66B	K105	K66D	N103A	K65A	K66D	K66A
Amphibole	58.00	55.3	37.6	35.8	98.0	80.7	70.2	61.4	47.3	24.7	62.8	59.5	47.5	38.2	32.9	32.1	67.5	59.9	53.5	30.0	9.3	4.3	1.8	--	--
Plagioclase	21.3	--	20.5	15.3	--	--	17.4	21.5	--	--	28.1	30.1	9.8	55.9	8.0	34.6	11.9	--	--	49.5	40.0	20.7	55.0	54.2	30.0
Epidote	7.7	22.4	26.8	19.1	1.7	12.1	2.8	3.0	45.9	--	--	--	37.4	--	48.8	6.2	3.0	20.0	25.0	5.9	4.8	34.1	8.7	4.8	15.8
Quartz	4.5	8.1	2.9	5.7	--	--	5.5	2.0	5.0	--	1.6	2.4	2.0	2.4	8.0	7.0	10.6	--	12.0	9.0	4.3	15.8	6.2	--	4.5
Chlorite	1.2	2.5	7.0	16.0	--	3.5	Tr	1.3	--	--	--	2.9	2.1	Tr	Tr	1.1	--	16.5	1.8	--	26.0	16.0	23.9	25.1	42.0
Biotite	--	Tr	--	1.5	--	--	--	6.8	--	--	2.0	Tr	--	2.5	--	5.9	--	--	--	--	--	--	--	--	--
Garnet	Tr	--	2.0	2.2	--	--	--	Tr	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Magnetite	3.9	6.0	2.7	4.0	--	--	Tr	2.6	--	--	1.7	4.3	1.2	1.0	2.3	3.4	1.2	2.0	3.7	5.6	1.7	4.9	3.0	0.9	4.0
Sphene	3.4	5.7	0.5	0.4	0.3	2.0	4.1	1.4	1.8	--	0.3	0.8	Tr	Tr	Tr	5.3	5.8	4.6	4.0	--	--	--	--	--	--
Talc	--	--	--	--	--	1.7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Calcite	--	--	--	--	--	--	--	--	--	75.3	--	--	--	--	--	--	--	--	--	--	12.0	--	0.9	--	--
K-Feldspar	Tr	--	--	Tr	--	--	--	--	--	--	3.5	--	--	--	--	4.4	--	--	--	--	--	--	--	--	--
Apatite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Muscovite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.5	--	0.5	15.0	3.7
Zircon	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	Tr	--	--

Thak Striped Amphibolites: Though derived from Kamila amphibolite, it is a distinctive and unique unit. Its field description has already been given in detail. It is a dark green and pale white banded rock. The dark green parts are rich in mafics while the pale white to white parts are rich in felsics: The white part is of two types.

1. Pegmatitic

2. Thin granitic layers.

The rock is strongly, though variably, mylonitized. It is very well foliated as a consequence.

Textures are from ultramylonitic to orthomylonitic to protomylonitic. At places, the rock is blasto-porphyritic. It may vary from hypidioblastic to xenoblastic and granoblastic. Wherever porphyroblasts occur, they have a ragged outline and are distinctly poikiloblastic. Crude, irregular and discontinuous segregations into mafic and felsic layers are often seen. Twin planes, cleavage traces and crystal faces may, at many palces, be bent and kinked. Sectorial extinction is a common feature.

In the mafic bands, amphibole, chlorite and magnetite are often concentrated. In felsic bands plagioclase, some epidote and quartz occur. Sphene, where it occurs, tends to be concentrated in the mafic bands, The composition of mafic and felsic bands has been given in Table-1.

Greenstones

There are a number of greenstone exposurs. The greenstones occur as slices in various areas such as Sumal, Tarla Babusar, Ledi, Maidan Gali, Buto Gah and Babusar pass. The modal compositions are given in Table-2.

In the following they will be described together because they have the same gross lithology and have been subjected to the same range of P-T conditions.

The greenstones are invariably strongly schistose. They may at places show catacalasis. They are non porpyroblastic to subporphyroblastic. The megacrysts are generally of albite and quartz. The mega-crysts are generally, subpoikiloblastic to poikiloblastic. The porphyroblasts are anhedral to subidioblastic. Albite may often be untwinned. Amphibole is an actinolite. It generally occurs as acicular to slender, subprismatic crystals. The rock may often be nematoblastic because of acicular amphibole. Both zoisite as well as clinozoisite are present. Epidote minerals form granular aggregates. Prismatic to subprismatic crystals may also occur. Chlorite occurs as flaky aggregates.

Sphene occurs as small grains and granular aggregates. It is irregularly distributed and is associated with mafics. The amount of sphene varies from sample to sample. Magnetite, biotite, muscovite and antigorite may occur as accessories.

The mineral assemblages of greenstone from various areas are as follows:

Sumal Greenstones:

K-82. Actinolite - epidote - chlorite - sphene - quartz - albite - muscovite - apatite.

K-83. Actionolite - epidote - chlorite - sphene - quartz - apatite.

K-83-A. Actinolite - epidote - chlorite - sphene - quartz - apatite.

K-84. Actinolite - epidote - sphene - apatite.

K-85. Actinolite - epidote - chlorite - sphene - quartz - albite - magnetite - calcite - apatite.

N-36A. Actinolite - epidote - chlorite - sphene - quartz - albite - magnetite - apatite.

N-36B. Actinolite - epidote - chlorite - sphene - quartz - apatite.

Tarla Babusar Greenstone:

K-56. Actinolite - epidote - chlorite - sphene - quartz - albite - apatite.

K-56B. Actinolite - epidote - sphene - quartz - albite - magnetite - apatite.

Ledi Maidan Gali Greenstone:

K-10. Actinolite - epidote - chlorite - sphene - quartz - albite - magnetite - calcite - apatite.

K-10-A. Actinolite - epidote - chlorite - sphene - quartz - magnetite - apatite.

K-12-F. Actinolite - epidote - chlorite - sphene - magnetite - muscovite - apatite.

K-14-D. Actinolite - epidote - chlorite - sphene - quartz - magnetite - apatite.

Table - 2 Modal Analyses of Greenstones of Indus Suture Zone

	Sumal Greenstone				Tarla Babusar Greenstone					
	K84	K82	N36B	N36A	K83	K85	K83A	K56B	K56	K10A
Actinolite	91.8	49.8	44.3	39.6	39.5	34.0	30.2	69.6	7.0	54.9
Epidote	3.5	20.2	39.8	28.0	39.0	17.4	48.8	9.2	39.8	24.2
Chlorite	--	2.5	7.0	4.3	12.4	13.8	13.3	--	43.2	7.8
Sphene	4.7	7.0	3.7	8.9	5.9	0.9	4.0	6.5	2.6	2.0
Quartz	--	9.6	5.2	10.4	3.2	8.0	3.7	6.0	3.0	9.8
Albite	--	10.1	--	5.7	--	9.7	--	5.6	4.4	--
Megnetite	--	--	--	3.1	--	8.2	--	3.1	--	1.3
Calcite	--	--	--	--	--	8.0	--	--	--	--
Muscovite	--	0.8	--	--	--	--	--	--	--	--
Biotite	--	--	--	--	--	--	--	--	--	--
Antigorite	--	--	--	--	--	--	--	--	--	--
Apatite	Tr	Tr	Tr	Tr	Tr	--Tr	Tr	Tr	Tr	--Tr

Ledi Maidan Gali Greenstone				Buto Gah Greenstone	Babusar Pass Greenstone
K10	K14D	K12F	K101	K94	K49
53.8	45.8	19.6	53.2	48.6	61.0
18.3	29.0	63.1	34.8	38.1	3.5
6.0	16.9	4.5	1.3	--	--
1.8	2.4	7.0	0.9	Tr	1.8
7.1	4.6	--	8.2	7.0	9.0
7.5	--	--	--	3.7	15.9
4.0	1.3	2.6	1.6	1.2	8.6
1.5	--	--	--	--	--
--	--	3.2	--	--	--
--	--	--	--	0.5	0,2
--	--	--	--	0.9	Tr
Tr	Tr	Tr	Tr	Tr	Tr

Buto Gah Greenstone:

K-101. Actinolite - epidote - sphene - quartz - albite - magnetite - biotite - antigorite - apatite.

Babusar Pass Greenstone:

K-49. Actinolite - epidote - sphene - quartz - albite - magnetite - antigorite.

From the mineral assemblages listed above it may be concluded that the rocks are metabasalts which have undergone regional metamorphism in greenschist facies or low-grade metamorphsim. No evidence of high pressure and low temperature metamorphism was found.

Suture Ultramafics

Ledi Ultramafics: The ultramafics occur as a "tectonic slice" near Ledi, Naran. The modal compostion of this body is given in Table 3. The Ledi rocks are invariably serpentinised but they also contain olivine and pyroxene. Clinopyroxene is predominant and orthopyroxene is rare. The rock is a serpentinised peridotite and not a harzburgite tectonite. Sample K-11B is, however, a small associated pyroxenite patch. Olivine occurs as subhedral crystals and their aggregates. It shows alteration to antigorite. Pyroxene occurs as porphyritic to sub-porphyritic crystals. It also shows alteration to antigorite. The clinopyproxene, diopside/diopsidic augite. Antigorite is most common while chrysotile and asbestos occur along shear zones. Magnetite is the most common ore mineral. Magnesite occurs as an alteration product. The other accessories are chrysotile, magnetite, sulphide, chlorite and secondary iron oxides.

One sample of chromite bearing ultramafic was also studie. It contains 25% chromite. It contains small amount of nickle sulphide minerals like pentalandite and heazlewoodite.

Petrographic and textural studies show that Ledi ultrabasic body is a serpentinised peridotite.

Maidan Gali Pyroxenite: The Maidan Gali pyroxenite is a coarse grained and often pegmatitic rock. It shows uneven segregation and has inter-locking crystalline texture. The finer parts may contain 3 to 4 mm crystals while the larger crystals reach upto 50 mm. Megacrysts measuring upto 120 mm may also be encountered. At places, small amount of strongly serpentinized peridotites may also be present. This unit may show alteration to amphibole, antigorite and epidote.

Mineral composition of this unit is given in Table-3. The sample K-14c is a serpentinised periodtite while the rest of the samples are pyroxenites which have undergone variable alteration to antigorite, amphibole, epidote and chlorite. Relatively finer grained rocks have been studied petrographicaly. The pyroxenites are generally hypidiomorphic. The pyroxene is diopside/diopsidic augite. The olivine where present has been altered to antigorite. The pyroxene crystals show varying degrees of alteration to amphibole, epidote, antigorite and chlorite. Amphibole occurs either as acicular or columnar crystals or as irregular patches within the body of pyroxene. Antigorite appears to occur pseudomorphing olivine or as partial alteration product of pyroxene. Here it replaces the margins and occurs along the fractures and cleavages. Serpentinization is strong wherever the rock has undergone deformation. Epidote occurs as small prismatic, granular or acicular grains and their aggregates. It clearly forms due to the alteration of pyroxene. It is mainly a zoisite. Magnetite, chromite and magnesite are common accessories. Small quantities of Ni-sulphides are present. The sulphide minerals are haezalwoodite and pentalandite.

Chilas Complex

The "Chilas complex" has been studied petrogrpahically in Thak, Buto Gah, Thor, Thurli, Darel, Tangir, Thalpan, Basha, Gas and Chilas areas. The megascopic and field features have already been discussed.

The complex is predominantly a norite, but other rock types also occur in small amounts in this unit. The petrographic types found in this complex are, olivine norite, norite, hypersthene gabbro, amphibole gabbro (bojite), anorthosite, dunite, peridotite, harzburgite, pyroxenite, diorite, microdiorite, microtonalite, pegmatite, epidosite and quartz-veins.

Despite this great diversity of petrographic types, the norite petrographic type constitutes more than 90% of the outcrop. In the following the various rock types will be described. But the Chilas and Thurli ultrabasics will be described separately. The petrographic composition of the Chilas noite complex is given in Tables 4 and 5.

Norite: It is generally a layered rock. The leucocratic and melanocratic minerals may at many place tend to form imperfect segregations. The minerals often show a platy structure i.e. they tend to form parallel to subparallel layers. In some parts of the outcrop, segregated layers of mafics are present. These layers are composed of pyroxenes, amphibole and magnetite. Sometimes, plagioclase forms separate centimetric

Table - 3 Modal Analyses of Ultramafics of the Indus Suture Zone

	Maidan Gali Pyroxenites							Ledi Peridotites					Pyroxenites in Peridoties
	K14C	K22	K22B	K22D	K22A	K23	K22C	K11C	K11E	K11A	K-F	K11D	K11B
Antigorite	76.9	--	20.2	4.0	23.7	--	2.4	91.4	35.7	81.1	50.3	14.1	1.2
Pyroxene	9.5	84.0	51.9	64.6	49.0	75.3	76.0	--	9.0	--	14.8	44.8	93.6
Magnetite	10.0	--	3.0	--	--	--	--	5.9	--	0.8	6.9	--	0.8
Chromite	1.3	--	--	--	--	1.9	--	--	25.9	--	--	--	--
Ni-Sulphide	0.8	Tr	0.4	0.3	Tr	0.5	0.6	0.5	Tr	0.4	0.3	0.9	0.4
Magnesite	--	3.5	--	--	--	--	0.9	--	--	14.0	6.0	--	--
Amphibole	--	--	19.0	15.0	26.9	18.0	20.1	--	--	14.0	--	--	--
Sphene	--	--	--	--	0.4	--	--	--	--	--	--	--	--
Goethite	1.5	1.9				1.5	--						
Epidote		5.0	5.5	13.7	--	2.8	--	--	--	--	--	--	--
Chlorite	--	5.6	--	2.4	--	--	--	--	--	--	--	--	--
Olivine	--	--	--	--	--	--	--	--	29.4	1.0	20.0	42.2	4.0
Chrysotile	--	--	--	--	--	--	--	2.2	--	2.7	1.7		--

Table - 4 Modal Analyses of Chilas Norite Complex

	K-69A	K-74A	K-72	DS/1 (641)	29	My-Sh 32	45-2 (628)	19A	21	DS-3	28	D/S-14 640	24	DS-7 (638)	17	DS-15 (642)	18	50	36	K-73
Plagioclase	82.1	78.8	62.6	62.0	61.5	61.0	60.8	60.5	59.4	59.4	59.3	58.4	57.1	55.9	55.6	54.0	53.9	48.7	48.5	35.7
Pyroxene	14.8	Tr	32.0	28.5	28.8	33.8	30.1	33.1	28.0	26.0	29.0	31.0	35.7	21.4	33.0	24.7	44.4	46.8	34.0	47.4
Amphibole	--	17.0	5.4	5.9	8.2	3.5	4.9	1.2	9.8	7.6	11.7	5.7	5.0	6.0	9.8	6.3	1.0	3.0	6.9	10.9
Magnetite	Tr	3.9	--	3.0	0.5	1.0	4.2	0.8	1.0	5.0	Tr	4.1	0.8	1.5	1.1	3.0	--	1.5	0.5	2.0
Quartz	--	--	--	0.6	1.0	0.7	--	1.0	0.7	1.7	Tr	0.8	1.0	0.9	0.5	2.6	0.6	--	1.0	--
Apatite	--	--	--	Tr	Tr	Tr	Tr	Tr	0.3	0.3	Tr	Tr	0.4	0.6	Tr	0.2	0.2	Tr	Tr	--
Biotite	--	0.3	--	--	--	--	--	1.6	0.8	--	--	--	Tr	--	--	0.7	--	--	--	--
Sphene	--	--	--	--	Tr	Tr	--	--	Tr	--	--	--	Tr	--	Tr	--	Tr	--	Tr	--
Chlorite	2.3	--	--	--	--	--	--	--	--	--	--	--	--	8.7	--	7.0	--	--	6.8	--
Epidote	--	--	--	--	--	--	--	--	--	--	--	--	--	5.0	--	1.5	--	--	2.3	--
Limonite Haematite--		--	--	--	Tr	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Muscovite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Calcite	0.8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.8
K-feldspar	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3.2
Clay	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Olivine	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Serpentine	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Magnesite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Table - 5 Modal Analyses of Amphibole Norite, Olivine Mela Norite, Anorthosite, Amphibole Pyroxenite - Harzburgite, Hornblendites, Dorites, Microdiorites, Epidosite and Pegnatites of Chilas norite complex.

	Amphibole Norites			Olivine Norite	Anorthosite	Amphibole Pyroxenite	Harzburgites		Hornblendites	
	U.S-20 (632)	16	19	D/S-20 (637)	(629	U.S-11 (635)	U.S-17 (627)	U.S-16 (626)	U.S-15 (622)	U.S-21 (623)
Plagioclase	59.5	54.0	49.8	13.2	91.7	0.6	--	--	--	6.7
Pyroxene	23.0	30.8	29.1	70.0	--	79.5 (Ortho)	36.0 (Ortho)	34.7 (Ortho)	--	--
Amphibole	12.0	12.7	18.0	4.9	6.0	15.2	--	--	95.7	78.2
Magnetite	--	0.3	0.6	2.4	--	0.7	2.6	3.2	Tr	6.0
Quartz	--	2.2	2.5	--	2.3	--	--	--	--	--
Apatite	0.4	--	Tr	--	--	--	--	--	--	--
Biotite	2.8	--	--	--	--	--	--	--	4.3	5.0
Sphene	--	--	Tr	--	--	--	--	--	--	--
Chlorite	--	--	--	--	--	--	--	--	Tr	3.6
Epidote	--	--	--	--	--	--	--	--	--	--
Limonite/Haematite	--	--	--	--	--	--	--	--	--	--
Muscovite	--	--	--	--	--	--	--	--	--	--
Calcite	--	--	--	--	--	--	--	--	--	0.5
K-Feldspar	--	--	--	--	--	--	--	--	--	--
Clay	2.3	--	--	--	--	--	--	--	--	--
Olivine	--	--	--	9.5	--	4.0	61.4	49.3	--	--
Serpentine	--	--	--	--	--	--	--	12.8	--	--
Magnesite	--	--	--	--	--	--	--	--	--	--

Diorites						Micro-Diorites		Epidosite	Pagmatites			
52	26-A	26-B	U.S-3 (633)	11	30	U.S-14 (631)	U.S-7	34	U.S-12 (630)	U.S-63	D/S-8 (634)	31
57.0	56.0	54.5	54.8	44.7	40.5	47.8	47.1	--	94.8	84.5	75.7	68.3
--	--	--	3.0	--	3.6	1.7 (Ortho)	--	--	--	--	--	--
42.7	41.9	44.1	30.7	51.0	54.9	38.1	38.9	--	--	--	--	3.8
0.3	1.6	0.9	3.0	1.0	Tr	5.0	4.7	0.6	--	0.9	--	2.1
Tr	0.2	0.5	1.5	1.9	1.0	1.8	3.4	8.5	3.9	8.0	12.0	16.2
Tr	Tr	Tr	0.2	Tr	Tr	0.3	0.4	Tr	--	Tr	--	0.6
--	--	--	--	--	--	--	--	--	--	--	--	--
--	Tr	Tr	--	Tr	Tr	--	--	5.8	Tr	Tr	--	--
--	--	--	2.1	1.4	--	--	--	13.9	--	--	2.0	--
Tr	--	--	4.7	Tr	--	--	1.0	71.2	--	2.2	7.5	9.0
--	0.3	--	--	--	--	--	--	Tr	--	--	--	--
--	--	--	--	--	--	--	--	--	1.3	2.0	--	--
--	--	--	--	--	--	--	--	--	--	0.7	--	--
--	--	--	--	--	--	5.3	4.5	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	1.7	2.8	--
--	--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--	--

layers and is, therefore, called anorthosite.

The rock is generally medium to coarse-grained and hypidiomorphic to subporphyritic hypidiomorphic. At places, it may be poorly poikilitic. Porphyritic texture is less common.

However, norite has been affected by a number of faults and planes of dislocation. Along these planes norite is mylonised. Protomylonites, orthomylonites and ultramylonites have been encountered. Blastoporphyritic texture was also observed along certain zones. In the mylonite, xenoblastic texture and cataclastic effects are particularly pronouned.

Some rocks are affected by fracturing. One set of fractures took place during stages of consolidation or after consolidation when the rock was still hot. Microfractures were studied in these rocks. They tend to form a net work and cut both plagioclase as well as pyroxene. But the fractures cutting pyroxene may also contain talc, antigorite, chlorite and chrysotile. This has resulted in healing of the rocks. Wherever these fractures cut the ultrabasic rocks, formation of serpentine along these fractures is common.

The second set of microfractures post-date the first set and they only cause mylonisation and minor alteration. Some open to semi-open microfractures also occur.

The norite and noritic gabbro are composed essentially of plagioclase and pyroxene. Plagioclase is hypidiomorphic and may occur as subporphyritic crystals as well as smaller laths in the ground mass. It is generally well twinned and unaltered. It is mostly a labradorite. However, in the vicinity of ultrabasic cumulates bytownite composition may also be encountered. It may form segregations and layers in the layered portion of the complex. It may contain small inclusions of quartz, magnetite and even some pyroxene. Wherever affected by hydrothermal processes, it alters to sericite, epidote and calcite. At places, a network of chlorite and epidote may traverse plagioclase.

Hypersthene is the most abundant pyroxene in the area studied. It is strongly pleochroic from neutral green or pale green to pink or flesh pink. It often forms segregations which may either be regular or highly irregular. It often has exsolution lamellae of clinopyroxene. It also occurs as porphyritic to subporphyritic crystals as well as smaller grains and thin aggregates. The bigger crystals tend to be subhedral to eumorphic. The smaller crystals may be euhedral to subhedral. Some bigger crystals may partially enclose plagioclase. Quartz and magnetite inclusions may also occur. Clinopyroxene may or may not be present. Mostly it is clearly subordinate to orthopyroxene. It is a diopside or diopsidic-augite. In somee cases clinopyroxene may exceed orthopyroxene.

Pyroxene is very often partially rimmed by amphibole. Amphibole may form independent crystals, but these are not very common. Amphibole not only forms rims around pyroxene but may replace pyroxene. This amphibole is deep green and strongly pleochroic.

Phologopite or biotite may occur as accessories. They may occur either as products of further magmatic alteration of amphibole or may occur independently in rare cases.

Magnetite is the most common ore mineral. It is an accessory. It occurs as small grains associated with pyriboles. It may show alteration to haematite. At some places, other ore minerals which may occur are ilmenite, chalcopyite (and its alteration products like azurite and malachite), pentalandite and millerite. It is generally observed that pyroxene, amphibole and ores tend to be segregated in crude layers, patches, clots or as relatively regular thin layers.

Quartz is generally present in small quantities. It is fairly ubiquitous accessory mineral. It is invariably anhedral. Its size is generally very small and it occurs as interstitial grains or drop-like to irregular incusions in other minerals.

Biotite, sphene and apatite are other accessory minerals in addition to ore minerals.

The composition of this unit is given in table-4.

Bojite: Bojite is a layered/ foliated rock. It occurs as a facies variant of norite.It is a medium grained hypidiomorphic rock. Plagioclase is a labradorite. Amphibole occurs as subhedra as well as aggregates of slender crystals. It may pseudomorph pyroxene. Pyroxene occurs as relics enclosed in amphibole. Epidote and chlorite develop after amphibole. Quartz, magnetite and biotite are other accessory minerals. Amphibole is generally present in norite in small amounts. Bojite merely represents an extreme case of magmatic/metasomatic alteration of norite.

Diorite, Tonalite Granodiorites and Volcanohypabyssals

Thor-Darel Diorite Complex: It has a coarse grained and non-foliated to poorly foliated rocks. They are hypidiomorphic to hypidiomorphic subporphyritic. However, at places, the rocks are distinctly porphyritic. The diorite as well as tonalite both occur together.

Plagioclase is lath shaped to prismatic and well twinned. It is often subhedral to eumorphic. It may, at places, show alteration to epidote and sericite. It is an andesine.

Hornblende also occurs as subhedral to eumorphic crystals. Its phenocrysts may enclose tiny quartz grains. It is strongly pleochroic from pale green to dark green. It may show alteration to chlorite.

Quartz is anhedral and often strained. Fractured quartz grains may occur at many places. The grain size is highly variable. It may enter into myrmekitic growths with plagioclase.

Chlorite is an alteration product of amphibole. It is often light to medium green and slightly pleochroic. It shows inky blue as well as tobacco green interference colours.

Epidote is mainly clinozoisite. It is an alteration product of plagioclase. It occurs mainly as small grains and granular aggregates. However, rarely elongated or columnar crystals of epidote also occur.

Anhedral crystals of orthoclase show a very erratic distribution. Biotite and magnetite are ubiquitous accessory to subordinate minerals.

Muscovite, apatite, sphene, zircon and calcite are the accessory minerals which show erratic distribution.

Pyroxene occurs as an accessory to essential mineral in some rocks.

This unit varies in composition from diorite to tonalite to granodiorite. But diorite and tonalite predominate. The modal composition of this unit is given in Table - 6.

Minor Diorite: Like microdiorite and microtonalite, diorite also occurs as sills, dykes and minor intrusions. It is hypidiomorphic to hypidiomorphic porphyritic. The phenocrysts may be poorly poikilitic. In some cases, the rock may be somewhat foliated. At some places, segregation of mafic and felsic minerals may be present.

Microdiorite and Microtonalite: It occurs as sills/dykes and rarely irregular bodies. It is clearly later than norite. It is fine grained and hypidiomorphic to hypidiomorphic porphyritic. Andesine and amphibole are predominant phases. Microcline, quartz, magnetite, epidote, apatite and pyroxene may occur as accessories. Microtonalite is very similar to microdiorite. Microdiorite grades into tonalite with increase in the quantity of quartz.

Damyun Tonalite: Parts of this unit are well foliated while parts are non-to very poorly foliated. This unit intrudes, attacks and assimilates the greenstone unit. As a consequence, the rock is highly variable specially near the contacts with greenstone. The colour of the rock may vary according to the degree of assimilation. It also intrudes and assimilates slices of amphibolite.

It is a coarse grained and stippled unit. It is mainly hypidiomorphic to hypidiomorphic subporphyritic. Amphibole is green and pleochroic. It is subprismatic. The phenocrysts are often poikilitic. Where it attacks greenstone some bluish green amphibole may also be seen. The amount of amphibole varies widely. Epidote is a secondary mineral. It occurs as discrete grains as well as granular aggregates. Hybrid zones are specially rich in epidote. But it also develops due to the alteration of tonalite itself. Chlorite is often associated with epidotisation. These minerals develop in hybrid zones. However, they also develop as a consequence of low greenschist facies alteration. Chlorite is light green, pleochroic and shows from inky blue to tobacco green interference colours.

Plagioclase is an andesine. It occurs as stout prismatic to subprismatic crystals which may show alteration to epidote. Pyroxene was also encountered in one sample. Quartz occurs as anhedral grains and their aggregates. Epidote, amphibole and quartz show wide variation. Magnetite, sphene, biotite, apatite and muscovite are accessories. Modal composition of this unit is given in Table - 6.

Babusar Granodiorite Gneiss: For petrographic description of this unit the reader is referred to Ahmad and Chaudhry (1976).

Hornblendite: Hornblendite may occur either as independent bodies or as a part of complex ultrabasic bodies composed of peridotite, dunite, pyroxenite and honrblendite. The hornblendite bodies are mostly coarse grained and even pegmatitic. The grain size is quite variable. The rock is hypidiomorphic to hypidiomorphic porphyritic. It is composed predominantly of amphibole with small quantities of biotite. Plagioclase, magnetite, chlorite and carbonate may occur as accessories .

Epidosite: Epidosite occurs as small secondary veins in the norite mass. The veins may be hypidiomorphic to hypidiomorphic porphyritic. It is composed

Table - 6 Modal Analyses of Diorites of the kohistan Island Arc.

	N50F	N55	N43A	N53A	N48	N49B	N57A	N45	N49A	N50B	N44	N47	N62A	N53C	N57	N113	N59C	N50D	N50E	N53	N53D	N66	N46	N4A	K63	K64	K61	N21	K59	US 14-631	US-7
													Darle/Thor Diorite													Damyun Tonalite				Micro Diorite	
Plagioclase	42.0	40.0	34.0	30.7	24.7	21.4	10.9	70.8	69.9	65.2	60.1	60.0	55.8	54.7	55.1	57.0	51.0	50.9	50.0	45.0	44.1	43.9	44.3	--	--	58.8	50.8	58.9	50.1	47.8	47.1
Amphibole	36.7	19.7	--	30.3	8.0	60.2	--	7.0	18.5	--	14.5	11.3	30.1	18.2	39.7	18.7	--	20.1	27.8	3.3	5.7	5.0	28.8	48.8	25.1	18.7	13.7	12.7	--	38.1	38.9
Quartz	4.5	7.9	--	26.1	45.2	8.6	30.5	5.1	10.0	22.7	8.7	4.7	2.0	--	2.9	4.8	16.5	14.0	10.6	35.8	36.8	30.1	12.4	8.1	5.4	9.1	20.5	--	20.2	1.8	3.4
Magnetite	10.2	5.1	--	4.9	3.5	3.8	3.0	5.6	--	2.6	4.0	4.5	6.6	0.9	2.3	5.1	4.8	4.7	5.1	--	3.0	3.4	4.2	1.4	8.9	6.8	4.0	4.4	3.7	5.0	4.7
Biotite	6.6	5.7	--	4.0	5.8	6.0	--	3.9	0.6	8.0	4.6	7.9	--	--	--	3.9	7.0	9.4	5.9	5.9	2.5	6.8	6.6	--	--	2.0	5.0	0.3	2.6	--	--
Pyroxene	--	20.0	--	--	--	--	--	6.1	--	--	7.0	11.0	--	--	--	10.5	--	--	--	--	--	--	2.0	--	--	--	--	23.7	--	1.7	--
Epidote	--	--	0.8	2.5	2.1	--	37.9	--	--	1.5	--	--	--	5.5	--	--	2.5	--	--	1.4	4.1	--	--	38.0	45.6	1.0	4.1	--	9.8	--	1.0
Chlorite	--	--	15.2	--	3.7	--	6.7	0.5	--	--	--	--	--	15.0	--	--	--	--	--	Tr	3.8	--	1.7	--	15.0	1.4	1.9	--	10.1	--	--
Muscovite	--	--	20.6	--	--	--	11.0	1.0	--	Tr	--	--	--	--	--	--	1.1	--	0.6	2.8	--	2.1	--	--	--	1.2	--	--	1.0	--	--
K-feldspar	--	--	23.0	--	--	--	--	--	--	--	--	--	4.0	--	--	--	16.9	--	--	4.5	--	5.7	--	--	--	--	--	--	--	5.3	4.5
Calcite	--	--	4.9	--	5.0	--	--	--	--	--	--	--	--	5.7	--	--	--	--	--	--	--	3.0	--	--	--	--	--	--	--	--	--
Sphene	--	--	1.5	--	1.8	--	--	--	--	--	0.8	--	--	--	--	--	--	--	--	--	--	--	--	3.7	Tr	0.5	--	--	2.5	--	--
Apatite	--	1.6	--	0.9	0.2	--	--	Tr	--	--	0.3	--	1.5	--	Tr	--	0.2	0.9	--	1.3	--	--	1.0	--	--	0.5	--	--	--	0.3	0.4
Zircon	--	--	--	0.6	--	--	--	--	Tr	--	--	0.6	--	--	--	--	Tr	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pyrite	--	--	--	--	--	--	--	--	1.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Table - 7 Modal Analyses of Maidan Plutono-Volcanic Rocks

	K-12A	K-21E	K-21C	K-12C	K-12B	K-21D	K-21F	K-21H	K-21J	K-12E	K-12	K-12D
Amphibole	69.8	67.9	65.1	59.3	50.3	50.0	48.0	45.5	42.8	35.5	32.8	2.7
Chlorite	15.6	14.0	19.5	25.7	20.7	15.7	26.9	31.0	30.4	13.1	17.2	12.2
Epidote	12.1	15.3	12.9	12.1	20.1	21.1	18.0	16.8	15.0	28.8	33.5	26.6
Sphene	Tr	2.8	--	2.9	2.5	3.4	5.7	3.4	2.7	5.0	10.0	8.1
Magnetite	2.5	--	2.0	--	0.8	4.0	1.4	0.9	1.2	3.6	5.4	4.9
Goethite	--	--	0.5	--	--	0.8	--	--	--	--	1.1	--
Albite	--	--	--	--	--	--	--	--	7.9	--	--	--
Apatite	Tr	--	--	--	1.7	0.3	--	0.5	--	--	--	--
Quartz	--	--	--	--	3.0	4.7	--	1.9	--	14.0	--	45.5
Calcite	--	--	--	--	0.9	--	--	--	--	--	--	--

predominantly of epidote. Chlorite and quartz are other essential minerals. Sphene, magnetite, apatite and iron oxides are accessory minerals.

Pegmatites: Pegmatites occur as sills, dykes, pods, lenses and irregular patches. They are coarse grained rocks with uneven segregation of constituent minerals. They often show variable shearing effects.

They fall in three groups.

(1) Plagioclase - muscovite - quartz - epidote -calcite - sphene - iron oxides.

(2) Plagioclase - amphibole - quartz - magnetite - epidote - zircon -chlorite.

(3) Plagioclase - epidote - quartz - chlorite - sphene.

Quartz Veins: Quartz veins occur rarely. The veins are composed of a sutured mosaic of quartz grains.

Maidan Volcanics and Hypabyssals: These rocks are foliated to layered. The degree of foliation is variable. Most commonly these rocks are hypidioblastic to hypidioblastic - porphyroblastic. The porphyroblasts are from subpoikiloblastic to poikiloblastic. The inclusions are of quartz, sphene and sometimes epidote. At places, amphibole also occurs as acicular to columnar aggregates. The modal composition of this unit is given in Table - 7.

Epidote occurs as individual grains as well as granular aggregates. It is intimately associated with chlorite. Patches of epidote and chlorite are common. Rarely these occur as porphyroblasts. It is a clinozoisite. Zoisite is rare.

Chlorite is intimately associated with epidote. Together they form patches which additionally include sphene and iron oxides and sometimes calcite, apatite and quartz. Chlorite occurs as flakes and flaky aggregates.

Sphene occurs as tiny grains and granular aggregates. It is very irregularly distributed.

Quartz occurs as tiny xenoblastic grains and diffuse aggregates. Ilmenite/magnetite occur as tiny randomly distributed grains. Rarely goethite may occur. It pseudomorphs sulphide grains.

Tiny subidioblastic apatite grains show a random distribution. Calcite is rare and occurs as small xenoblastic to subidioblastic grains. The modal composition of this unit is given in Table - 7.

DISCUSSION

Kamila Amphibolites: The Kamila amphibolites have been interpreted as calc-alkaline retrogranulites (Jan, 1979). We suggest that the amphibolites were originally oceanic crust now metamorphosed to a mainly amphibolite facies. However, relics of eclogite and high-pressure granulites are present in Dir-Swat belt. It may therefore be concluded that the metamorphism ranges from amphibolite to eclogite facies. Most of the acid to intermediate bodies, some syntectonic, others post tectonic, within the amphibolites may be considered the partial melting products of amphibolites emplaced in situ or over a short distance. Some of these acid to intermediate differentiates, too, were metamorphosed to amphibolite facies and, at places, have developed a layered and foliated character. At other places this arc-type material is closely intermixed with the original oceanic. In other words, outcrops of amphibolized diorite and tonalites are met with in the overall outcrop of Kamila amphibolites.

The ophiolitic character of the Kamila amphibolites is also reflected by their association with ultramafic slices as in Thak Valley near Babusar and westwards at numerous places such as Tighik in Swat and Tora Tiga in Dir. These bodies have also been metamorphosed and modified along with amphibolites.

The Kamila amphibolites appear to be the oldest exposed unit of the Kohistan sequence. First, they show a stronger foliation and higher degree of metamorphism than later intrusives like diorites, granodiorites and volcanohypabyssals, or tectonically associated greenstones and norites. Second in the SE Kohistan they have been dismembered, fragmented and tectonically dispersed over an extensive area. Thus, the Kamila amphibolites today contain modified oceanic material as well as later arc material.

If their age and metamorphism is interpreted to indicate that they represent trench metamorphosed original Tethys crust which was later obducted and emplaced at the suture then their metamorphism would be older than the Himalayan metamorphism. It will be of amphibolite - eclogite type.

The tectonic dispersal of amphibolites in the form of slices in SE Kohistan is probably related in part to obduction and in part to Nanga Parbat related tectonism.

Indus Suture Greenstones: Like the Kamilla amphibolites the Indus Suture greenstones are a much dismembered unit and its major outcrops have been mapped separately as Sumal greenstone, Sangar Babusar greenstone and Buto Gah Gali greenstones. In characteristics and relationships they all appear to represent a single history. Not only that, the greenstones have relationships similar to even Kamilla amphibolites. Both greenstones and amphibolites have been dismembered and intruded by later dioritic and volcanohypabyssal rocks. The greenstones may thus be considered the less metamorphosed equivalents of amphibolites and like the latter represent obducted oceanic crust in main.

Chilas Complex: The Chilas complex occurs in the form of a belt extending in a general eastwest direction on both sides of Indus River between Bunar Gah and Khandia River south of Band-i-Sazin. Further west it extends through Swat and Dir continuing into Afghanistan. The length of the outcrop is thus at least more than 300 km. Norite and noritic gabbro comprise nealry 90% of the rock. The rest is in main comprised of an ultramafic association of mostly dunite, pyroxenite and peridotite apart from other relatively minor rock types.

The relationship between norite and the ultramafic association is complex and needs to be studied further. Xenoliths of norite are present in ultramafics and the Chilas complex reportedly intrudes early arc volcanics and sedimentary rocks and contains xenoliths of mafic rocks, biotite schists, paragneisses and garnet - pyroxene - scapolite rock (Khan *et al.,* 1989). On the other hand, near Thak Nala bridge on KKH, norite seems to be intrusive into dunite. Norite as well as the ultramafics are both intruded by hornblende-plagioclase pegmatites. Facies variates and small intrusive differentiates include bojite, microdiorite, tonalite, diorite, hornblendite and pegmatites. Layering and banding is common in the norite complex but at many places the rock is unfoliated.

Both the southern and the northern contacts of Chilas norite complex in SE Kohistan are sheared with development of mylonites and emplacement of huge bodies of hornblende-plagioclase pegmatites at or near the contacts. A number of shear zones also occur within the main body of the norite. Along these shear zones the highly foliated rock attains a light green to light greyish green shade.

This extraordinarily huge norite complex alongwith the Jijal ultramafic complex was interpreted for a long time as base of the Kohistan Island Arc sequence (Tahirkheli *et al.,* 1979; Bard *et al.,* 1980). Coward *et al.* (1986) further suggested that the complex was a huge anticlinal bulge of the basal part of the arc which structurally divides the Kohistan island arc into two or separates two island arcs. Furthermore according to him it continues both north and south under the Kohistan island arc to appear again at sutures along MKT and MMT respectively. The isoclinal folding and imbrication by thrust faulting would also account for its present exposed thickness.

Khan *et al.* (1989) have dealt at length with the origin of norite complex. On the basis mainly of geochemistry (marked negative Nb anomalies, positive Sr, Ba anomalies and high K/Rb ratios) and of correlation with Boarder Ranges Complex of Alaska and Ivrea Zone in the Alps. They have postulated three possibilites. Either the Chilas complex represents the root zone magma chamber of the Kohistan island arc or magma generated by mantle diaprism in the early stages of the intra-arc rifting or during the formation of the back - arc basin. They admitted the somewhat contradictory nature of the geochemical evidence and the presence of a major thermal problem invoking such huge and largely uniform body of arc related basic magma.

Any postulate regarding the origin of Chilas Norite Complex must take into consideration the following points:

1. The Chilas complex is thrust bounded on both north and south with associated mylonites.

2. The complex is by and large uniform and does not exhibit the high differentiation that would be expected of a basal magma chamber giving rise to the arc.

3. The norite mass is by and large not intruded by intermediate and acid arc rocks. Neither does the noritic mass contain significant xenoliths and screens of any roof rocks. From the field point of view the norite appears to be uniform, different and separate from the island arc mass which it is now in contact with on both sides.

4. If the norite complex is linked to the mafic ultramafic complexes of MMT and MKT from below the arc (Coward *et al.,* 1987) then there is an abundance of pillow lavas especially at the MKT. There is little doubt now as to the presence of ophiolites at MMT and MKT.

5. The apparent thickness of the complex may be due to folding and imbricate thrusting.

As to the suggestion that norites represent a magma chamber (Jan 1979; Bard *et al.,* 1980) which has given rise to the intermediate body of the arc, one wonders how huge intermediate to acid masses of plutonic nature greater in volume than norite itself could have been differentiated out of norite. On the other hand, the minor differentiates associated with norites such as diorite, microdiorite, bojite, tonalite and intermediate pegmatites understandably form a small proportion, no more than 10% of the norite mass.

We consider that the present view of Khan *et al.* (1989) which regards the norites as product of a mantle plume either rifting the arc apart or forming a back arc ocean is rather more plausible than the base of the arc hypothesis.

Although, the norites may have oceanic affinities, the intra-arc rift hypothesis does not yet explain the older than 80 to 90 Ma age of the norites (ages on hornblende from hornblende pegmatites by Rex *et al.* (1988) in Coward *et al.* (1987).

At present there is considerable evidence of tectonic transport of the norite body at the contact. It must be remembered that when a huge body like the norite is subjected to deformation and tectonic transport there is bound to be some melting on the contacts and intermixing with the country rocks even when the body was essentially transported in solid state.

One may conclude that the interpretation of norites as base of the arc magma chamber is not tenable whereas there is a fair amount of evidence in favour of their oceanic affinity. Finally the age of the norites appears to contradict the late stage formation of norites out of a rising mantle plume Tectonic contacts, relatively old age but fresh conditions all appear to indicate their tectonic emplacement between two acrs.

Diorites: Extensive belts of diorites occur both north and south of the Chilas norite complex. In SE Kohistan we have called these as the Darel diorite and the Thor diorite respectively. The Darel diorite body together with granodiorite further north has been called the Kohistan batholith (Coward *et al.*, 1986) and considered to extend right upto the MKT.

The main body of the Kohistan island arc complex between the MMT and MKT, if we exclude the Jijal ultramafics, Kamilla amphibolites and Chilas norites as oceanic would comprise the diorites and granodiorites. The volcanic fraction is indeed small in comparison.

Apart from the major basic and ultrabasic fraction, the Kohistan island arc consists mainly of diorite and granodiorites. We may, therefore, consider it a much uplifted arc mass in which the lower level plutonic rocks stand exposed.

It has been suggested (Coward et al., 1987) that the arc mass in the south is older and, therefore, belongs to an earlier phase of intraoceanic arc building while the Kohistan batholith occurring north is later and, therefore, belongs to a younger phase of arc building on an Andean type margin. The picture, however, is not all that simple, younger intrusions penetrate the older and limits of so called Kohistan batholith and the older Kohistan island arc remain undefined.

TECTONIC HISTORY OF KOHISTAN/THE TECTONIC MODEL FOR KOHISTAN

The first model for the tectonic history of Kohistan area was postulated by Tahirkheli et al. (1979) and Bard *et al.* (1980). This considered the entire sequence from Jijal to Yasin and Utror and Drosh as a single island arc sequence, the "Kohistan island arc". The model envisaged northward intra-oceanic subduction of the oceanic part of the Indian plate in Tethys leading to the formation of the "Kohistan island arc" and eventual suturing of India with the Island Arc forming the MMT. This was followed by the northward subduction in the marginal sea leading to the suturing of Kohistan Island Arc with Asia forming the MKT.

Chaudhry *et al.* (1984) model though basic did not explain a number of facts on ground including the more than due amount of basic mass in Kohistan, the presence of volcanic arc material south of MMT in Swat and whatever happened to the product of second northward subduction. These writers suggested that the Jijal complex represents a subduction zone and is, therefore, genetically not a part of Kohistan island arc.

Coward *et al.* (1986) have summarized the more recent formation of the tectonic model. This, inter alia, says that the Kohistan island arc sutured first in the north with Asia in Cretaceous times. A second Andean type northward subduction (Coward, 1986) of the oceanic lithosphere during Palaeocene and Lower Eocene generated the calc-alkaline Kohistan batholiths in northern Kohistan eventually leading to the suturing of India with Kohistan Asia along MMT in Eocene times (40 Ma). It has also been suggested that most of the deformation in kohistan occurred in Late Cretaceous rather than Tertiary times.

The nature of the MMT, too, has been disputed. It was suggested by Tahirkheli *et al.* (1979) and Bard *et al.* (1980) that MMT was one of the two continuations of the Indus- Tsangpo suture zone in Northwest Himalaya. Still they considered it a megashear and included the ultramafics as well as the associated basics as the bottom part of the Kohistan island arc sequence. Since then information has been added towards a better understanding of the MMT (Zeitler, 1985; Butler, 1986; Lawrence *et al.,* 1983; Chaudhry and Ghazanfar 1987; Kazmer, 1986; Spencer *et al.* 1989; Baig, 1989). MMT is now recognized as an overthrust shear towards SSE. It is a complex discontinuous zone and not a single thrust. There are different structural levels of obduction - subduction complex at different sites along MMT due to differential uplift (Lawrence *et al.,* 1983) or due to break back faults (Butler, 1986). Fission track and 40Ar/39Ar cooling ages confirm progressive increase in uplift rates form W to E (Zeitler, 1985). Mylonites have been reported along MMT at various places (Chaudhry and Ghazanfar 1986, 1987; Lawrence *et al.,* 1983) Chaudhry *et al.* (1984) considered the ultramafics and associated basic rocks along MMT as a trench melange complex and not as the bottom part of Kohistan island arc (Tahirkheli *et al.,* 1979; Bard *et al.,* 1980; Jan and Asif 1981; Coward *et al.,* 1986).

The present work has entailed a detailed study of the geology of the terrain but the work is still confined to the southeastern segment of the much larger Kohistan entity.

REGIONAL TECTONIC ELEMENTS

Now that a relatively detailed geology of at least the eastern part of the Kohistan and of parts to its south has been worked out it is possible to discuss the structural relationship of rocks with better control. The following points may be made about the broad tectonic framework of the area:

The area of Kohistan and its surrounding area to the south comprise at least four main tectonic components:

i) Late Precambrian to Cambrian Indian Platform on which Kashmir, Muzaffarabad and Hazara basins of Phanerozoic time were formed.

ii) The Proterozoic wedge-shaped slice of old Indian shield which is a continuation of the Higher Himalayas from Kashmir and India. This is separated from the Indian platform on the south by a continuation of the MCT (Ghazanfar and Chaudhry, 1986) from Kashmir and Indian Himalayas into Northeast Pakistan. The MCT here constitutes a north dipping thrust zone along which a slice of Indian shield has been upthrust on the platform rocks.

iii) A thick and wide "Island arc - ocean complex" in the northeast of the shield and occupying the area of Kohistan. This "Island arc - ocean complex" has been thrust onto the slice of Indian shield by the north dipping Main Mantle Thrust Zone or MMTZ.

iv) Ultramafic and basic shreds occurring as a narrow discontinuous zone, along the MMTZ forming in main an ophiolite complex.

Indian Platform: The Indian platform which forms the underlying basement on which rocks of Kashmir basin, Muzaffarabad basin and Hazara and Kohat - Potwar basins were laid down comprises the Precambrian Tanols, Hazara slates and comparable rocks like Kaghan group in Kaghan and Dogra slates in Kashmir. Stable shelf conditions or continental subaerial conditions prevailed on variable parts of the platform from Palaeozoic to Paleogene except for a rift related mainly submarine magmatism etc. during Upper Palaeozoic in Kashmir.

Higher Himalayan Crystallines or the Nanga Parbat - Haramosh Massif and the MCT: Recent geologic investigation in Kaghan and Neelum Valleys (Ghazanfar and Chaudhry, 1985 a-b; Ghazanfar *et al.,* 1983, 1985; 1985 a; Ghazanfar *et al.,* 1986) have revealed that the Main Central Thrust at the base of Higher Himalaya extends eastwards into Azad Kahsmir and Northeast Pakistan. It occurs as a zone of mylonites between Luat (Neelum Valley), Batal and Chhalayyan (in Kaghan Valley). Further west this zone seems to close in but opens again. The nature of rocks and the style of tectonics on two sides north and south of the MCT in Pakistan and Kashmir is strikingly different (Ghazanfar and Chaudhry, 1986). The same set of rocks and style of tectonics as in Higher Himalaya of Upper Kaghan continues into what has been called the Nanga Parbat - Haramosh massif. This indicates that the Nanga Parbat - Haramosh massif is nothing more than a continuation of the shield slice which occurs in the area of Naran and Babusar in Kaghan Valley, Kel and Shauntar in Neelum Valley and continues eastwards as the Higher Himalayas crystallines in Kashmir

MCT and MMT: The wedge shaped nature of the Indian shield slice and a closing in of the MCT and MMT indicates greater translation along MCT. in the Chhalayyan area.

The north dipping MMT as seen at Babusar and Niat indicates that the Kohistan island arc has thrust over the Nanga Parbat gneisses in this area. Further north near Raikot the MMT becomes vertical and then overturns to become SSE dipping Lawrence and Ghauri (1984) have postulated that the much younger Raikot fault replaces the MMT in this section. It is also likely that the peculiar shape of the Nanga Parbat - Haramosh massif is older and not the result of a late stage anatectic rise. After all, the thrusting is not limited to the area of Nanga parbat Haramosh massif but continues as MMT far to the west of it juxtaposing the island arc - ocean complex against the Indian shield crystalline slice around the Kohistan-Kaghan watershed in the region of Upper Kaghan.

The Ophiolite Complex Along the MMTZ: Ultrabasic and basic rocks have been reported, described and interpreted at various places along and close to MMTZ. For details the reader is referred to Jan (1968, 1977, 1979b, 1980) Jan and Howie (1981), Jan and Asif (1981) and Jan *et al.* (1985), Lawerence and Ghauri (1983, 1983b, 1984), Butt *et al.* (1980), Tahirkheli (1979), Tahirkheli *et al.* (1979), Majid and Shah (1985), Bard (1983, 1983a), Martin *et al.* (1962), Shah and Majid (1985), Kazmi *et al.* (1984), Chaudhry *et al.* (1980, 1984), Ghazanfar and Chaudhry (1985a) Chaudhry and Ashraf (1986) and Baig (1989). and Baig(1989).

These rocks include peridotites, pyroxenites, chromjtites, talc-carbonates, greenstones and gabbros/norites. The ultrabasic rocks have been variously interpreted as upper mantle/crustal cumulates while the basic rocks have been interpreted as arc flows or oceanic crust.

In fact the tendency to consider most of the ultramafic and mafic rocks along and close to MMTZ as arc related is on the increase. Many ultrabasics have been considered as detached basal cumulates of the Chilas norite complex (Coward *et al.* 1987).

We however, suggest that most of the ultramafic/mafic rocks within and very close to the MMTZ should be considered a separate zone. These are mostly slices of dismembered ophiolite complex which mark the position of the former trench (Chaudhry *et al.*, 1984).

Kohistan Island Arc Complex: Investigations in the Kohistan area have revealed that it comprises one (Tahirkheli *et al.*, 1979; Bard *et al.*, 1980) or more than one (Chaudhry *et al.*, 1984) island arcs. The present work did not cover. full extent of the area between MMT and MKT and the detailed work was limited to the southeastern portion of the complex. The rocks of SE Kohistan comprise a sequence of diorites, tonalites, granodiorites and basic to intermediate rocks which have greenstones and amphibolites as well as ultrabasic bodies and shreds

STRUCTURE OF SOUTHEAST KOHISTAN

The structure of SE Kohistan resembles the structure of Southeast Hazara in some ways. The southeast Hazara a sedimentary terrain comprising the area of Abbottabad and Murree and geologically continuing to north of Islamabad occurs to the southwest of the Hazara Kashmir Syntaxis, a bend of folds and faults around a north-south directed wedge of Murree molasse. The Main Boundary Thrust, MBT which is a major fault in Kashmir and eastern Himalayas breaks into a series of faults which radiate from the MBT and diverge towards southwest. Along these faults it is believed, the offset of the MBT has been distributed (Yeats and Lawrence, 1984). in an analogous manner the southwest margin of the Nanga Parbat - Haramosh is marked by the MMTZ which then continues further southwest and west to Pattan. A number of thrusts radiate from the west of Nanga Paraat and diverge to the southwest penetrating the sequence of Kohistan island arc. Most of these thrusts are high angle and north dipping. In the region of SE Kohistan these thrusts separate major units. The thrusting has eliminated most of the older folding in the metamorphic terrain of SE Kohistan.

At least four major thrusts in addition to a large number of smaller thrusts can be readily recognized apart from the MMT zone. Two of the thrusts separate the central noritic sequence from the diorites on the two sides, the Thor diorite in the south and the Darel diorite to the north. Another thrust separates the granodiorite sequence north of Darel from the Darel diorites. These thrusts are marked by the development of mylonites. The contact between the Thak Striped amphibolites and the tonalites to their north is also faulted and this zone of thrusting is represented by extensive mylonization. Strong foliation, mylonization and strong metamorphic differentiation are phenomena traceable to thrusting.

Elsewhere folding within the thrust sheets is not much in evidence except occasionally like the one outcrop of folds showing on a cliff face at Thak Kot. Gentle flexures are seen at many places. No evidence of frequent large scale isoclinal folds, was noticed in the area. It is possible that a few units are repeated through thrust faulting. Frequent gradational contacts showing effects of mixing indicate that intrusive relationships have been greatly altered by later tectonics.

CONCLUSIONS

The Kohistan arc-oceanic complex is a major phenomenon hundreds of kilometres long and scores of kilometres across. Only preliminary field studies exist of selected sections. The present is a relatively detailed field oriented study of east and southeastern Kohistan. Still many problems remain unresolved and will only be solved after more work in future. Some salient points arising out of the present work are summarized as follows.

Southeast Kohistan is unique is as much as major rock belts of Kohistan thin out and have been telescoped into a relatively small section. Tectonic contacts between various units are the normal. some of these contacts are marked by mylonites and ultramylonites.

The Chilas norite complex, with spreading centre affinities appears to have been emplaced tectonically between two belts of island arcs. The one in the north of the complex considered younger than the one in the south.

Some of the largest pyroxenite bodies reported from anywhere in Pakistan were mapped in the Ledi-Nili Nadi section (of Kaghan) of the southern suture. These suture pyroxenites as well as the southern arc granodiorite/tonalite towards south have been intruded by a minor intermediate to basic volcanic - hypabyssal suite. The latter must post-date the emplacement of ophiolites along MMT and represents lithologically the youngest arc phase occurring due south.

A thin dismembered sequence of low grade carbonaceous phyllites, calc-pelites and marbles (shelf sediments and lagoonal anoxic shales) is fairly continuously present between Babusar and Nili-Nadi section between the Indian continental rocks and the ophiolitic suite of the southern suture. We consider these as a part of the faulted remnants of the Tethys. Himalayan sedimentary regime which is so well developed in Kumaun and Nepal Himalayas to the east of Kashmir.

The stark difference in the grade of metamorphism of ophiolitic greenstones and amphibolites is probably not related to age and may only indicate different levels of subduction. Amphibolites, as greenstones are considered a part of the ophiolitic suite along southern suture. Thin patches and layers of associated sediments have been noted. The general apparent absence of associated sediments may in part be related to high degree of metamorphism attained by amphibolites. Kyanite/ sillimanite have been reported by Bard (1983a) from the metasediments associated with amphibolites.

A number of granite, aplite and pegmatite bodies intruding the Kohistan complex are not arc related, nor indeed a melting product of amphibolites. They are S-type and indicate a mainly continental derivation. These may be related to underthrusting along MMT and thrust piling of the Indian mass. As such they may be quite young. The S-type tourmaline - mica pegmatites within Babusar granodiorite gneiss and greenstone near Buto Gah Gali north of the MMT also belong to the same continental regime.

As far as the Chilas norite complex is concerned the field evidence favours a spreading centre rather than base of the arc magma chamber origin.

A model could envisage development of the arc and its later suturing with Indian Shield. If the basic suite of the ultramafics/amphibolites/greenstones (or a part thereof) is ophiolitic then they would be considered to have been emplaced at the time of suturing after the arc had been built. However, contrary to this expectation all the major arc units including granodiorite, tonalites and volcanohypabyssals appear to have intruded the basic to ultrabasic (assumed) ophiolitic suite. The relationship is clearly intrusive with xenoliths and even screens of basic and sometimes ultrabasic rocks in acid to intermediate rocks. Veins, sills, dykes and apophyses of acid to intermediate material are found cutting mafic to ultramafic rocks. Thus ultramafics, greenstones and amphibolites were all present possibly in a tectonic sliced relationship when the intrusions of the main acid to intermediate rocks of southeast Kohistan took place.

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THE STRUCTURE AND TECTONIC SETTING OF ATTOCK-CHERAT AND KALA-CHITTA RANGES IN NIZAMPUR AREA, NWFP, PAKISTAN

By

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ABSTRACT: The southern belt of Paleozoic strata of Attock-Cherat Range comprising of limestone, argillite and quartzite, constitutes a major overturned south-verging fold. The southern limb of this fold is truncated by north dipping Hissartang thrust which is the part of late Tertiary imbricate thrust system in this area. This fault has emplaced the Paleozoic rocks of Attock-Cherat Range over the Mesozoic sequence of Kala-Chitta Range. From the town of Nizampur in the east, the Hissartang fault runs at the foot of Attock-Cherat Range but near the Indus river it swings northeast and a low-angle Hissartang backthrust appears. The tectonically emplaced patches of Jurassic limestone over the Paleozoic rocks of Attock-Cherat Range are quite common east of Indus. The emplacement of Jurassic limestone over the Paleozoic rocks is the result of back thrusting of Hissartang thrust. The late extentional phase in the area is marked by the north dipping listric normal faults.

INTRODUCTION

As a part of routine field work during a filed camp at Nizampur and later on the basis of field reports compiled by M.Sc. students working in the Attock-Cherat Range (Fig. 1; Hussain and Rehman, 1980; Shaukat and Shatter, 1986; Sultan and Rabab, 1986), some new aspects of structural and stratigraphic relationship of different rock units were observed.

The area is traversed by three major eastwest-trending thrusts. From north to south these faults are:

1. The Khairabad thrust
2. The Cherat thrust
3. The Hissartang thrust

The Khairabad thrust serves as a boundary between the Precambrian slates, phyllites, quartzites, limestone and the unfossiliferous flysch deposits of the late Precambrian (?) age. The later is recently named as Dakhner formation (Yeats and Hussain, 1987).

Southward, the Dakhner formation is thrust over the Siluro-Devonian sequence along the Cherat fault. The Siluro-Devonian rocks are relatively more competent than Dakhner formation and are deformed and folded to a lesser degree. The minor folds in the Inzari limestone near the fault shows a constant vergence to the south. Although the characteristic tight isoclinal folding of Dakhner formation is not the common feature of these rocks, but a major overfold verging south has been identified.

The Hissartang thrust marks the boundary between the Attock-Cherat and Kalachitta Ranges in Nizampur area. Along this fault, the Siluro-Devonian rocks are thrust over the Mesozoic rocks. The movement along this fault deformed the rocks of the Kalachitta Range. The first appearance of outcrops of Kalachitta Range after the alluvial cover in this area, are folded into a synclinorium with folds again verging to the south.

The Nizampur quadrangle map (1:50,000) produced earlier (Hussain, 1984), is on a regional basis and does not include some of the smaller outcrops appearing from the alluvial cover at the southern foot of the Attock-Cherat Range (Fig. 1).

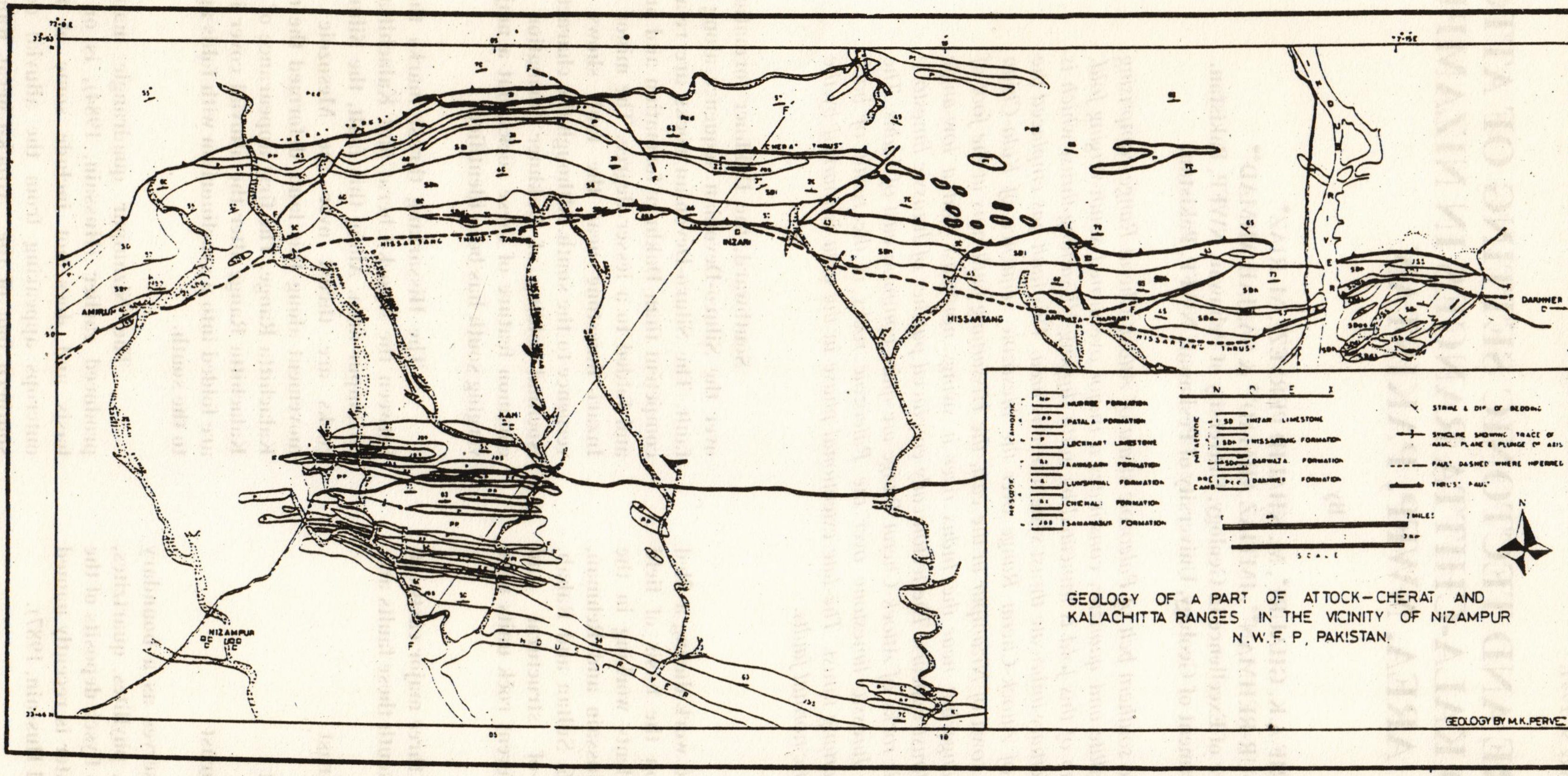

Figure 1. Geology of a part of Attock-Cherat and Kalachitta Ranges in the vicinity of Nizampur, NWFP, Pakistan.

These outcrops belong to Darwazai formation, the oldest unit of the Paleozoic sequence in the area, and Jurassic limestone which are exposed near Tarkhel village. These two units are important because they modify the structure significantly and indicate the trace of Hissartang thrust in this area.

The discontinuous chain of small hillocks, west of Tarkhel village, exposing the lower limestone unit and an upper shale unit of Darwazai formation, gives an indication of overturning of Lower Paleozoic sequence on itself and thus forming a large overturned fold with its southern limb truncated against the Hissartang thrust (Fig. 1). The shale unit of this formation can be seen underlying the calcareous unit in these outcrops.

The Jurassic limestone (? Samana Suk Formation) is exposed at the foot of the Attock-Cherat Range as low-lying outcrops, mostly visible in quarries on both the eastern and western side of Tarkhel village. It dips between 10° and 20° toward north, and has a sharp contact with the Hissartang formation which dips around 60° north. At Amiruh village, towards west, the same limestone has been mapped as a small outcrop directly in contact with Darwazai formation with intervening Hissartang fault. The continuation of the same fault eastward is shown under the alluvium extending upto the Campbellpur Basin (Yeasts and Hussain, 1987). The Hissartang fault brings Paleozoic sequence of the Attock-Cherat Range over the Mesozoic and Paleocene rocks of the Kalachitta Range. The contact between the Samana Suk Formation (Jurassic) and the Hissartang formation (Paleozoic at Tarkhel village (Fig. 1), marks the eastern continuation of the Hissartang thrust. The presence of these few outcrops of the Samana Suk Formation at the southern foot of the Attock-Cherat Range strongly support the idea that the Hissartang thrust is running at the foot of the Attock-Cherat Range rather than under the alluvial cover of Nizampur Basin.

Rocks of the Kalachitta Range are exposed south of the Attock-Cherat Range. In Nizampur area they form a big synclinorium, gently plunging towards southeast. The exposure of Jurassic limestone at the foot of the Attock-Cherat Range shows that the Kalachitta sequence extends under the alluvium of the Nizampur Basin upto this range.

East of Indus river, several large and small isolated patches of fossiliferous limestone, covering parts of the unfossiliferous Inzari, Hissartang and Darwazai formations were previously identified as the Lockhart Limestone of Paleocene age (Riaz and Latif, 1986). This limestone has a sheared and unconformable lower contact with the Paleozoic rocks (A. Hussain, verbal commnu., 1989).

During the present study it was found that this limestone contains some megafossils and it was suspected that it may be of Jurassic age. The fossils found in this limestone were identified by A.N. Fatmi (1989) of Geological Survey of Pakistan as the corals of Jurassic age. This discovery has added more complexity in the formation and depositional environment of the structure of the area.

The field relationship of this rock unit with the underlying rocks is unique. In the entire Attock-Cherat Range west of the Indus, this limestone is found only at one peak, overlying the Inzari limestone (Figs. 1 and 3) However, east of Indus, the same unit forms rootless patches lying on different Paleozoic rock units (Fig. 2). About one meter thick, pink colored, crushed quartz zone points towards the tectonic nature of the contact of Jurassic limestone with the underlying rock units almost everywhere in this part. However, a dolerite intrusion is present at the contact of Jurassic and Inzari limestones at the top of the hill (Fig. 2). This structure has been traced for about half a kilometer along the contact. In the central part the intrusion is about 6 meter thick. At the margins, instead of exposed dolerite rocks, the trace of the body can be seen as a reddish or rusty brown weathered material. This intrusion was previously identified as a laterite band and was considered to mark an unconformity between Lockhart Limestone and underlying Paleozoic sequence (Yeats and Hussain, 1987).

The present study shows that at the eastern block of the Attock-Cherat Range, east of Indus the contact of the older rocks with the Jurassic limestone is of tectonic origin. Thus the main problem encountered during this work, was the anomalous Paleozoic/Mesozoic rocks relationship on hilltops and a number of small faults oriented in different directions, complicating the structure across the Indus river. Within the main Attock-Cherat Range, there are two major thrusts and the intervening block has uniform stratigraphy and structural behavior almost upto the river. East of the Indus river, in a small area the structural style changes to a great extent as compared to the western side. This anomaly demanded a thorough mapping of this part of the range and a

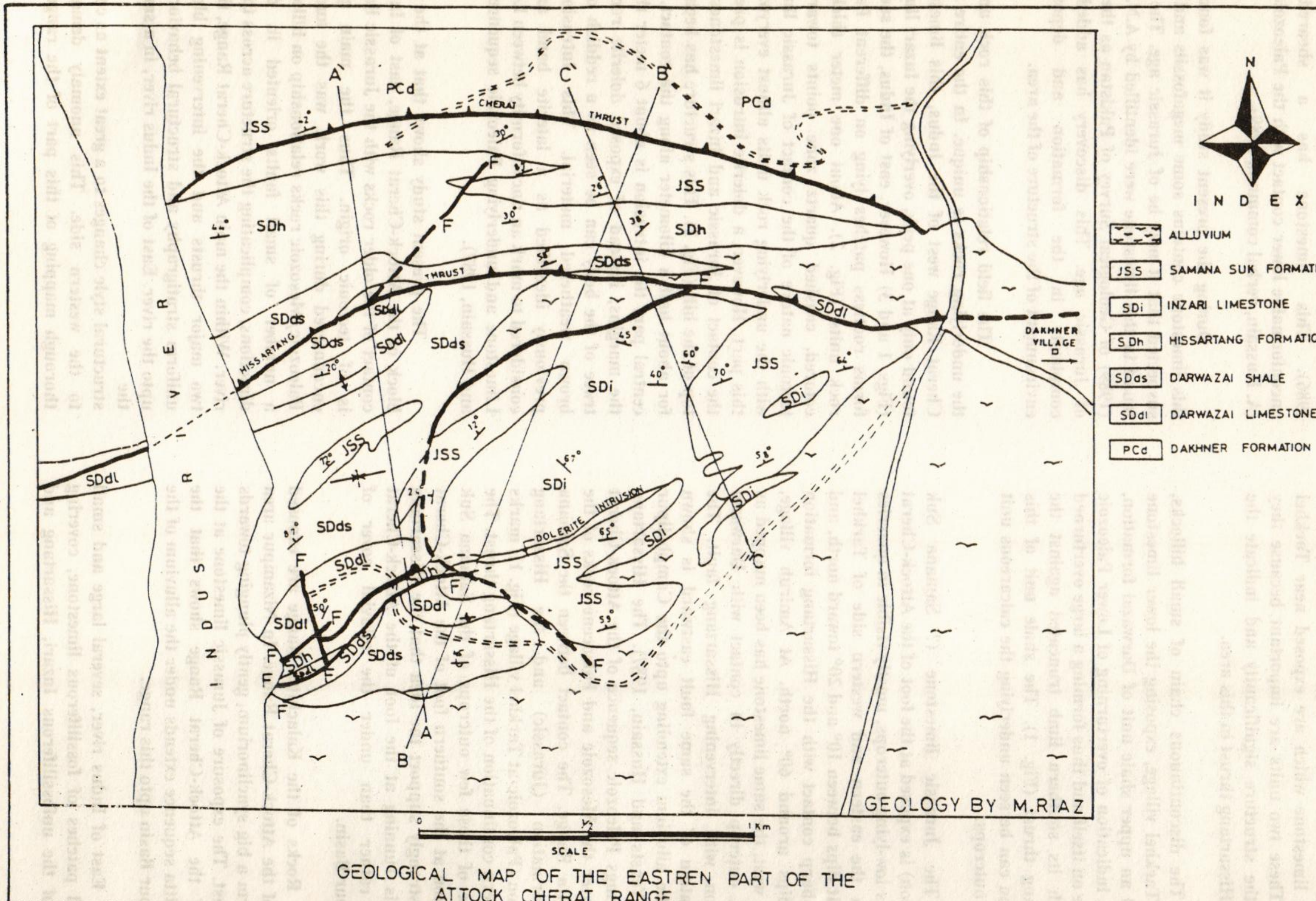

Figure 2. Geology of the eastern part of the Attock-Cherat Range east of Indus river.

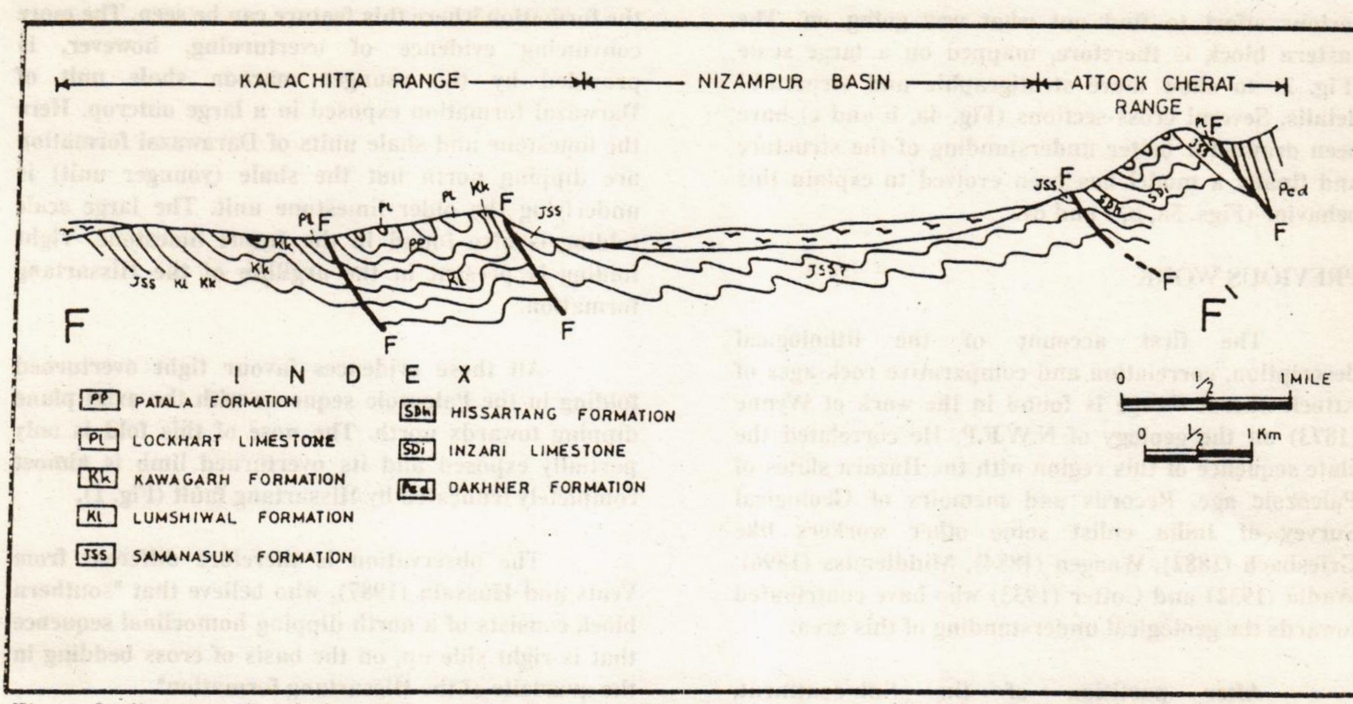

Figure 3. Cross-sectional view of the Attock-Cherat and Kalachitta Ranges, along line FF' of Fig. 1 (Index same as in Fig. 1).

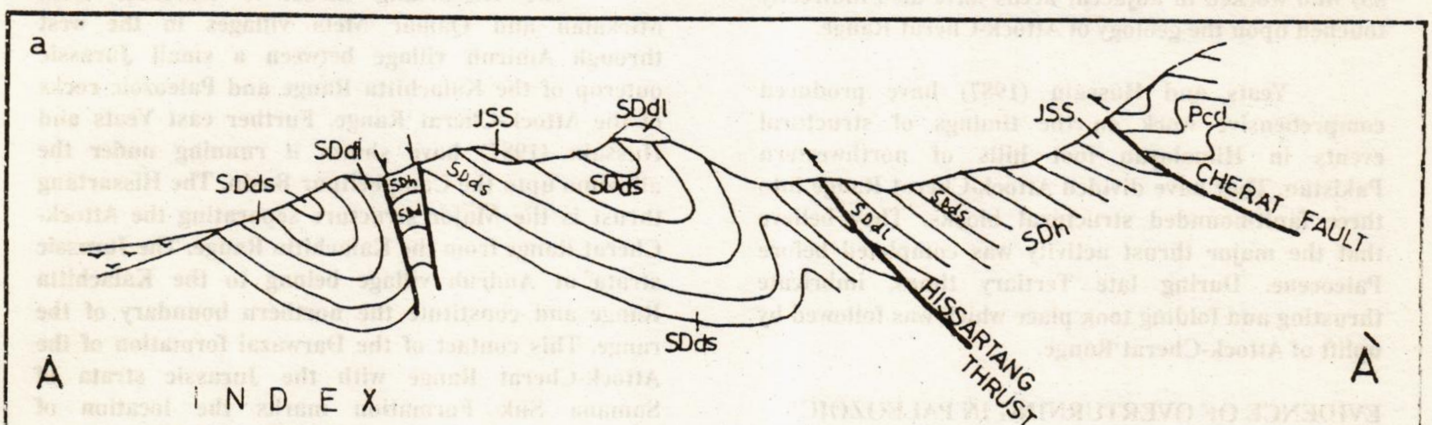

Figure 4. Cross-sectional view of eastern part of Attock-Cherat Range; a = along line AA', b = along line BB' and c = along line CC' of Fig. 2. (Index same as in Fig. 2).

serious effort to find out what was going on. The eastern block is therefore, mapped on a large scale (Fig. 2) to show more stratigraphic and structural details. Several cross-sections (Fig. 4a, b and c) have been drawn for better understanding of the structure and finally a model has been evolved to explain this behavior (Figs. 5a, b, c and d).

PREVIOUS WORK

The first account of the lithological description, correlation and comparative rock ages of Attock-Cherat Range is found in the work of Wynne (1873) on the geology of N.W.F.P. He correlated the slate sequence of this region with the Hazara slates of Paleozoic age. Records and memoirs of Geological Survey of India enlist some other workers like Griesbach (1882), Waagen (1884), Middlemiss (1896), Wadia (1932) and Cotter (1933) who have contributed towards the geological understanding of this area.

After partition of the Sub-continent, Tahirkheli (1970) carried out detailed mapping of the area, subdivided argillite and other rocks into many mappable units and assigned ages to different rocks. Other geologists (Meissner *et al.*, 1974; Burbank, 1982, 83) who worked in adjacent areas have also indirectly touched upon the geology of Attock-Cherat Range.

Yeats and Hussain (1987) have produced comprehensive work on the timings of structural events in Himalayan foot hills of northwestern Pakistan. They have divided Attock-Cherat Range into three fault-bounded structural blocks. They believe that the major thrust activity was completed before Paleocene. During late Tertiary times, imbricate thrusting and folding took place which was followed by uplift of Attock-Cherat Range.

EVIDENCE OF OVERTURNING IN PALEOZOIC SEQUENCE OF THE ATTOCK-CHERAT RANGE

The isolated, low-lying hillocks of Darwazai formation at the foot of the Attock-Cherat Range west of Tarkhel village, display the overturning of strata. The lower limestone unit of Darwazai formation shows tight folding at small scale. These folds are commonly south verging Z folds as viewed from west, but in some layers M folds have also been observed. In one outcrop the limestone beds are overturned with a small fault dipping steeply to the north and marking the axial plane trace of this fold. This exposure confirms the large scale folding of the unit but unfortunately this is the only outcrop out of a few poorly exposed parts of the formation where this feature can be seen. The more convincing evidence of overturning, however, is provided by the younger maroon shale unit of Darwazai formation exposed in a large outcrop. Here the limestone and shale units of Darawazai formation are dipping north but the shale (younger unit) is underlying the older limestone unit. The large scale folding is also found in the Inzari limestone. Tight folding is present in the argillite of the Hissartang formation.

All these evidences favour tight overturned folding in the Paleozoic sequence with the axial plane dipping towards north. The nose of this fold is only partially exposed and its overturned limb is almost completely truncated by Hissartang fault (Fig. 1).

The observation is therefore different from Yeats and Hussain (1987), who believe that "southern block consists of a north dipping homoclinal sequence that is right side up, on the basis of cross bedding in the quartzite of the Hissartang formation".

HISSARTANG THRUST AND THE NORTHERN MARGIN OF THE KALACHITTA RANGE

The Hissartang thrust is traceable from Mirkalan and Qamar Mela villages in the west through Amiruh village between a small Jurassic outcrop of the Kalachitta Range and Paleozoic rocks of the Attock-Cherat Range. Further east Yeats and Hussain (1987) have shown it running under the alluvium upto the Campbellpur Basin. The Hissartang thrust is the Major structure separating the Attock-Cherat Range from the Kalachitta Range. The Jurassic strata at Amiruh village belong to the Kalachitta Range and constitute the northern boundary of the range. This contact of the Darwazai formation of the Attock-Cherat Range with the Jurassic strata of Samana Suk Formation marks the location of Hissartang thrust (Fig. 1). Further east there is a sizeable exposure of Jurassic limestone between Inzari and Tarkhel villages. This gently dipping limestone is being excavated for construction purposes. At Tarlkhel village there is a sharp contact between the gently dipping Jurassic limestone with the steeply dipping quartzite of the Hissartang formation. This is the place where the Hissartang thrust reappears.

East of Darwazai village a major eastwest-trending fault is marked within Darwazai formation with a distinct fault breccia zone which extends eastwards across the river. This fault brings Darwazai formation in direct contact with younger Inzarai

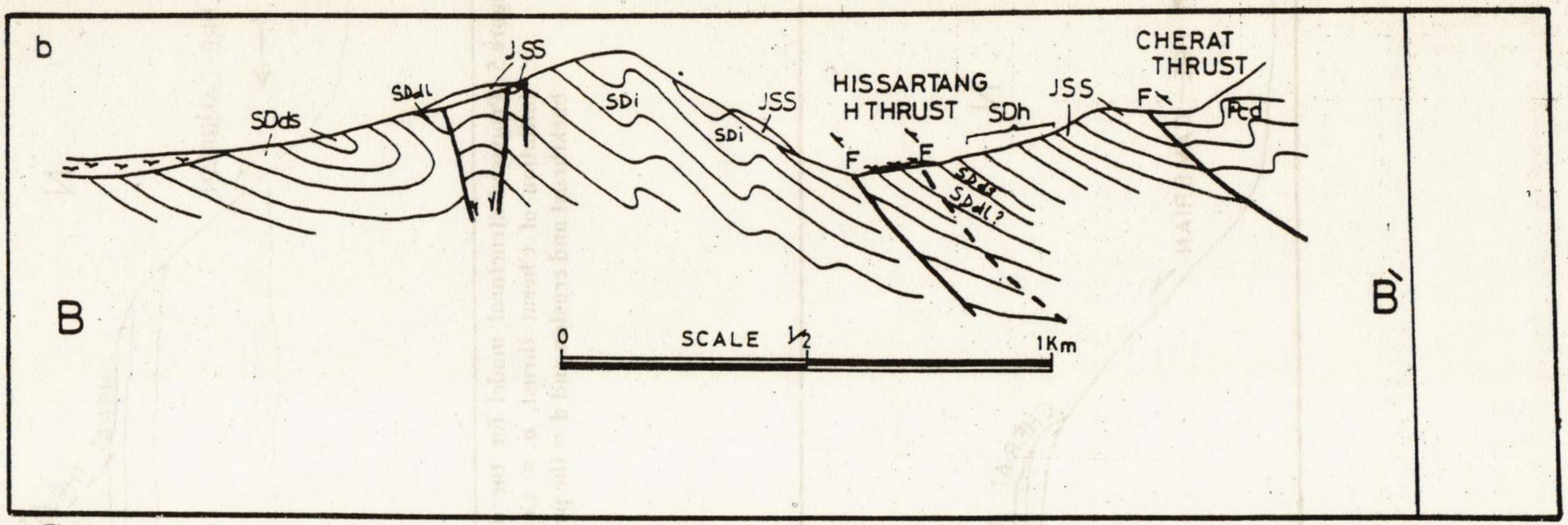

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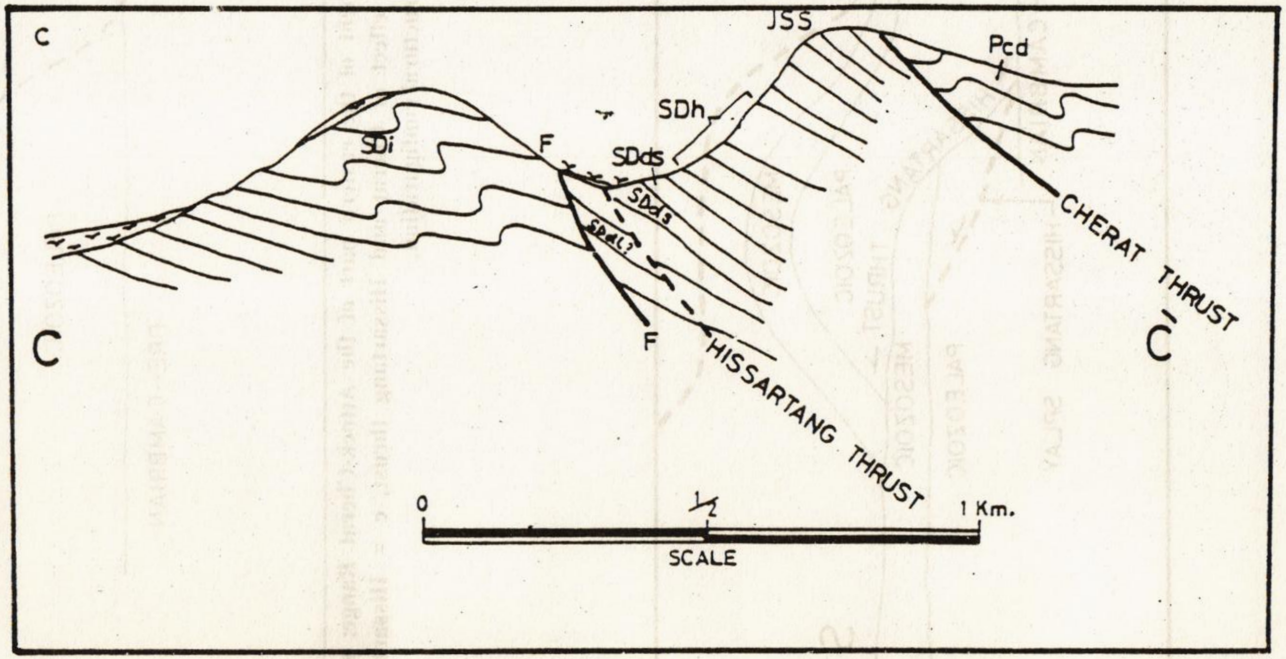
Fig. 4



c
SDi
F
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SDds
SDdl?
SDh
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CHERAT THRUST
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HISSARTANG THRUST
C
C'
0
1/2
1 Km.
SCALE

Fig. 4

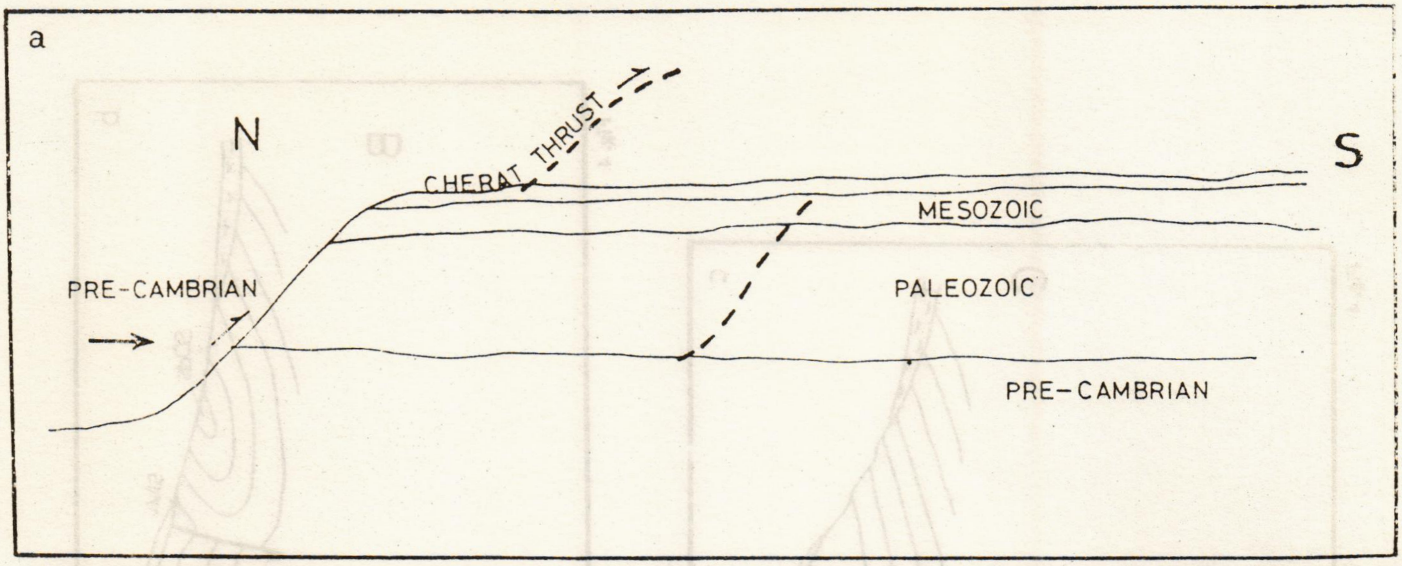

Figure 5. **Proposed structural model for the development of the eastern part of the Attock-Cherat Range; a = initiation of Cherat thrust, b = Combined effect of Cherat and Hissartang thrust, c = Hissartang backthrust and erosion and d = the present structural configuration.**

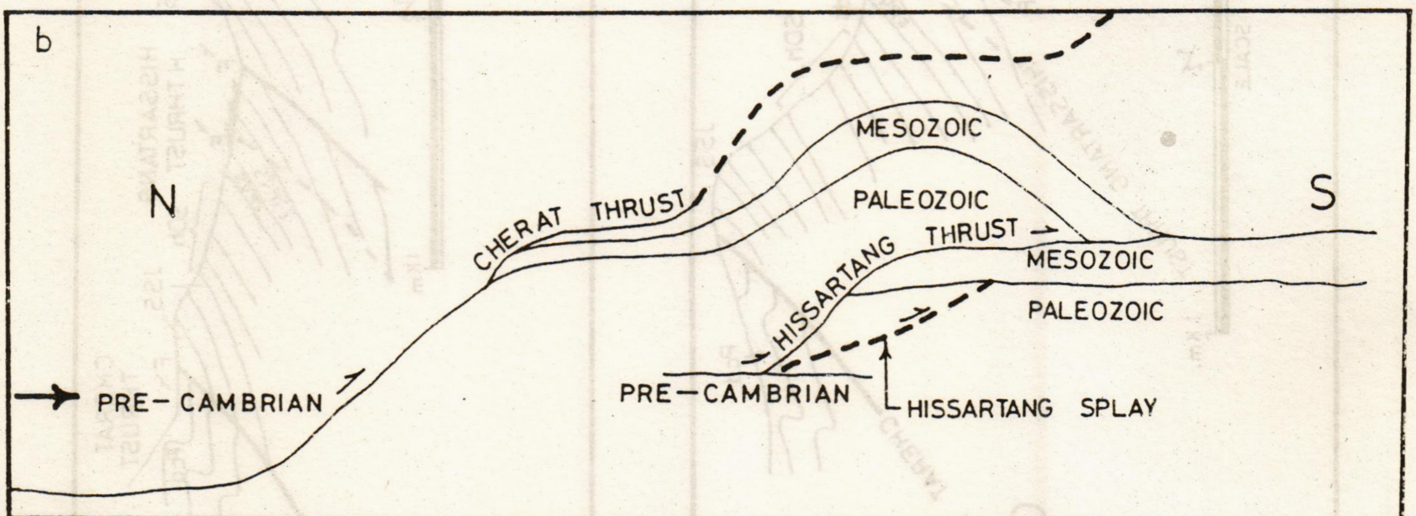

Fig. 5

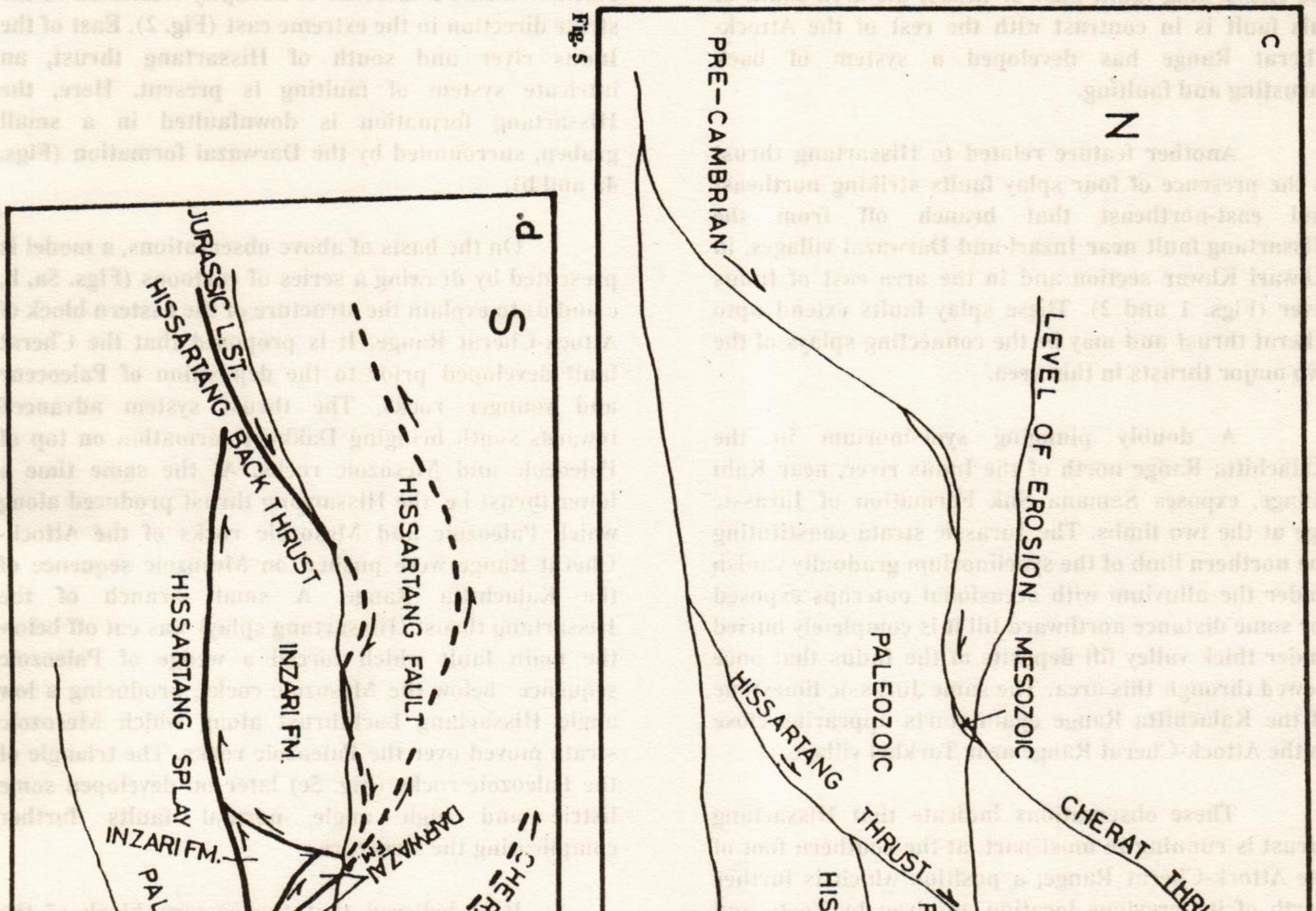
c
N
LEVEL OF EROSION
MESOZOIC
PRE-CAMBRIAN
PALEOZOIC
HISSARTANG THRUST
CHERAT THRUST
PALEOZOIC
MESOZOIC
HISSARTANG SPLAY
PALEOZOIC
HISSARTANG BACK THRUST
KC-MESOZOIC
S
d
S
JURASSIC LST.
HISSARTANG BACK THRUST
HISSARTANG FAULT
CHERAT THRUST
DARWAZAI
HISSARTANG SPLAY
INZARI FM.
INZARI FM.
PALAEOZOIC
PRE-CAMBRIAN
HISSARTANG
INZARI FM.
DAKHNER FM.
N

Fig. 5

Fig. 5

formation in the eastern part of the range (Figs. 1 and 2). Its eastern continuation across Indus river swings NE and runs close to Cherat fault. The authors believe that this structure marks the eastern continuation of the Hissartang fault. East of Indus, the area south of this fault is in contrast with the rest of the Attock-Cherat Range has developed a system of back thrusting and faulting.

Another feature related to Hissartang thrust is the presence of four splay faults striking northeast and east-northeast that branch off from the Hissartang fault near Inzari and Darwazai villages, in Khwari Khwar section and in the area east of Indus river (Figs. 1 and 2). These splay faults extend upto Cherat thrust and may be the connecting splays of the two major thrusts in this area.

A doubly plunging synclinorium in the Kalachitta Range north of the Indus river, near Kahi village, exposes Samana Suk Formation of Jurassic age at the two limbs. The Jurassic strata constituting the northern limb of the synclinorium gradually vanish under the alluvium with occasional outcrops exposed for some distance northward till it is completely buried under thick valley fill deposits of the Indus that once flowed through this area. The same Jurassic limestone of the Kalachitta Range again starts appearing close to the Attock-Cherat Range near Tarkhel village.

These observations indicate that Hissartang thrust is running in most part, at the southern foot of the Attock-Cherat Range; a position which is further north of its previous location as given by Yeats and Hussain (1987). Towards east, the fault turns east-northeast.

The presence of Jurassic strata at Amiruh and Tarkhel villages indicates that the rocks of the Kalachitta Range extend all the way under the thick alluvial cover of the Nizampur Basin upto the Attock-Cherat Range (Fig. 4).

THE PROPOSED STRUCTURAL MODEL FOR EASTERN BLOCK

East of the Indus river in the Attock-Cherat Range, Jurassic strata are extensively present lying on Inzari, Hissartang and Darwazai formations as rootless patches. Since the early workers mapped the Jurassic limestone as Paleocene, they have not taken into consideration the changes occurring eastwards. The Hissartang thrust in this area is clearly running within the Darwazai formation, the indication of which is very well documented. Besides, the fault patterns on the eastern side is also very different. Several small faults, apparently having no bearing with the regional fault geometry, are mapped in this area. The main block of Inzari Limestone is abruptly truncated in the strike direction in the extreme east (Fig. 2). East of the Indus river and south of Hissartang thrust, an intricate system of faulting is present. Here, the Hissartang formation is downfaulted in a small graben, surrounded by the Darwazai formation (Figs. 4a and b).

On the basis of above observations, a model is presented by drawing a series of cartoons (Figs. 5a, b, c and d) to explain the structure of the eastern block of Attock-Cherat Range. It is proposed that the Cherat fault developed prior to the deposition of Paleocene and younger rocks. The thrust system advanced towards south bringing Dakhner formation on top of Paleozoic and Mesozoic rocks. At the same time a lower thrust i.e. the Hissartang thrust produced along which Paleozoic and Mesozoic rocks of the Attock-Cherat Range were pushed on Mesozoic sequence of the Kalachitta Range. A small branch of the Hissartang thrust (Hissartang splay) was cut off below the main fault which forced a wedge of Paleozoic sequence below the Mesozoic rocks, producing a low angle Hissartang backthrust along which Mesozoic strata moved over the Paleozoic rocks. The triangle of the Paleozoic rocks (Fig. 5c) later on developed some listric and high angle normal faults further complicating the structure.

It is believed that the eastern block of the Attock-Cherat Range is a part of this tectonic slice or triangle and thus has structurally different setting as compared to the area west of Indus. The fault which brings Inzari and Darwazai formations in contact with each other and other small faults producing the graben, are the listric and/or high angle normal faults restricted to this zone only (Fig. 2). The Hissartang thrust shifts north in this part of the range and lies close to Cherat thrust. The Paleozoic sequence north of the Hissartang thrust comprises of Darwazai and Hissartang formations with Jurassic strata lying unconformably on them. The southern block of the central part of Attock-Cherat Range therefore, gets fairly squeezed east of Indus.

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TOR GHAR, AN ALKALINE INTRUSION IN THE SULAIMAN FOLD-AND-THRUST SYSTEM OF PAKISTAN

By

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ABSTRACT: The Carboniferous to early Tertiary alkaline rocks are known from the Peshawar Basin of northern Pakistan. These alkaline rocks are generally considered to be related to the pre-Himalayan and Himalayan extensional tectonics.

The Sulaiman fold-and-thrust belt along the western margin of the Indian plate is the result of Himalayan collision between the Indian plate and the Afghan block. The broad (> 300 km) and gentle (< 1°) Sulaiman fold-and-thrust belt is known to consist of an Eocene to Permian platform sequence. The platform sequence is overlain by ophiolites. It is bordered by Tertiary molasse at the front and flysch at the rear. Previously igneous rocks were recognized to occur from the Sulaiman fold-and-thrust belt in the form of volcanics and some mafic intrusions. No alkaline rocks have been reported from the Sulaiman fold-and-thrust belt. This paper reports an alkaline intrusion from the Tor Ghar area of the Sulaiman fold-and-thrust belt of Pakistan.

The Tor Ghar intrusion from the hinterland of the Sulaiman lobe is recognized here as a circular, cone shaped and unmetamorphosed igneous body. The presence of alkali feldspar, nephelene, biotite, diopside, apatite and sphene shows that the Tor Ghar intrusion is alkaline in nature. This is the first report of alkaline intrusion from the Sulaiman fold-and-thrust belt of Pakistan. On the basis of field relationship, the maximum age of the intrusion is post-early Cretaceous.

The post-early Cretaceous alkaline intrusion may be related to intra-plate alkaline magmatism over a hot spot or rifting of Indian plate and/or intrusion of alkaline magma through rebound relief tension zones of the under going slab of the Indian plate, during the initial Himalayan collision.

INTRODUCTION

The broad (>300 Km wide) and gentle (<1° topographic slope) Sulaiman fold-and-thrust belt (Fig. 1) is located southwest of the Himalaya along the western boundary of the Indian plate (Kazmi and Rana, 1982). The Sulaiman fold-and-thrust belt is the result of Himalayan collision between the Indian plate and the Afghan block. The deformation in the Sulaiman thrust lobe is suggested to be thin-skinned based on the structural cross-section and modelling of Bouguer gravity anomalies (Jadoon, 1991).

Recent to Permo-Triassic rocks are progressively exposed from the foreland towards hinterland (Kazmi and Rana, 1982). The thick platform sequence (Jadoon, 1991) is overlain by ophiolites (Abbas and Ahmad, 1979; DeJong and Subhani, 1979) that were emplaced during Paleocene, evidenced by the onlape of Eocene rocks (Allemann, 1979; Otsuki *et al.*, 1989).

Unlike Sulaiman, granitic rocks of Precambrian to Cenozoic age are recognized from the Himalaya and Karakorum (Bhanot *et al.*, 1979; Le Fort *et al.*, 1980, 1983; Sharma, 1983; Baig *et al.*, 1988; Baig and Snee, 1989; Baig *et al.*, 1989; Zeitler *et al.*, 1989; Baig, 1990). Besides granitic rocks, rift-related alkaline rocks of Carboniferous to Tertiary age are

Pakistan (Kempe and Jan, 1970; Kempe, 1973; Ashraf and Chaudhry, 1977; Kempe and Jan, 1980; Chaudhry *et al.*, 1981; Jan *et al.*, 1981; Chaudhry and Shams, 1983; Rafiq *et al.*, 1984; Kempe, 1986; Le Bas *et al.*, 1987; Rafiq and Jan, 1988).

In Sulaiman, volcanic agglomerates are reported, which are considered to be related to arc volcanics or hot spot activity (Kamzi, 1984; McCormick, 1985). Ahmed (1991) reports a swarm of dikes in the Pishin District of Baluchistan. These igneous rocks are recognized as alkali basalts and ultramafic lamprophyres that cut lower Jurassic strata. Basic dike swarm in Jurassic and older rocks in the hinterland of the Sulaiman fold-and-thrust belt (Loralai, Qilla-Saifullah section) have been seen by first author during filed season in 1988 and 1990. Besides these extrusive and intrusive igneous rocks, a Neogene volcano center based on the study of landsat images is reported south of Kohlu in the central Sulaiman (Fig. 1, Bannert *et al.*, 1989). The nature of this volcano is not known. However, unlike Himalayas, no plutons of acidic or alkaline nature have previously been reported from the Sulaiman fold-and-thrust belt. This paper reports Tor Ghar as an alkaline intrusion from the Sulaiman fold-and-thrust belt.

TOR GHAR ALKALINE INTRUSION

Tor Ghar is located at Longitude 68^{o} 48' 15" and Latitude 30^{o} 18' 25" in the Loralai valley, about 10 Km SEE of Loralai town (Fig. 1). The Tor Ghar is a circular, cone shaped and unmetamorphosed igneous intrusion (stock). It gives an impression of a volcano from a distance due to its cone shape and dark colour. It has a diameter of about 2 km and is about 175 m high from the ground level. It intrudes the early Cretaceous Sember shale and has not been seen intruding Tertiary rocks. It preserves a rim of crypto-crystalline basic rock and an outer layer of hornfels. It contains the xenoliths of the early Cretaceous Sember shale. These field relations show that the maximum age of the intrusion is post-early Cretaceous.

The bulk of stock consists of an intermediate rock with phenocrysts of alkali feldspar. Mineralogically, Tor Ghar body constitutes the alkali feldspar, nephelene and biotite as major phases and the diopside, muscovite, apatite and sphene as minor phases. The texture of the rock is holocrystalline. The rock is devoid of any fabric. The silica deficient Tor Ghar intrusion is herein classified as nephelene syenite. The recognition of Tor Ghar as an alkaline body is the first field report about the existence of a stock of anomalous alkaline affinity in the Sulaiman fold-and-thrust belt.

DISCUSSION

The alkaline rocks have been reported from the Peshawar Basin of northern Pakistan (Kempe and Jan, 1970; Ashraf and Chaudhry, 1977; Kempe and Jan, 1980; Chaudhry and Shams, 1983). The alkaline rocks of the Peshawar Basin yield Rb/Sr whole rock isochron ages of 315 $\pm$ 15 Ma to 297 $\pm$ 4 Ma (Le Bas *et al.*, 1987) and K/Ar and $^{40}Ar/^{39}Ar$ dates of 50 Ma to 30 Ma (Maluski and Matte, 1984; Kempe, 1973, 1986; Le Bas *et al.*, 1987). Le Bas *et al.* (1987) interpreted that the 315 $\pm$ 15 Ma to 297 $\pm$ 4 Ma Rb/Sr dates are the age of rift-related alkaline magmatism in the Peshawar Basin. However, Baig *et al.* (1989) and Baig (1990) interpreted that the Carboniferous (315 $\pm$ 15 Ma to 297 $\pm$ 4 Ma) alkaline magmatism in northern Pakistan predated the Permian mafic Panjal volcanism, during the rifting of Gondwana, to form the Cimmerian microcontinents. The Tertiary alkaline rocks have been interpreted to be related to rebound relief tension of the under going slab of the Indian plate, during the Himalayan collision (Kempe and Jan, 1980; Chaudhry and Shams, 1983; Rafiq *et al.*, 1984). Baig (1990) suggests that the most of the Tertiary $^{40}Ar/^{39}Ar$ and K/Ar dates in the Peshawar Basin are related to tectonometamorphic events.

The post-early Cretaceous Tor Ghar alkaline intrusion occurs in a collisional mountain belt. It is certainly younger than the Carboniferous alkaline rocks of the Peshawar Basin. The post-lower Jurassic alkali basalts, ultramafic lamprophyres (Ahmed, 1991) and Neogene volcanos (Bannert *et al.*, 1989) are reported from the western margin of the Indian plate. The genetic relation between post-lower Jurassic mafic and ultramafic rocks, post-early Cretaceous alkaline rocks and Neogene volcanos is unknown. Ahmed (1991) interpreted that the alkali basalts and ultramafic lamprophyres are related to intra-plate hot spot magmatism.

In general, alkaline rocks are related to rifting. Different mechanisms can be proposed for the alkaline rocks of the Sulaiman fold-and-thrust belt. Post-early Cretaceous alkaline rocks may be related to the rifting of the Indian plate or intra-plate magmatism over a hot spot and/or intrusion of alkaline magma through rebound relief tension zones of the under going slab of the Indian plate, during the initial Himalayan collision. The detailed major and trace element chemistry, petrographic and isotopic

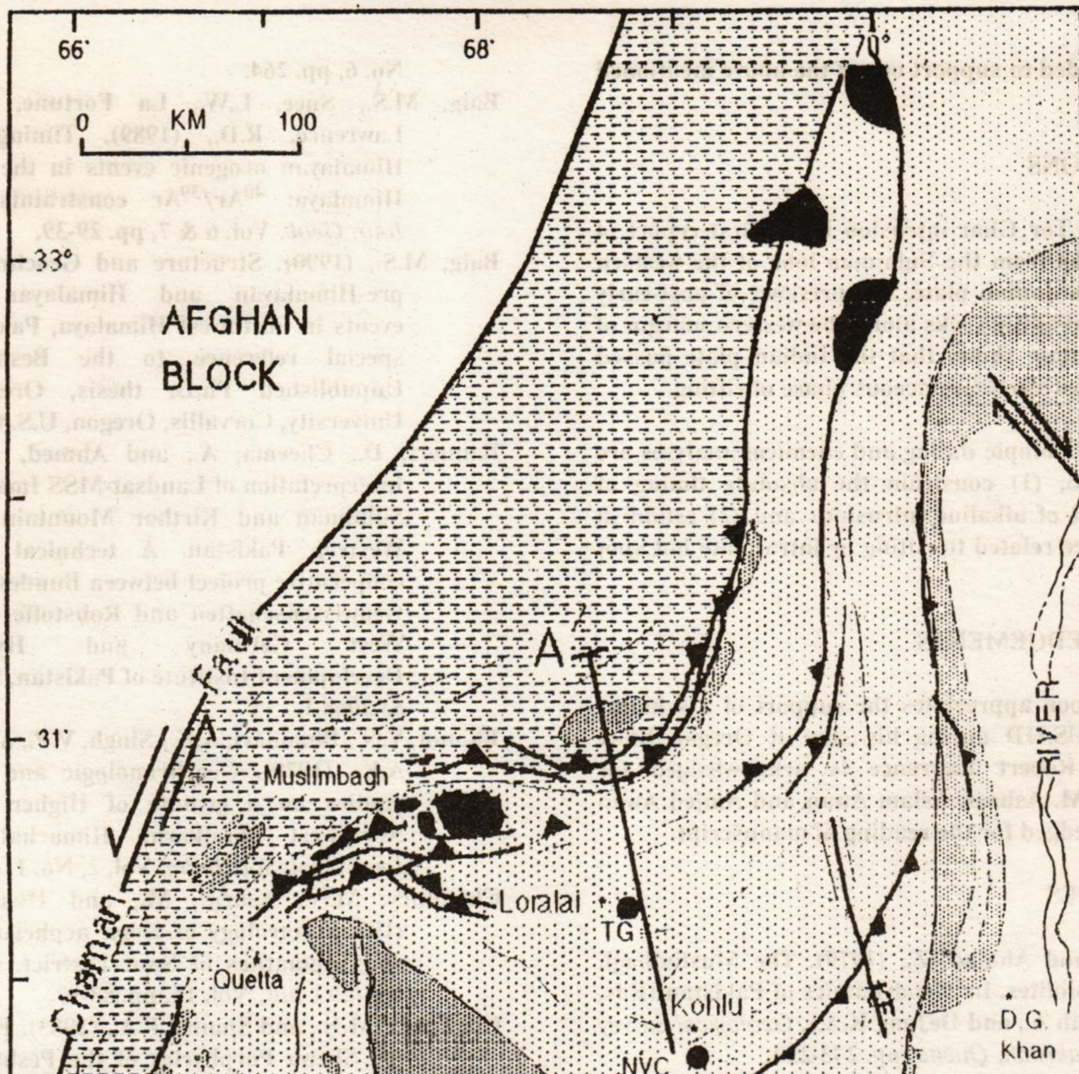

Figure-1. Simplified tectonic map of the Lobate Sulaiman fold-and-thrust system in Pakistan at the western margin of the Indian plate (modified after Kazmi and Rana, 1982). Dark circles (not to the scale) show the location of Tor Ghar (TG; alkaline intrusion) and Neogene volcano (NVC) of uncertain nature (Bannert *et al.*, 1989).

data are needed to support one of the above mentioned models.

CONCLUSIONS

The Tor Ghar intrusion is the first report of alkaline rocks from the Sulaiman lobe of the western margin of the Indian plate. The presence of post-early Cretaceous alkaline rocks along the western margin of the Indian plate shows that the Indian plate passed through a post-early Cretaceous phase of rifting.

The isotopic dating and chemical analyses are important to; (1) constrain the absolute timing of emplacement of alkaline intrusions and (2) establish that these are related to rifting or intra-plate hot spot activity.

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STRIKE-SLIP FAULTING ALONG THE WESTERN BOUNDARY OF INDIAN PLATE, IN PAKISTAN.

By

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ABSTRACT: In northern and western parts of Pakistan some strike-slip faults are considered lateral ramps of thrust sheets. However, in this area, a system of strike-slip Riedel R and R' shears is expected to develop due to a dominant component of simple shear along the western transform boundary of the Indian plate. The majority of strike-slip faults trend between N-S and NNW-SEE, close to the expected orientation of R shears. A few strike almost parallel to the expected orientation of R' shears. Faults close to R shears show sinistral and those to R' shears show dextral sense of displacement.

Both the orientation and sense of displacement suggest that the majority of these strike-slip faults are secondary Riedel shears, developed in response to plate scale sinistral simple shear, along the Chaman transform fault.

INTRODUCTION

The headon collision between Indian and Eurasian plates resulted in the uplift of the highest mountains of the world, the Himalayas, which run through northern India and Pakistan. The western boundary of the Indian plate running through western Pakistan and eastern Afghanistan is generally considered to be a transform boundary marked by major strike-slip faults (Lawrence and Yeats, 1979; Lawrence *et al.*, 1981). The most famous of these strike-slip faults is the Chaman fault, first recognized by Griesbach in 1893. This fault connects the Himalayan collision zone to the north and the Makran convergence zone to the south (Farah *et al.*, 1984). Lawrence and Khan (1991) suggest a sinistral displacement 450 Ⅰ 10 km along the Chaman fault. Oblique convergence produced a system of strike-slip faults and thrusts along the western boundary of the Indian plate (Sarwar and DeJong, 1979; Lawrence *et al.*, 1981). Recently, several studies (Yeats and Lawrence, 1984; Coward and Bulter, 1985; Baig and Lawrence, 1987; Lillie *et al.*, 1987; Baig, 1990; Abbasi and McElroy, 1990; Jadoon *et al.*, 1991a, b) evaluated the thrusts systems of Pakistan. However, little work has been done on strike-slip faults.

This preliminary study is an attempt to evaluate the possible origin of the strike-slip fault system, in a transpression zone, along the western boundary of the Indian plate.

THE MAJOR STRIKE-SLIP FAULTS AND ASSOCIATED SECONDARY STRUCTURES

Laboratory studies (Cloos, 1928; Riedel, 1929; Tchalenko, 1970; Wilcox *et al.*, 1973) show that a wide range of secondary strike-slip shear zones could develop along a major strike-slip fault (Fig. la). The most important of these secondary shear zones are a conjugate set of Riedel shears, generally designated as R and R' shears (Ramsay and Huber, 1987). The en-echelon R shears generally develop first followed by R' shears and other structures (Sylvester, 1988). The R shear form at an angle of 15-20^{0} and R' shear at an angle of 60-75^{o} to the principal displacement zone (Tchalenko and Ambraseys, 1970). The sense of slip along the R shears is the same as that of the principal displacement zone, whereas that of the R' shears is opposite (Fig. 1a).

In field, conditions exactly similar to the laboratory experiments are rarely found. However, Keller *et al.* (1982), Erdlac and Anderson (1982) and Woodcock (1988) reported good field examples of Riedel shears associated with major strike-slip faults.

PATTERN OF STRIKE-SLIP FAULTING IN PAKISTAN

Along the western boundary of the Indian plate a large number of recognized active faults are

strike-slip faults (Kazmi, 1979). Strike-slip faults of many different orientations are present (Fig. 1b). A careful observation indicates that the orientation and sense of displacement of the majority of these strike-slip faults fairly corresponds to a system of Riedel shears developed after sinistral strike-slip along the Chaman fault. A very significant number of these faults strike between N-S and NNW-SSE close to the expected orientation of secondary R shears of the Chaman fault (Fig. 1b). The sense of displacement for these faults is generally sinistral.

The dextral South Bannu fault and the Kallar Kahar fault (Fig. 1b) trend parallel to the expected orientation of secondary R' shears of the Chaman fault. The less common occurrence of faults of this orientation correspond with the earlier field observations of Keller *et al.* (1982), who suggested that R' shears rarely develop in nature.

RIEDEL SHEAR/LATERAL RAMPS IN NORTHERN PAKISTAN

The simplified model in fig. la relates majority of strike slip faults along the western boundary of Indian plate to a secondary Riedel shears system. However, in northern Pakistan most of these faults are located in a zone of direct collision. This collision resulted in imbrication, stacking and southward translation of cover strata belonging to the Indian plate (Baig and Lawrence, 1987; Lillie *et al.*, 1987; Baig, 1990). Swat (Baig, 1989) and Salt Range/Potwar Plateau (Lillie *et al.*, 1987) are considered allochthonous southward verging thrust sheets bounded by N-S oriented lateral ramps (Fig. 1; Baig, 1990; Mac Dougal and Khan, 1990). These lateral ramps are Thakot and Shinkiari faults for Swat sheet, and Kalabagh and Jhelum faults for Salt Range Potwar sheet (Fig. 1a; Baig, 1990; Mac Dougal and Khan, 1990). All these faults are oriented N-S and could be related to R shears as discussed earlier. However, Thakot and Kalabagh faults with a dextral displacement in contrast to R shears favour their origin as lateral ramps to Swat (Baig, 1990) and Salt Range thrust sheets (Mac Dougal and Khan, 1990).

DISCUSSION

Close to the western boundary of the Indian plate, the mechanism of deformation should have strong component of simple shear due to plate scale sinistral strike-slip displacement along the Chaman fault zone. The orientation of strike-slip faults in Pakistan, east of the Chaman fault may be controlled by; a) the orientation of pre-existing basement fractures or weak zones (Swaminath *et al.*, 1964) and b) transpression along the Chaman fault (Sarwar and DeJong, 1979; Lawrence *et al.*, 1981). Presently, there is not much evidence for an array of pre-existing basement fractures, corresponding to the observed orientation of strike-slip faults. Alternatively, we propose that these strike-slip faults represent a set of Riedel shears related to a major sinistral simple shear along the western transform boundary of the Indian plate. This is based on a consistent relationship present between these secondary strike-slip faults and the major Chaman fault (Fig. 1b). For these secondary faults minor deviations from the orientation observed in laboratory experiments are possible due to local geological changes. Average trend of faults close to R shears is a few degrees anti-clockwise from that observed in experimental models. Such anti-clockwise rotation is expected because of continuous sinistral displacement along plate boundary rather than the nearly instantaneous development of R shears in laboratory. At present, mapping of these faults show little continuity up to the transform plate boundary. This may be due to the lack of detailed mapping in areas close to the Chaman fault or because of the fact that this system is still in its early stages of development. Other reason of this discontinuity may be local dominance of thrusting over strike-slip faulting due to transpression along this transform plate boundary.

CONCLUSIONS

Along the western boundary of the Indian plate, the majority of strike-slip faults trend between N-S and NNW-SSE with sinistral sense of displacement. They may correspond to the R shears of the Chaman fault. The NNW-ESE trending South Bannu fault and the Kallar Kahar fault may correspond to R' shears. This paper is first step to discuss the development of secondary strike-slip faults close to the western boundary of the Indian plate. Future work will address the interaction between the evolution of strike-slip and thrust faults.

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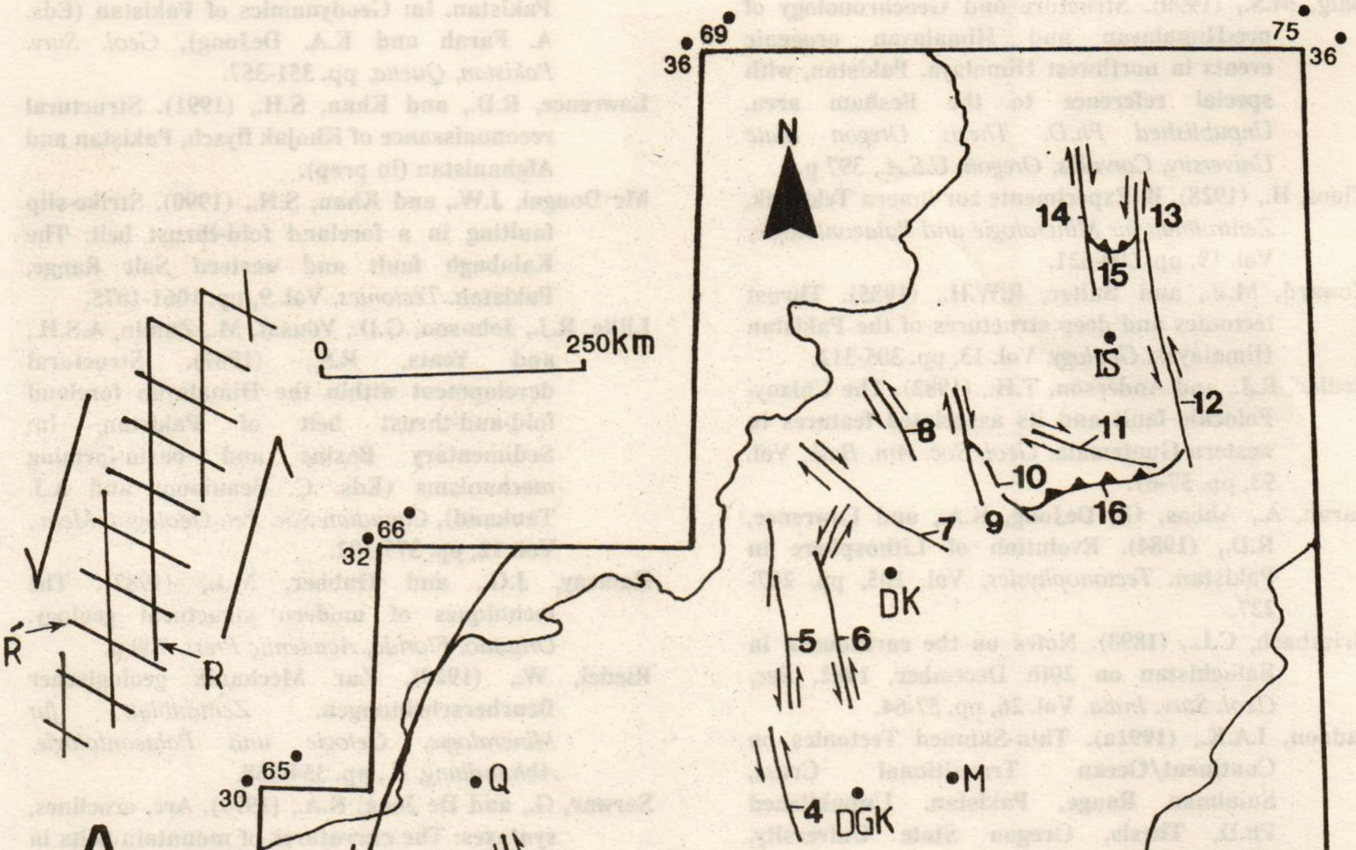

Figure- 1. a) Model orientation of Riedel shears associated with a major sinistral fault, compared with b) a system of strike-slip faults in Pakistan (modified after Kazami, 1979; Baig, 1989). Q = Quetta, DGK = Dera Ghazi Khan, DK = Dera Ismail Khan, M = Multan, IS = Islamabad. 1 = Chaman fault, 2 = Ornach Nal fault, 3 = Mach fault, 4 = Kingri fault, 5 & 6 = Sulaiman Range fault zone, 7 = the South Bannu fault, 8 = North Bannu fault, 9 & 10 = Kalabagh fault zone, 11 = Kallar Kahar fault, 12 = Jhelum fault, 13 = Shinkiari fault zone, 14 = Thakot fault, 15 = Ogli shear, 16 = Salt Range thrust.

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LANDSLIDE HAZARDS IN SOUTHERN MUZAFFARABAD AZAD KASHMIR AND SOUTHEASTERN HAZARA PAKISTAN

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ABSTRACT: The Jhelum River Valley in southeast of Hazara and southern part of Muzaffarabad are the areas of high landslide hazards. Steep slopes, silty, sandy and clayey soils, heavy rains, water seepages all contribute to the landsliding in the region. The instability of the area has been further increased by road widening and effect of the Main Boundary Thrust (MBT) resulting in the form of many major landslides, such as slumping, earthflows, rockfalls, sinkholes and combination of these.

The active Kohala and Rara landslides were investigated in detail because of their large size and proximity to roadways. Soil samples were collected to evaluate engineering properties of the materials involved in these failures. The investigated area lies in a structurally complex belt of folded and faulted sedimentary rocks which have been further deformed by the locally important Murree Thrust and regionally significant Main Boundary Thrust (MBT).

In addition landslide map of the area was prepared by performing field work and using areal photographs. All slope failures were classified according to their movement and state of activity, with variation and change of water content (6.7-45%), liquid limit (22.6-41.5), plastic limit (6-23.7), swellability (8.9-55), compressive strength (2-15MPa), shear strength (3-10 MPa) and pore water pressure (4-6MPa). The results suggest that slope failure occurs due to high swelling potential of soils, active faults and shear failures.

INTRODUCTION

Regional landslide studies of Azad Kashmir Area have not yet been conducted, but southern part of Muzaffarabad and southeastern part of Hazara have been identified as areas of high landslide incidence. The high events of landsliding are especially evident near Rara and Kohala (Fig. 1). The majority of landslides that occur in this area are concentrated within the Jhelum River Valley and can be classified as earthflows, slumps, rockfalls or combination of these three types. The Jhelum River and its tributaries have cut deeply into river deposits and bedrock giving rise steep sided ravines separated by high divides. The high concentration of steep sloped ravines and the fine grained nature of the slope deposits are the primary factors influencing landsliding in Rara and Kohala Areas. Landslides affect the area in two ways. First, they damage roadways situated in the foothills of valley slopes and near the tops of the hill slopes. Muzaffarabad-Kohala Road, Kohala-Murree Road and Muzaffarabad-Rawalakot Road (Fig. 1), are good examples of this type of damage. Second, slide material blocks roadways located at the base of the slopes. For example, in the southern part of the study area, the Rara slide buried Rara-Kohala Road with as much as 10m to 15m of slide debris. Similarly the Kohala slide buried the Kohala-Murree Road with about 25m to 50m of slide debris. The landslide also effect residential buildings occurring close to the valley

Fig-1 LOCALITY MAP OF THE AREA

slopes (Rara village,Bakot village, Kohala Bazar flour mill and food storage building). Most of the landslide hazards were found and investigated in Murree Formation in the Main Boundary Thrust zone. The zone mainly consist of reddish brown Murree clays, highly fractured Murree sandstones, silty and sandy clays and claystones. If landslide hazards are not adequately mapped and mitigated with increasing commercialization and urbanization, the problems of landslides will have great impact on economy. Thus the purpose of this study is to investigate selected grave landslides in Rara and Kohala and to map and classify the landslide area to examine the overall distruction of slides and to suggest remedial measures.

GEOLOGICAL SETTING

The sedimentary rocks in southern Muzaffarabad consists of argillaceous sandstones, silicified claystones, silty and sandy clays of Murree Formation (Miocene age). Hazara limestone, slates, gypsum and shales of Hazara formation and Hazara slates of Precambrian age (Wieczorek, 1984, Middlemiss, 1986, Wadia, 1928, Ali, 1954 and Wynne, 1879). The area was uplifted during the Miocene-Pliocene times. Erosion of the rocks reshaped the surface into steep hills and deep valleys. During Pleistocene, southern part was repeatedly filled with river deposits. As river deposits retreated, bed rock valleys were filled with different thicknesses of heterogeneous river sediments that currently mask much of the bed rock surface.

In southeastern Hazara, only Pleistocene river terraces can be identified. At least four readvances of river deposits are recorded in the terrace deposits of this area. Two deposits, which makeup the bulk of the Pleistocene material exposed along the valley tributaries, are the most susceptible to landsliding. They consist of red clays, silty clays of medium plasticity, silts, fine grained sands, well graded coarse grained sands, well graded coarse sands, claystone, pieces of sandstones, gravels and boulders of 1m to 1.8m in size. The stratigraphic succession of the area and surroundings is as under:

FORMATION	AGE
Alluvium	Recent
Alluvium & Colluvium	Pliestocene
Murree Formation	Miocene
Kuldana Formation	Early to Middle Eocene
Margalla Hill Limestone	Eocene
Patala Formation	Paleocene
---------Unconformity----marked by bauxite/laterite------	
Abbottabad Formation	Cambrian
Hazara formation	Precambrian

METHODOLOGY

Areal photographs (1:25000 and 1:10000) were used to identify and map landslides of the area under study. The topographic sheets Nos 43-F/7 were used in the field to plot the locations of slope movements. Slope movements were located by field investigations. The resulting investigated map showed numerous landslides within the study area, most of which had not been identifid in the previous years. Wieczorek (1984), methodology was applied to identify each landslide by its state of "activity" and "certainty of identification." The state of activity of each landslide is classified as either active or dormant. The dormant landslides have been identified in whole the northeastern Hazara and southern Muzaffarabad (a part of Hazara and Kashmir). Recently activated landslides were identified during road widening in recent years. The new exposures are located along Muzaffarabad-Kohala road particularly in Rara and Kohala where main scarps, distinct crowns, transverse and radial cracks, disruption of original material and mass movements are marked (Fig. 3). Landslides lacking these distinct features are designated as dormant. Some landslides considered as dormant have slow creep (Galian and Gharat). The evaluation and identification with certainty of the landslies were based on the interpretation of geomorphic features. The degree of identification depends on the phase of erosion and the degree to which the geomorphic features have been modified by erosion, revegetation and the processes associated with road construction and residential development. The relative certainty of dormant landslides identification is qualified as definite (100%), probable (75%) and questionable (50%), as suggested by Wieczorek (1984).

Two sites of major and active slope movements are studied in detail because of their large size and proximity to the roadways and residential buildings. These sites include slope failure near Rara

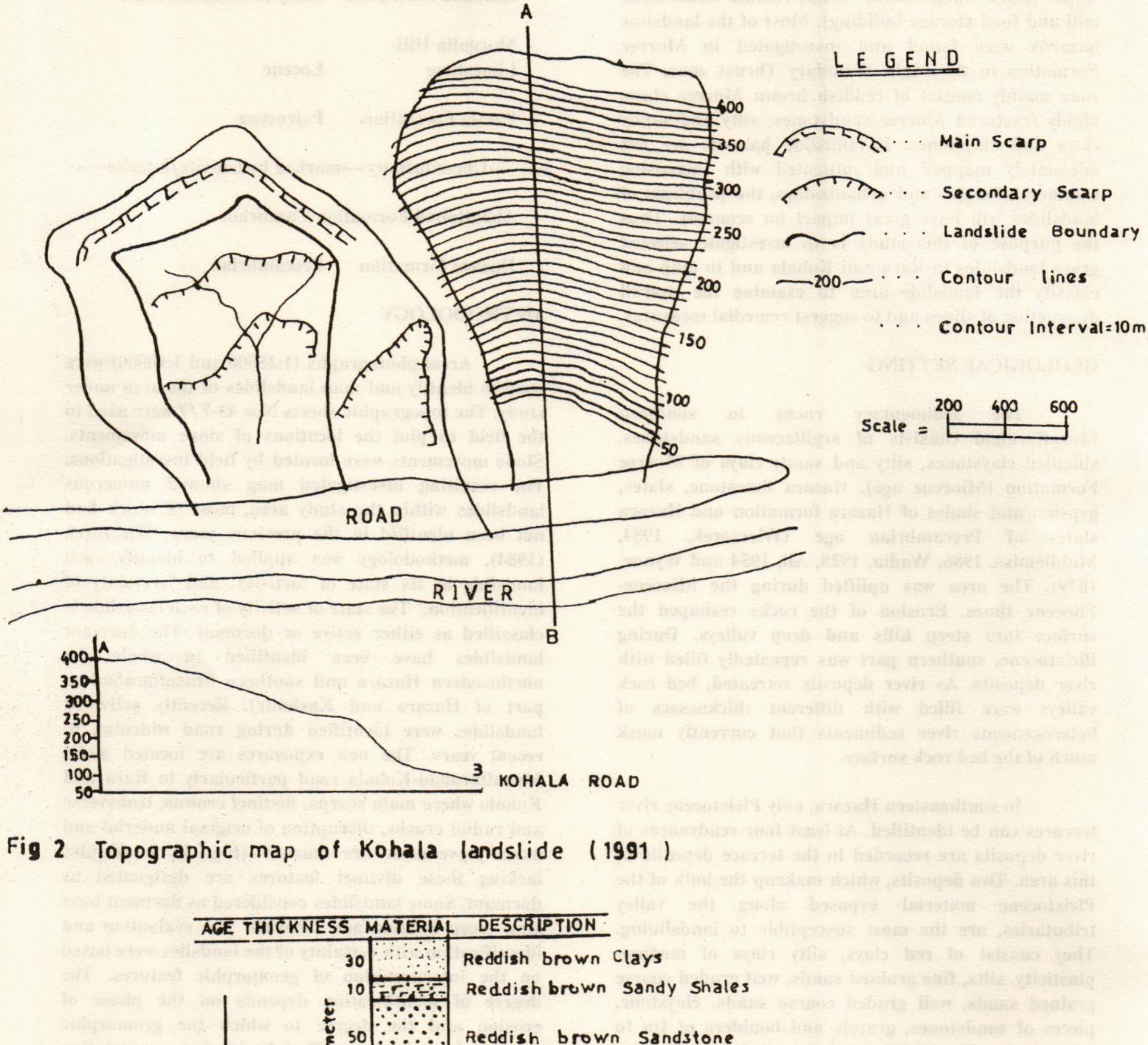

Fig 2 Topographic map of Kohala landslide (1991)

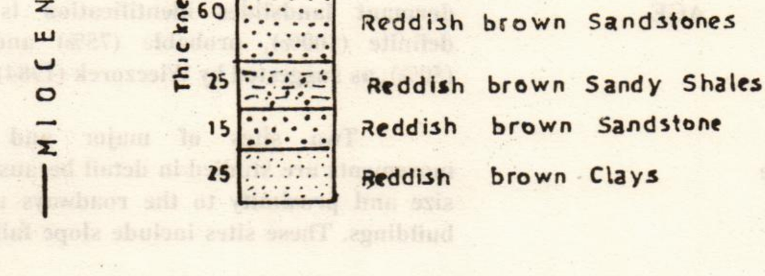

Fig 2 Generalized Stratigraphy of Murree Formation at Rara site (1991)

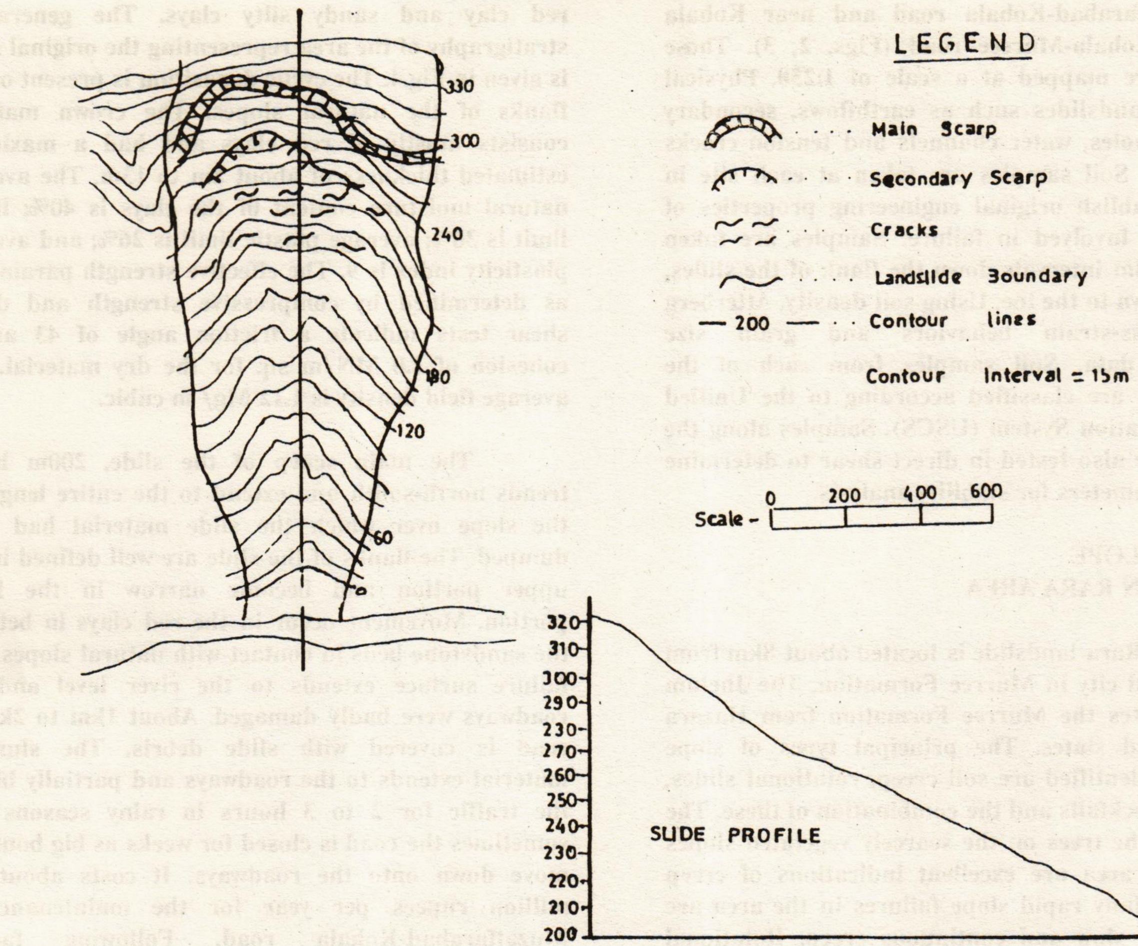

Fig 3 – Topographic map of Kohala Landslide (1991)

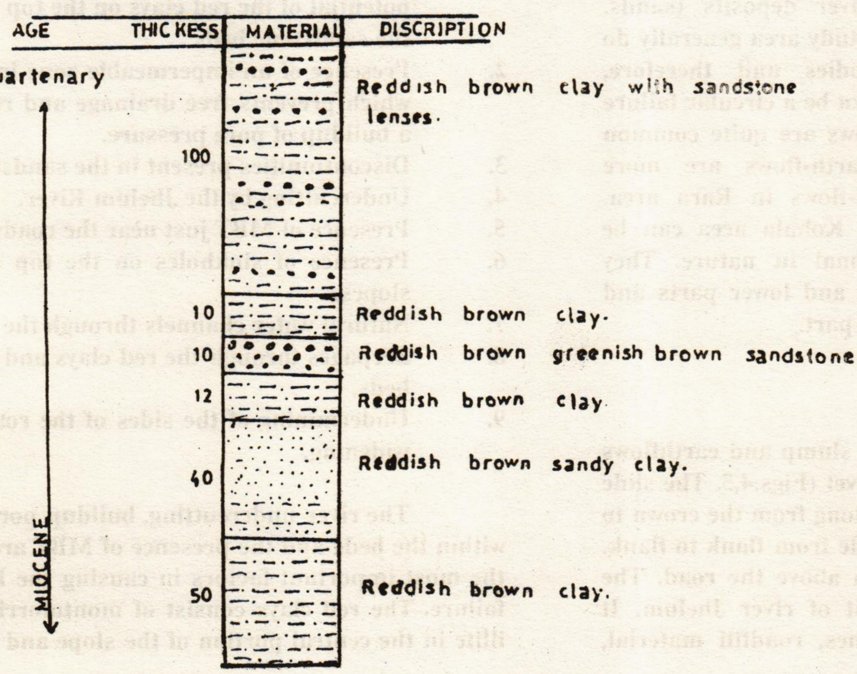

Fig-3 Generalized Stratigraphy of Murree Formation at Kohala site.

Area Muzaffarabad-Kohala road and near Kohala village on Kohala-Murree road (Figs. 2, 3). These landslides are mapped at a scale of 1:250. Physical features of landslides such as earthflows, secondary scarps, sinkholes, water channels and tension cracks are mapped. Soil samples are taken at each site in order to establish original engineering properties of the material involved in failure. Samples are taken from 3m to 4m intervals down the flank of the slides, from the crown to the toe. Using soil density, Atterberg limits, stress-strain behaviors and grain size distribution data. Soil samples from each of the selected sites are classified according to the Unified Soil Classification System (USCS). Samples along the road side are also tested in direct shear to determine strength parameters for stability analysis.

TYPES OF SLOPE FAILURES IN RARA AREA

The Rara landslide is located about 8km from Muzaffarabad city in Murree Formation. The Jhelum River separates the Murree Formation from Hazara limestone and slates. The principal types of slope movements identified are soil creep, rotational slides, earthflows, rockfalls and the combination of these. The direction of the trees on the scarcely vegetated slopes of the Rara area are excellent indications of creep movement. Many rapid slope failures in the area are preceeded by slow and continuous creep. Rotational slides, or slumps, makeup a large portion of the slope movements in Kohala area.Slumps generally, occur most frequently in fine grained and homogeneous clayey soils.The interbedded river deposits (sands, silts, clays and pebbles) in the study area generally do not act as homogeneous bodies and therefore, character of the movement cannot be a circular failure surface. Earthflows and mudflows are quite common during rainy season. The earth-flows are more frequent in Kohala than mud-flows in Rara area. Finally many slope failures in Kohala area can be classified as complex transitional in nature. They consist of slumps in the upper and lower parts and become earthflows in the middle part.

THE RARA LANDSLIDE

The Rara landslide is a slump and earthflows about 50m to 60m above river level (Figs.4,5. The slide is approximately 200m to 300m long from the crown to the toe of the slope and 60m wide from flank to flank. The crown of the slide is 500m above the road. The failure is situated on southeast of river Jhelum. It occurred in fractured sandstones, roadfill material, red clay and sandy silty clays. The generalized stratigraphy of the area representing the original slope is given in Fig.4. The cyclic deposition is present on the flanks of the natural slopes. The crown material consists mostly of red clays and had a maximum estimated thickness of about 8m to 13m. The average natural moisture content 0f the clays is 40%; liquid limit is 36%; average plastic limit is 26%; and average plasticity index is 9. The effective strength parameters as determined by compressive strength and direct shear tests indicate a friction angle of 43 and a cohesion of 2.0 MN/m sq. for the dry material. The average field density is 1.12 Mg/ m cubic.

The main scarp of the slide, 200m hight, trends north-south and extend to the entire length of the slope over which the slide material had been dumped. The flanks of the slide are well defined in the upper portion and become narrow in the lower portion. Movement occur in the red clays in between the sandstone beds in contact with natural slopes. The failure surface extends to the river level and the roadways were badly damaged. About 1km to 2km of road is covered with slide debris. The slumped material extends to the roadways and partially blocks the traffic for 2 to 3 hours in rainy seasons and sometimes the road is closed for weeks as big boulders move down onto the roadways. It costs about 140 million rupees per year for the maintenance of Muzaffarabad-Kohala road. Following factors probably are responsible for failure of the Rara slope:

1. The high absorption of water and swelling potential of the red clays on the top and under the sandstone beds.
2. Presence of an impermeable zone in the clays, which prevents free drainage and results into a buildup of pore pressure.
3. Discontinuities present in the sandstone beds.
4. Undercutting by the Jhelum River.
5. Presence of MBT just near the roadways.
6. Presence of sinkholes on the top of the hill slopes.
7. Natural water channels through the red clays.
8. Seepages through the red clays and sandstone beds.
9. Undermining of the sides of the roadways for widening.

The river undercutting, buildup pore pressure within the beds and the presence of MBT are probably the most important factors in causing the Rara slope failure. The red clays consist of montmorrilonite and illite in the central portion of the slope and on the top of the slope. A secondary clayey bed depositd across the sandstone bed in the central portion of the slide, forms a relatively impermeable zone. During the last three months the slope failed for about 12 to 20m depth due to high water pressure particularly in secondary clay bed zone. The trapped water behind the impermeable primary barrier, saturated the clayey material and significantly reduced its shear resistance.

The stability of Rara slide was analyzed quantitatively using the method of slices (Figs. 5, 6). The Fig. 5 shows steps of the slopes before failure and the location of the probable failure surface. The safety factor for the dry condition was calculated to be 1.89 and for the saturated condition was about 1.0. These analyses supports the role of the pore pressure in causing this failure and suggests that the water table was close to the ground surface at the time of failure.

KOHALA LANDSLIDE

The Kohala landslide is located southeast of Hazara just south of Kohala village along Murree-Kohala roadways (Fig. 3). The failure occurs on a south-east facing slope with crown near village Bakot and toe touching Jhelum River bed (Figs. 4, 5). This slide is 900m wide and 1000m long from the crown to the toe. The slope angle is 45 to 55. The landslide is entirely located within the sandstone and red clays. It is a combination of slump and earthflows. It moves conti-nuously at a slow rate in dry seasons 10 to 20m per year and 100 to 300m in rainy season particularly in July and August. At its crown small tributaries run down the slope.It is indicated by repeated cracking and subsidence of the road down to the toe. The stratigraphy of this site is shown in Fig. 6. Along the base of the slope 5m red clays; 100m red cyclic beds of sandstones, shales and claystones are exposed. The sandstone and clays alternate material over the length of the slope by a homogeneous red and yellowish brown shales and clays. The average water content of the material involved in failure in rainy season is 41%; the average liquid limit is 34%; the average plastic limit is 23%; and the average plasticity index is 13 (Table-1). The main scarp of this slope fails and over topple the Kohala-Murree roadways. The material extends along the road for a length of about 1500m. The section of the road within the scarp area has subsided about 35m during six months of early 1991. Five such secondary scarps have been identified along the slide. These scarps are modified by erosion between wet and dry seasons. Water channels have been formed at many places. At places trees in the slide area tilt downward showing slow and continual movement of the slided material.

Failure of this slope can be attributed to three main factors. The first factor is the general steepning of the slope by the undercutting of the Jhelum River. The second factor is the increased load at the top of the slope, which is developed due to failure of rock stuff caused by rainwater. The continuous downward movement of the failed material on steep slope cause cracks in the bedrock. The cracks thus developed form sinkholes throughout across the profile of this slide and therefore, these sinkholes cause a catastrophy. A third factor that contribute to slide movement is the activity of MBT passing near the toe of slided area.Slumping of the lower part of the slope destabilized the upper part of the slope where secondary scarps begin to form (Fig. 3). The upper part of the slide moves as a complex slump-earth-flows. The road subsides about 35m (recorded in 1990-1991) every year which indicates a high rate of movement.

Small landslides were also located along the road on the right and left bank of the Jhelum River. In particular area near Kohala flour mill was investigated.Slope failure occurs in alternating beds of clays and sandstones. The average natural water content of the material involved in slope failure is 30%, the average liquid limit is 36%, the average plastic limit is 23% and the average plasticity index is 15. The slope angle at this site is 75. The steep slope angle and the fine grained sediments contribute to landsliding. The most important factors contributing to these landslides are due to gully development by the removal of clay and mudstone beds of the steeply dipping Murree Formation which is aggravated by the undercutting of the Jhelum River.

DISCUSSION

The Rara and Kohala landslides are of the type of slope movement in the area (Figs. 2, 3). The factors that contribute to these slope movements and natural hazards have been discussed.The hazards to transportation routes are of particular importance,because previous slope movements in the area disrupted the construction works which costs about 14 million rupees every year on repairing (Muzaffaranad-Kohala and Kohala-Murree roadways). The continuous movement of the material delayed the repairing and widening of the highway and damaged the constructions. The geologic conditions of the area, MBT and undercutting by the river are the factors in landslide promotion.The landslide activity in

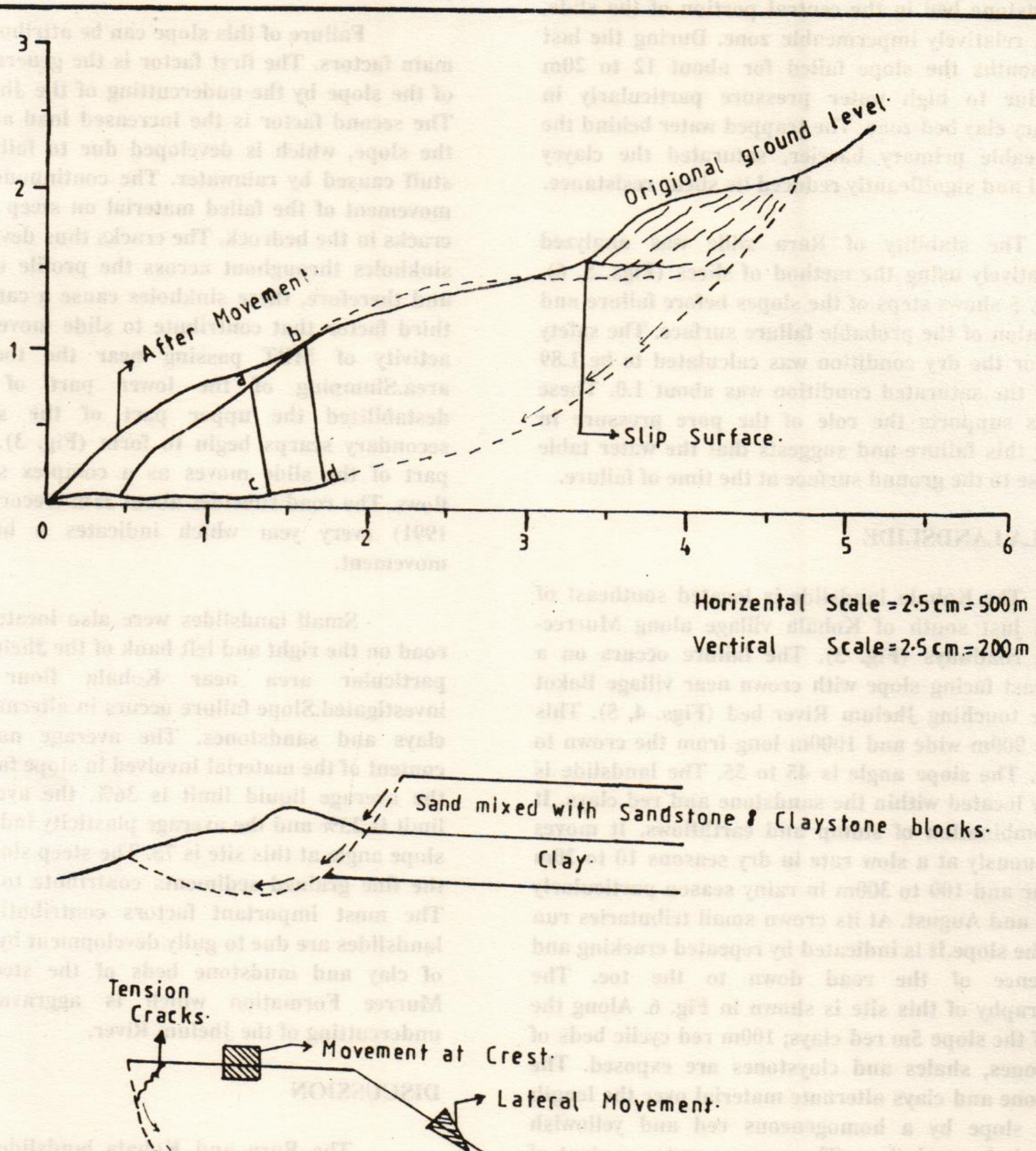

Fig-4 Slip Surface of the Kohala Landslide.

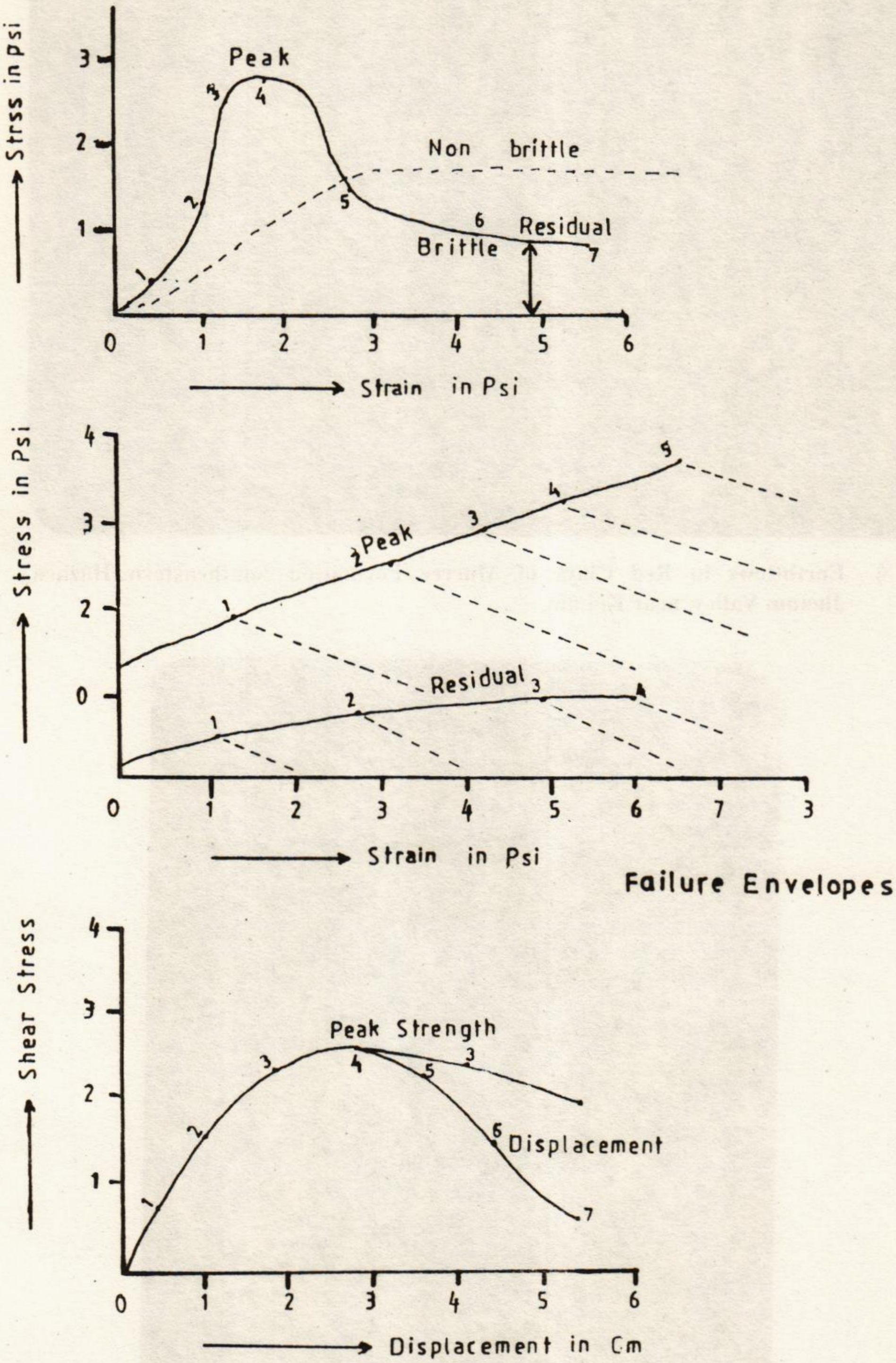

Fig. 5 Effect of Stress on soils and Strain conditions.

Fig. 6 Earthflows in Red Clays of Murree Formation Southeastern Hazara, Jhelum Valley, near Kohala.

Fig. 7 Sinkholes in Murree Red Clays, and Weathering Pattern.

this area primarily relates to two main factors. 1) The fine grained nature of the soils, great thickness of alternate beds of clays and sandstones of Murree Formation deposited during the Miocene times. 2) The steep valley slopes, which have been cut by Jhelum River and destabilized the slopes. 3) the Main Boundary Thrust passing through the valley also destabilize the slope material. 4) seepage through the soils and widening of the roads.

The destabilization of the southwestern and southeastern sides of Muzaffarabad-Kohala and Kohala-Murree roadways are due to river cutting, which allows for the development of more long and deep ravines on both sides. This in turn, results in a much higher concentration of slope movements on the eastern and western sides of Jhelum River. Further the regional fault that crosses the landslides at its lower level may also contributed in promoting the slides and perpetuating and enlarging it, but the relationship is not very clear (Fig. 7). The unusual heavy rains (256 mm in July and 288 mm in August,source Metrological Department Muzaffarabad), get loaded the loose material on the slopes and the whole mass becomes more heavy than, what the present slope can contain. This is an important element in the formation of the tensile cracks (sinkholes) at the crest, which merely open the width and help in the progress of failure in vertical and lateral directions (Figs. 2, 3). The effective stress on the clay and sandstone beds and the fluid filling the pores affect the particle to particle contact forces. It was evident that the introduction of fluid pressure acting in the pores does have the effect of reducing grain to grain contact loads. Hence, frictional resistance to movement depends on the pore fluid pressure. This difference effects the generation of shear resistance and mass movement in the study area.

The dormant landslides have been found all over the study area and good examples are the slopes of Chile area in Jhelum River valley and Maisina Kalan in southeastern Hazara, where these landslides have been modified and stabilized. This is probably due to fine grained clayey matrix acting as a cement for the boulders and cobbles into a bulk mass which is further stabilized by vegetation.Such dormant slides become active whenever, undercutting of the slopes are done for road widening.

The Main Boundary Thrust (MBT) play very active role in the promotion of landslides in the area. Very high seismicity (about 5.5, Tarbela observatory 1990) also destabilizes the high angle slopes (45 to 75). On the other hand, red clays on the slopes in rainy season swell to about 55% and moves downslopes into the roadways. The good examples are the slopes of Jhelum valley and western slopes of Kohala Murree highway. All the landslides have been investigated in thick beds of Murree Formation. Thinning of the clay beds decrease the landsliding in the area.

The high water content (about 45%) in the pore spaces of the soils during the rainy seasons increase the volume of the sediments to about 70% and it decreases to 40% in dry season. This continuous volume changes also destabilizes the high angle slopes in the region. Solutioning effects decrease the shear strength of the material on the slopes. The liquid limit (22% to 42%) indicates that the water absorption is higher in the clayey soils as compared to the sandy soils. The swelling potential (8 to 55) further supports this investigation.

A combination surface and subsurface drainage channels, mass grading, buttress type retaining structures and long root trees would be the most effective remedial measures to reduce the potential of further slope movement in the southern part of Muzaffarabad and Hazara area. The construction of a series of wide benches with drainage channels outward would be suitable. Both the benches and the channels should have distinct slopes towards the two lateral ends of the landslides. The benches and the intervening beds should be covered with the seeds of quick growing trees. The filling of the sinkholes of the slides on the crown and removal of the loose material from the slope would be very effective remedial measures.

CONCLUSIONS

Alternate clay and sandstone beds in Murree Formation, steep slopes flanking stream valleys, undercutting of the slopes by Jhelum River, water drainage through the steep slopes and seepages, and Main Boundary Thrust appear to be the main factors contributing to slope instability.

Many of the slope failures along the roadways resulted from the alteration of these slopes during widening of roadways and the seepages during rainy season.

Soil creep and earth flows or the commbination of these are the most common forms of slope failure in southern part of Muzaffarabad and a part of Hazara area. The slope movements pose a serious hazard to Muzaffarabad-Kohala road and Kohala-Murree road and some residential places in the study area.

ACKNOLEDGEMENT

The authors are thankful to M. Ashraf Professor and Director Institute of Geology, Universaity of Azad Jammu and Kashmir, for critical review of this manuscript.

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Table-1 Average Natural water content, Liquid limit, Plastic limit, Swellability, Compressive strength, Shear strength and Porewater pressure.

Area	N.W.C %	L.L %	P.L %	S.P %	C.S %	S.S. PSI	P.P PSI
Rara landslide	40	36	26	50	10	12	15
Kohala landslide	41	34	23	55	15	13	15
Flour mill	30	36	23	56	10	12	13

Abbreviations NWC = Natural water content, L. L Liquid limit, P.L. = Plastic limit, S. P = Swell potential, C. S = Compressive strength, S. S = Shear strength, P. P = Porewater pressure.

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GEOLOGICAL SETTING AND LANDSLIDE HAZARDS AT KALABUN AND RIALA SOUTH-EAST HAZARA, NWFP.

By

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ABSTRACT: Location of Kalabun and Riala in the vicinity of regional thrusts; presence of extensive faulting and folding; very high relief; denudation of softer shales at the toe of high ridge by local streams and chemical and mechanical action together seem to be responsible for sliding in the area.

INTRODUCTION

Landslides were reported in 1987 to have affected the villages of Kalabun and Riala 1½ kilometres apart, situated 4 kilometres east-southeast of Khanspur bounded by co-ordinates 73° 25" E, 34°00 45" N and 73" 27' 45" E, 34° 01" N respectively (Fig. 1). A reconnaissance of the area was arranged in 1987 to investigate the landslide problems in the area. Most of the houses in the two areas were either destroyed completely or abandoned. Keeping in view the complex nature of the geology, the area was mapped geologically on a scale of 1:12000 in 1988, to provide a base for further detailed studies.

STRATIGRAPHIC SETTING

The following sequence was recorded in the area (Latif, 1970), with lithological details as found locally.

Formatoin	Lithology	Age
Murree Formation	Clay, sandstone, subordinate conglomerate and siltstone.	Early Miocene
Kuldana Formation	Shale, marl, sandstone, gypsum, gypsiferous clays & limestone lenticles.	Early Middle Eocene
Chorgali Formation	Interbedded limestone, shale and marl.	Early Eocene
Margala Hill Limestone	Nodular to thick-bedded limestone.	-do-
Patala Formation	Shales with subordinate marl and limestone.	Paleocene
Lockhart Limestone	Limestone with subordinate shale.	-do-
Hangu Formation	Laterite, carbonaceous shale and clay.	-do-
Kawagarh Formation	Marl and marly limestone.	Late Cretaceous
Lumshiwal Formation	Glauconitic, ferruginous sandstone with silty shale at the base.	-do-

Chichali Formation	Sandy and silty shales.	-do-
Samana Suk Formation	Oolitic, dolomitic and arenaceous limestone.	Early Jurassic

STRUCTURAL SETTING

Kalabun and Riala Villages are situated in an intensely thrusted, faulted folded region of Hazara (Fig. 1). Murree Thrust culminating at the Jhelum Fault, a major event in the geology of the Himalayas, pass through Kanher Kas and the Jhelum River in the southern parts of the area. (Fig. 1). It is situated at the foot of the steeply inclined Khanspur Ridge populated towards the lower reaches by the villages of the Kalabun and Riala.

Another thrust located and named after Changla Gali, situated about 5 kilometres west-northwest of Kalabun, extends to this area and passes right through the northern reaches of the Kalabun and Riala villages (Fig. 1). The thrust brings the Samana Suk Formation, Jurassic, in contact with the Patala Formation, Upper Paleocene. As a result of this thrust, the older set of sequence in the northern block of Khanspur overides the younger set of southern block of Kalabun and Riala.

The other is the active fault (Kazmi 1979, Fig. 2) that passes directly through the Kalabun village and extends northeast towards north of Riala village. The faults constitute a jigsaw puzzle and more active faults are expected in the area.

Two cross-sections A-A and B-B (Fig. 2). have been drawn to elaborate the structure of the area, which indicate the presence of Changla Gali Thrust in the upper reaches of the Khanspur slope. The other important faults (F6 to f*) are present at the base of this ridge across Darwaza Kas in the south of Kalabun and towards the ridge in the south of Riala. Kalabun village itself is situated on 3 faults (F3 to F5) (Fig. 3) with F3 being an active fault (Kazmi 1979). The same set of faults surround the Riala village, F3 on the northern side and F4 and F5 on the southern side (Fig. 1 + 2). The rocks are folded as well into synclines and anticlines (Fig. 2). It seems that synclines are relatively stable as compared to anticlines that are generally cut by the faults.

DISCUSSION

The location of the area in a tectonically active region of the Himalayas with complex structural settings, high relief, youthful streams, high rainfall and the nature of the sediments have jointly contributed in the same order, apparently towards the occurrences of landslides at Kalabun and Riala.

It is difficult to evaluate the tectonics of a small area like this, as tectonics deal with large scale structures. It can however be deduced from unstable nature of the area and due to the presence of several thrusts, that tectonics play an important role in landslides.

The affected villages are situated close to the Murree Thrust (MBT) which passes through the Kanher Kas. Many imbricated faults pass through the affected areas as shown in Fig. 1. it may be safely assumed that these faults are the off shoots of the main thrust. In this imbricated zone Changla Gali Thrust (Fig. 1) and Active Faults (after Kazmi *et al.* 1979) (Fig. 1, F-3) are most important. The active fault F-3) (safely assumed) is responsible for sliding of village Kalabun where this fault has produced cracks in the alluvial terraces. So we can say that the slide at Kalabun is actually situated at the active fault plane. Whenever any earthquake of small or medium magnitude hits the area this faults (F-3) may become active and may cause the damage in the form of sliding as also noticed in a recent earthquake.

Landslides normally occur when the driving forces are greater than the shear strength of the materials (Judd). The shear strength of the materials may decrease by excessive water contents, (the Murree, Khanspur and Nathiagali being areas of maximum rainfall in Pakistan). Slides normally occur during rain or shortly after rain like, for instance on roadside between Murree and Kohala. In this case, the slides are reported to occur during the dry season, as per local information. This could be due to chemical changes in the materials of rocks. The shales and clays of Chichali, Patala and Chorgali formation are present at the base of the two villages. During rainy season, the shale formations absorb water, may swell or expand, expanding, the fissures and cracks accordingly. shales may contract, and dehydrate, during the dry season. Alternate expansion and contraction for longer periods coupled with other chemical changes in the

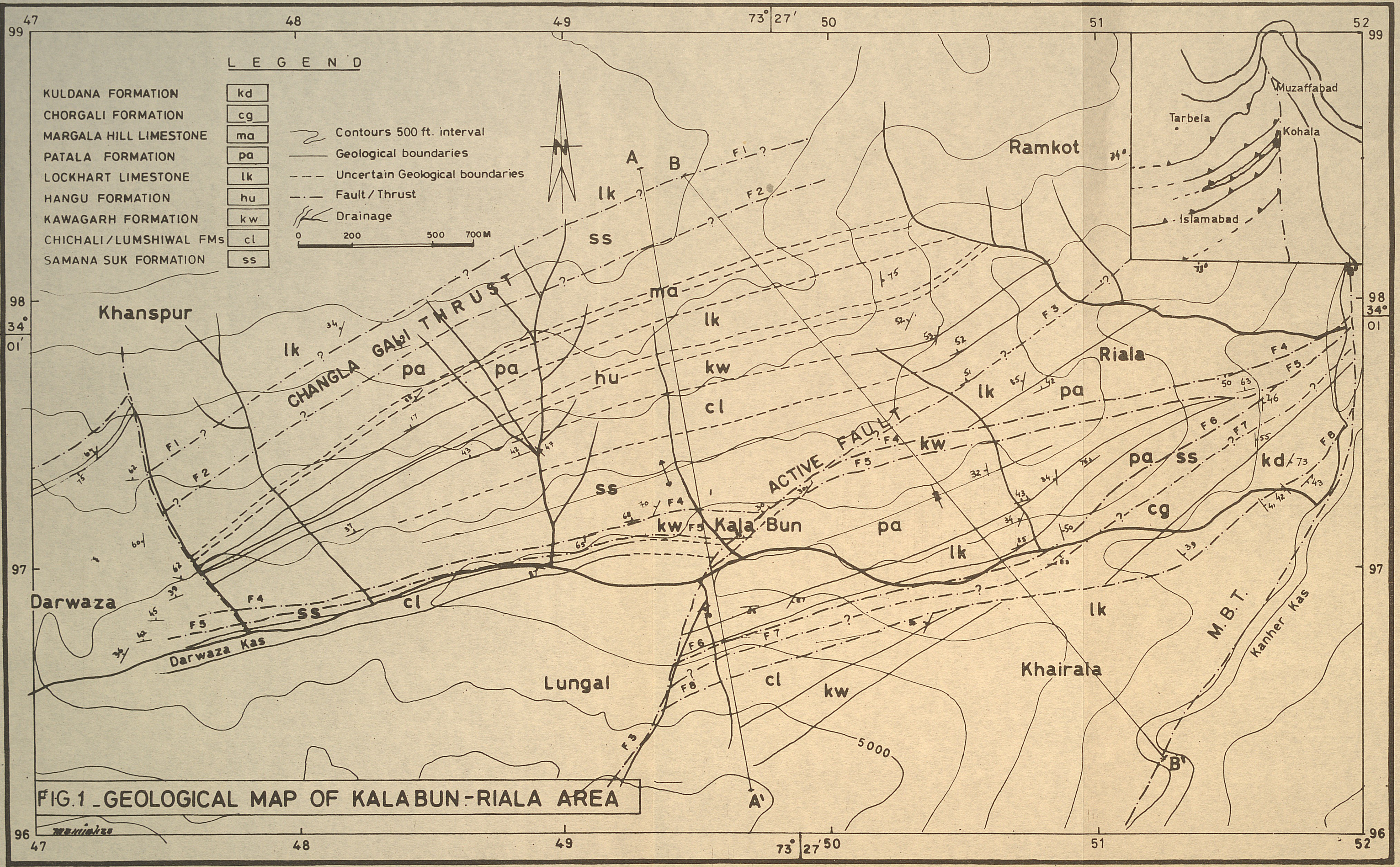

FIG.1 _ GEOLOGICAL MAP OF KALABUN - RIALA AREA

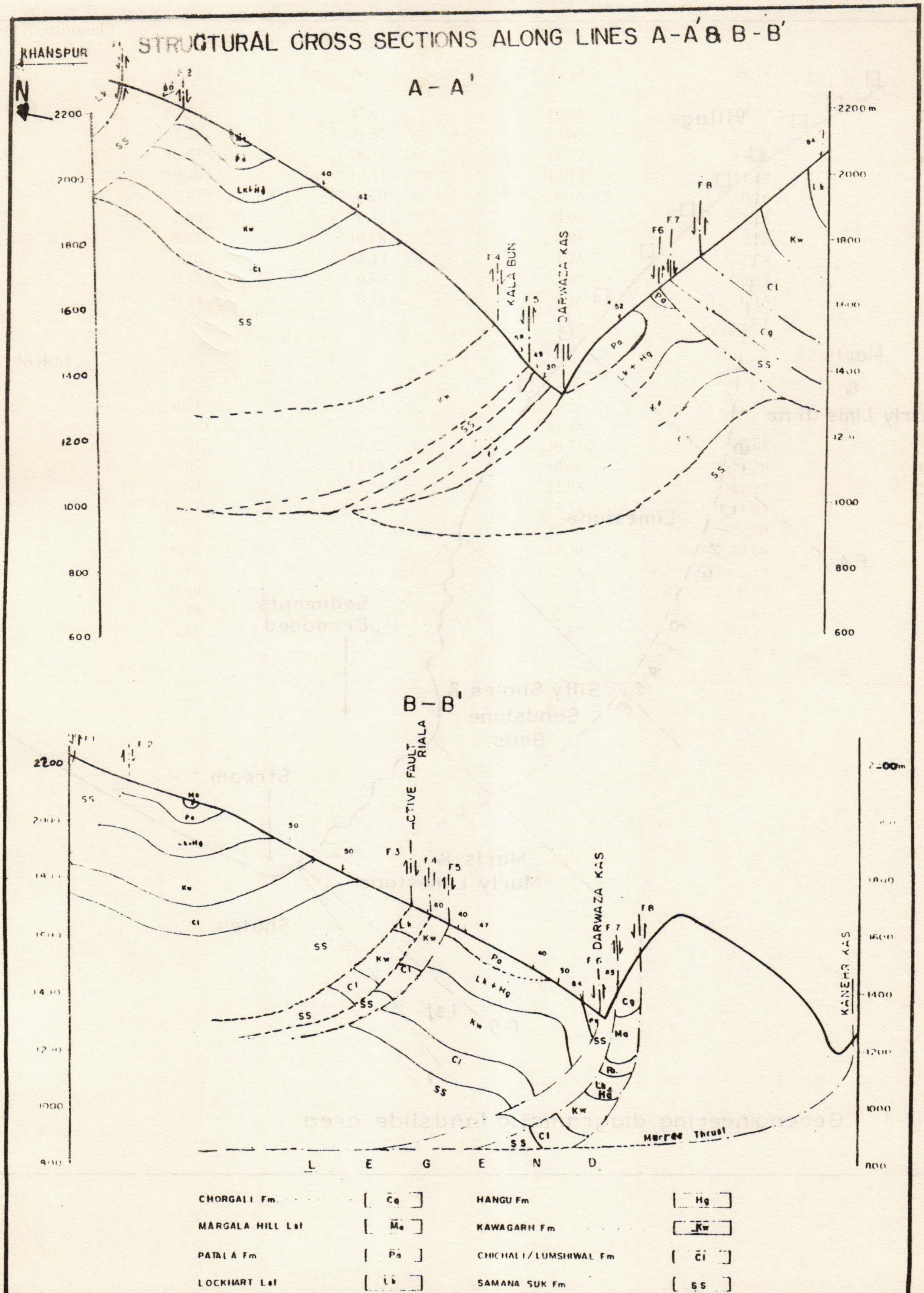
STRUCTURAL CROSS SECTIONS ALONG LINES A-A' & B-B'
KHANSPUR
N
A - A'
KALA BUN
DARWAZA KAS
F 2
F 4
F 5
F 6
F 7
F 8
SS
Pa
Lk+Hg
Kw
Ci
Cg
Lk
2200 m
2000
1800
1600
1400
1200
1000
800
600
B - B'
ACTIVE FAULT
RIALA
DARWAZA KAS
KANEHR KAS
Murree Thrust
F 3
Ma
Pa
Lk+Hg
Kw
Ci
SS
Cg
L E G E N D
CHORGALI Fm. [Cg]
MARGALA HILL Lst [Ma]
PATALA Fm [Pa]
LOCKHART Lst [Lk]
HANGU Fm [Hg]
KAWAGARH Fm [Kw]
CHICHALI / LUMSHIWAL Fm [Ci]
SAMANA SUK Fm [SS]

FIG. 2

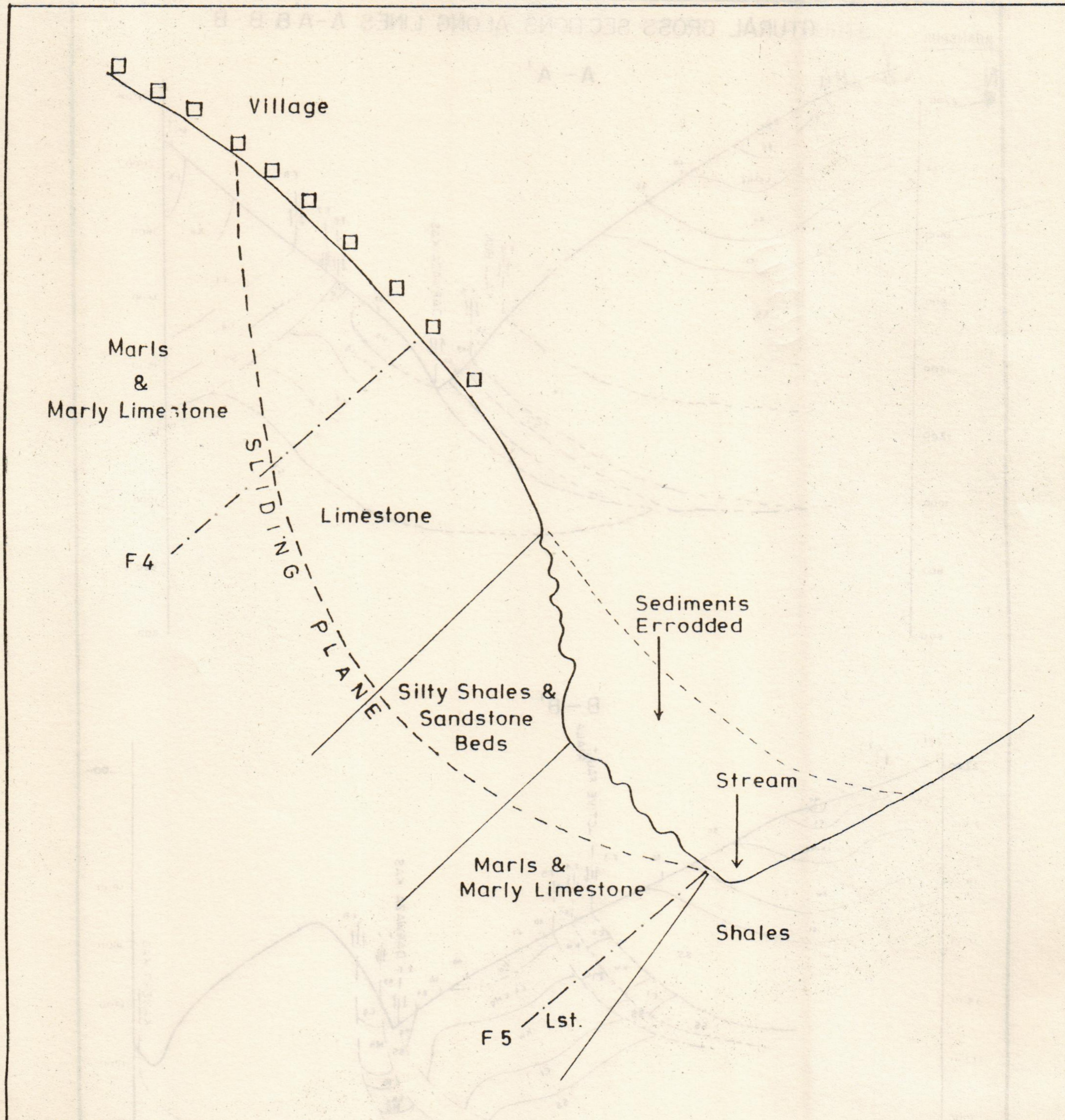

Fig 3 _ Geoengineering, diagramatic, landslide area rocks may provide a weak zone for slides.

Another important factor responsible for sliding is the gravity force. Generally erosion, removes the lateral support, at the toe of the slope in particular and causes the slides (Fig. 3)

The strike (Fig 2) of the rocks is nearly parallel to Darwaza Kas (stream), particularly, near Darwaza village, The Darwaza Kas, stream, is continuously eroding the toe of the slope, below the village of Kalabun (fig. 2).

Further downstream at the confluence of Darwaza Kas and Kanher Kas near the village Riala the rate of erosion is more significant.

The toe of the slope of Khanspur Ridge at Riala is being eroded jointly by Darwaza Kas and the Kanher Kas (Fig 1 & 2) thus providing base for gravity sliding as evidenced by slides at Riala.

CONCLUSIONS

Keeping in view the above mentioned tectonics we can safely conclude that tectonics play a dominant role in the occurrence of slides in the area followed by high relief and nature of sediments. The whole region is unsafe for settlements as more areas may be affected by the slides in the near future.

ACKNOWLEDGEMENTS:

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EVALUATION OF CRETACEOUS TO MIOCENE SANDSTONES OF SIND AS GEOMATERIAL

By

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ABSTRACT: The geotechnical, petrographical and lithologic characteristics and dynamic and static test results are presented for four sandstone types. Comparison is made between a number of static properties of the sandstones and their geotechnical performance, particularly giving different geotechnical properties with changing chemical contituents and mineralogical composition.

The sandstone samples have been collected from Pab Range, (Pab sandstone, Cretaceous), Manghopir, (Nari Sandstone, Oligocene), Gaj Sandstone (Miocene), and Surjan Range Manchar Sandstone (Middle Miocene-Pliocene).

The test results of six parameters of the four sandstone types vary differently. The soundness varies from 0.21% to 14.32%, porosity range from 18% to 23%, specific gravity is 2.5 to 2.7, compressive strength varies from 38 MPa to 270 MPa, Aggregate Impact Value range from 6.1% to 43.2% and Aggregate crushing Value range from 5.3% to 43.5%.

The test results suggests that Pab Sandstone and Gaj Sandstone are suitable for construction as building stones, rip-rap, aggregate subbase and concrete. The Nari Sandstone is medium hard and is useful for gravestones. The Manchar Sandstone is brittle and is not suitable for main construction purposes.

INTRODUCTION

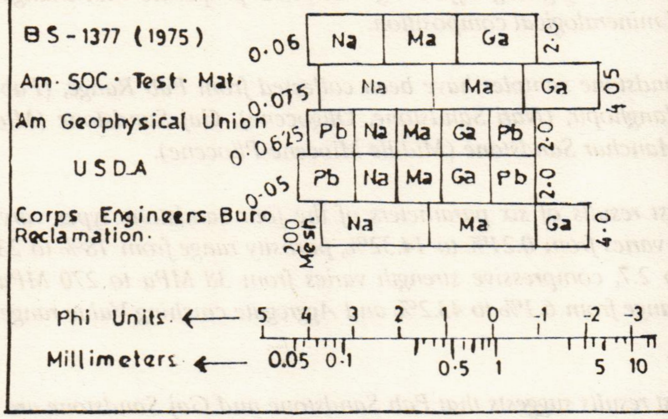
The sandstones in Sind region form an estimated 10% of the surface outcrops in Pab Range, Orangi Hills, and Surjan Range. The majority of these arenaceous rocks are contained within four main stratigraphic units: Green sandstone (Cretaceous), Ranikot Sandstone (Paleocene), Nari Sandstone (Oligocene), Gaj Sandstone (Miocene) and Manchar Sandstone (Middle Miocene-Pliocene).

The four sandstone types vary considerably in their grain size, texture and mineralogy. This variation suggests a division of sandstones into 1) arenites and 2) wackes based on the percentage of matrix material present. Wackes containing more than 16% matrix material which is of less than 0.04mm diameter. The grain size boundaries were proposed by Pettijohn, Potter and Siever, 1987. It is modified in the present study (Fig. 1). The grain boundaries change the primary sedimentary fabric, diagenesis and stress due to regional metamorphism and weathering which influence the strength and deformability of the sandstone to be used as geomaterial.

This paper describes the geotechnical properties of four sandstones with respect to their use as construction raw material, such as building stones, aggregate subbase and concrete. All the possible problems are given due consideration during evaluation of sandstone as geomaterial.

BASIS OF SELECTION

The four sandstones were selected for this paper because these rocks are mainly used in construction in Karachi and other parts of Sind for over centuries. The rocks range in age from



Pb = Pab formation
Na = Nari formation.
Gaj = Gaj formation.
Man = Manchar formation.

Fig. 1. Variation of grain size boundaries for sandstones.
(Modified from Pettijohn, 1987)

Cretaceous to Miocene, with the exception of Paleocene sandstone from Ranikot Formation. The rock samples were collected from the Pab Range, Orangi Hills and Surjan Range (Table-1). Most of the sandstone samples were fresh 6 x 3 inches (16.50 x 7.25 cm) cores from working quarries in the area. The specimens were prepared by cutting with diamond saw and 3 x 3 x 3 inches (7.25 x 7.25 x 7.25 cm) blocks were prepared for geotechnical examination. Remaining samples were put to geomechanical, petrographical and aggregate tests. The mineralogical study of the sandstones were conducted by point counting which indicates the relative percentages of the main sandstone components (quartz, feldspar and lithic rock fragments). The megascopic and microscopic properties of four sandstone types are described in situ and in hand specimens (Table-2).

The green stone is medium to coarse grained, grey, light grey and green, very hard and compact. The strata were generally thin to thick and massive with occasional cross-bedding. In thin section the sandstones can be seen to be immature containing abundant rock fragments and at places some unstable constituents. The quartz grains show poorly developed quartz overgrowths and calcite cement at grain boundaries. Ferrogenous cements are in most of the samples present in small amount. Cracks, deep seated fractures and joints are present which make the quarry operation easy.

The Orangi Sandstone is a dense, medium to coarse grained, reddish, light grey with some calcite concentrations along bedding planes; the strata being thinly to very thick bedded at all exposed outcrops. In thin section the dense microfabric appears to have intergranular porosity while the mineralogy is dominated by detrital quartz with some clay minerals including some Nari fossils Lepidocyclina dilatata. Two silica sand quarries are supplying silica sand to the glass factories working in the region.

Some sandstones of Pab Range and Orangi Hills in Karachi are greyish, reddish and limonitic and are medium to coarse grained. They are highly tenaceous, very hard jointed and fractured. Mostly they are extremely dense and the quartz welded nature of the grain boundaries indicate that they have passed through extensive pressure solution. Rock fragments in them are (20% to 25%) and quartz 50% to 60% (Fig. 2).

The Manchar Sandstone is formed during Middle Miocene-Pliocene times. It is medium to coarse grained. About 50% of the rock is composed of quartz with a total of 15% sedimentary, metamorphic and carbonate rock fragments. The well developed calcite cement has been studied by point counting which comprises about 20% of the rock mass (Table-2). Many of the detrital grains are coated with haematite and the rock is reddish in colour. In most places the strata is thinly to thickly bedded.

GEOTECHNICAL EXAMINATION

The unconfined compressive strength test, magnesium and sodium soundness, Aggregate Impact Value, Aggregate Crushing Value, porosity, specific gravity and abrasion resistance tests were carried out on each of the sandstone types in order to assess their suitability as construction geomatrial.

Compressive Strength: The unconfined compressive strength tests were undertaken on 2 x 2 x 2 inches (5.50 x 5.50 x 5.50 cm) blocks and 6 x 3 inches (16.50 x 7.25 cm) cores in accordance with American Standard for Testing Material (ASTM). Samples of each rock type were oven dried and half of them were vacuum saturated in order to determine unconfined compressive strength in dry and saturated states. The samples were then loaded to failure in an uniaxial compression machine. Axial and radial strains were monitored during each test for determination of Young's modulus and Possion.s ratio (Fig. 4). These results are presented in Table-3. The siliceous sandstone was strongest with an average dry uniaxial compressive strength of 163 MPa while the Orangi sandstone failed at 150 MPa (Fig. 5).

Soundness: The soundness tests were carried out on 1000 gm and 500 gm prepared aggregate samples as recommended by American Standard for Testing Material (ASTM, C-170, 1986). Five cycles were completed as recommended by the Geological Society Engineering Working Party on aggregates (Table-4). The results are given in original weight, weight loss and percentage loss and show a wide variation in performance. The Pab Sandstone and Gaj Sandstone showed very little deterioration while the Manchar Sandstone disintegrated completely during the fourth cycle.

The results of the Aggregate Impact Value and Aggregate Crushing Value tests are presented in Tables-5 and 6. The samples were tested in accordance with British Standard (BS: 812,1975) and care was taken to ensure that the rammer fell freely between correctly aligned vertical guide runner mounting the

Table-1 The names, ages and sample localities for the sandstone evaluation.

Unit names	Age	Sample localities
Manchar Sandstone	Middle-Miocene to Pliocene	Surjan and Gujo Ranges.
Gaj Sandstone	Miocene	Orangi Hills, Orangi Town.
Nari Sandstone	Oligocene	Gondbow Hills.
Pab Sandstone	Cretaceous	Pab Range and Gondbow Hills.

Table-2 Mineral Composition of the four sandstone types.

Mineral names	Pab	Nari	Gaj	Manchar
Quartz	60	55	52	50
Quartz overgrowth	--	--	4.6	--
Microcrystalline quartz	2.3	--	--	--
Alkali feldspar	4	2.5	--	1.0
Plagioclase feldspar	1.8	--	0.1	--
Phyllitic rock fragments	4.6	--	--	--
Muscovite mica	0.3	0.1	0.3	2.1
Biotite mica	--			--
Haematite	2.1	0.3	1.5	3.1
Calcite cement	5.2	6.8	10.0	6.9
Clays	2.8	5.7	4.8	6.9
Opaques	1.7	0.7	1.5	1.0
Heavy minerals	1.8	--	--	--
Pores	22	23	18	21

Table-3 Dry unconfined compressive strength values and degree of strength loss on saturation.

Sandstone type	Compressive strength (MPa)	Strength loss (MPa)	specific gravity	Porosity %
Manchar Sandstone	**38-100**	**8**	**2.5**	**21**
Gaj Sandstone	**120-150**	**5**	**2.7**	**18**
Nari Sandstone	**40-180**	**10**	**2.6**	**23**
Pab Sandstone	**160-270**	**5**	**2.7**	**22**

Table-4 Magnesium soundness for four Sandstone types.

Sandstone type	Original weight(gm)	Weight loss (gm)	Loss %
Manchar Sandstone	1000	**143.2**	**14.32**
Gaj Sandstone	1000	**38.9**	**3.89**
Nari Sandstone	1000	**123.5**	**12.35**
Pab Sandstone	1000	**2.1**	**0.21**

Table-5 Aggregate Impact Value for four sandstone types.

Sandstone type	AIV %	Loss%	AIVR %
Manchar Sandstone	43.2	50	22.1
Gaj Sandstone	13.9	35	17.5
Nari Sandstone	23.8	32	23.8
Pab Sandstone	6.1	25	15.5

Table-6 Aggregate Crushing Value for four sandstone types.

Sandstone type	ACV%	Loss%	ACVR%
Manchar Sandstone	43.5	32	23
Gaj Sandstone	10	35	50
Nari Sandstone	12.9	28	48
Pab Sandstone	5.3	23	48

Abbreviations used in table-3 to 6 are; ACV = Aggregate Crushing Value. ACVR = Aggregate Crushing Value Ratio. AIV = Aggregate Impact Value. AIVR = Aggregate Impact Value Ratio. Loss = Loss percent.

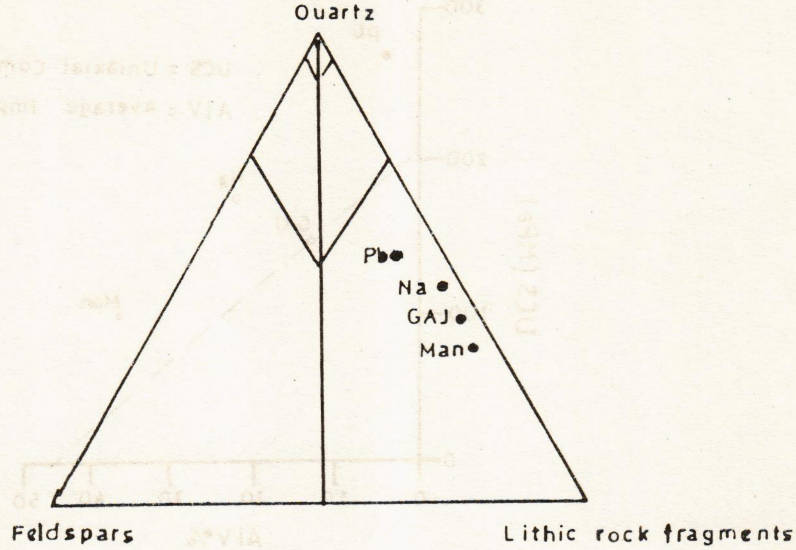


Fig. 2. Quartz– feldspar– lithic rock fragments ternary diagram showing position of four sandstone type.

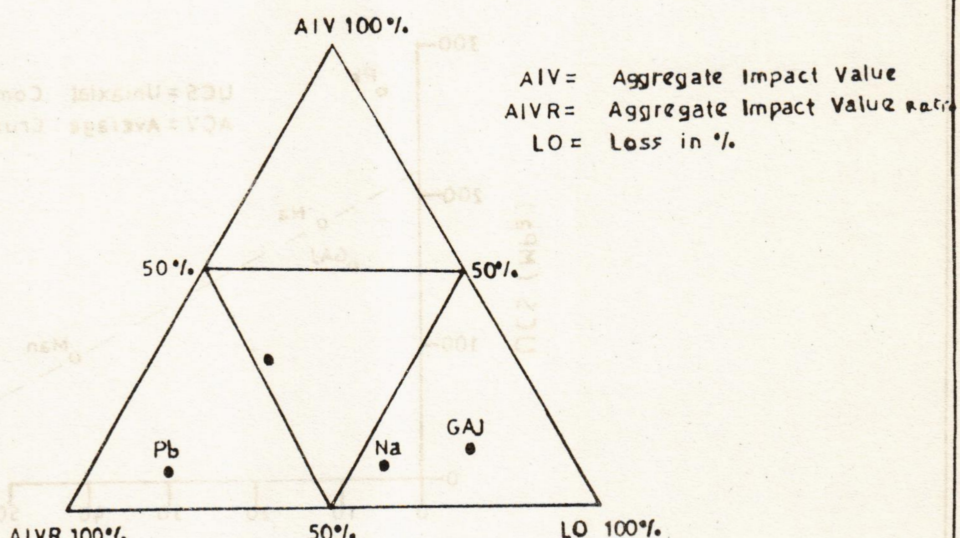


Fig. 3. Ternary diagram for Aggregate Impact Value.

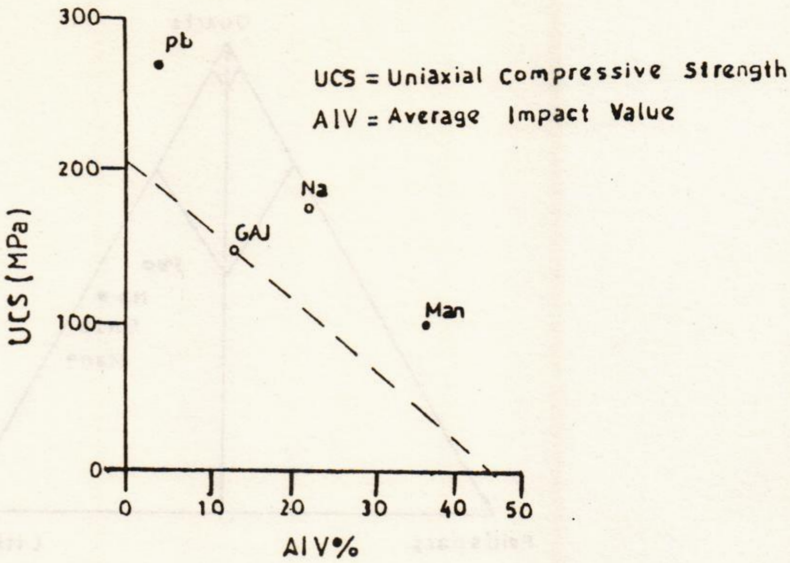


Fig. 4. Relationship between Uniaxial Compresive Strength and Aggregate Impact Value for four sandstone type.

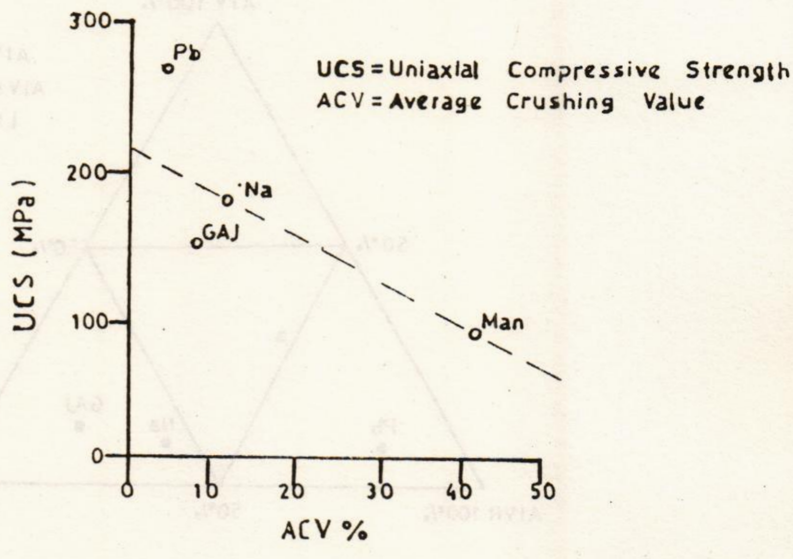
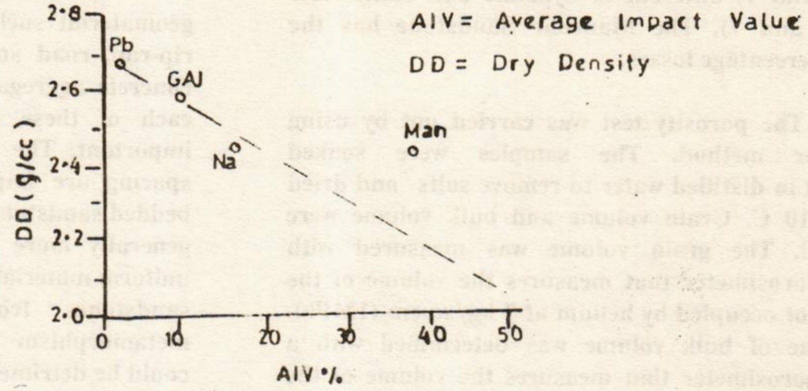
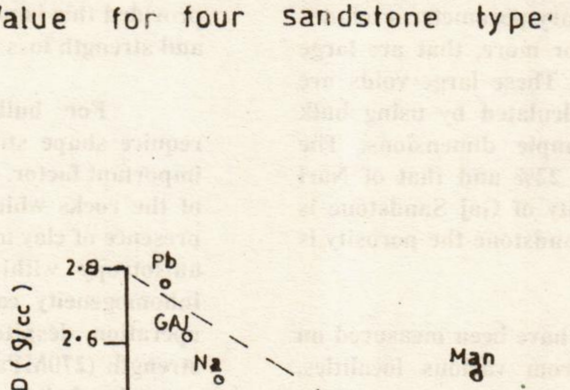


Fig. 5. Relationship between Uniaxial Compressive Strength and Aggregate Crushing Value for four sandstone type.



Fig·6· Relationship between Dry Density and Aggregate Impact Value for four sandstone type



Fig·7. Relationship between Dry Density and Aggregate Crushing Value for four sandstone type.

apparatus on a concrete soiled floor. The Aggregate Impact Value and Aggregate Crushing Value were plotted on a triangular diagram (Figs. 2 and 3). It can be seen that the Aggregate Impact Value for the Pab Sandstone and the Oragni Sandstone perform much better than the Manchar Sandstone. The performance of these rocks for Aggregate Crushing Value test is best but the change in relative positions indicate that the behavior is different in dynamic and static tests (Figs. 6 and 7). The Manchar Sandstone has the highest percentage losses.

Porosity: The porosity test was carried out by using porometer method. The samples were soaked overnight in distilled water to remove salts and dried out at 110 C. Grain volume and bulk volume were measured. The grain volume was measured with helium porosimeter that measures the volume of the sample not occupied by helium at 7 kg/sq cm (1MPa). One value of bulk volume was determined with a helium porosimeter that measures the volume of the mercury, at atmospheric pressure, displaced by the sample. A second value of bulk volume was calculated from measurements of the height and diameter of the sample. Matrix porosity was calculated using bulk volume, determined with mercury porometer, excludes voids with diameter of 1mm or more, that are large enough for mercury to enter. These large voids are included in bulk porosity, calculated by using bulk volume determined from sample dimensions. The porosity of Pab Sandstone is 22% and that of Nari Sandstone is 23%. The porosity of Gaj Sandstone is about 18% and in Manchar Sandstone the porosity is 21% (Table-3).

Density: Values of dry density have been measured on 30 samples of sandstones from various localities. Various methods have been proposed for determining dry density (ASTM, 1986, Brown, 1981, Colback and Wiid, 1965, Hawkins and McConnell, 1991). It has been shown that there is no unique method for giving a lowest value for all sandstones. For convenience, a single method has been adopted here. The specimens were dried in an oven for 24 hours at 110 C. After drying the samples, they were put in a desicator for 30 minutes., and then weighed. After that the specimens were completely immersed in water for 48 hours and after drying them with a damp cloth the specimens were again weighed. Specific gravity was calculated by using formula:

Absorption weight percent = B-A/AX100 where A is the weight of dried sample and B is the weight of the sample after immersion.

The specific gravity of Pab Sandstone is found to be 2.7, in Nari Sandstone it is 2.6, the Gaj Sandstone has specific gravity 2.7. The Manchar Sandstone has specific gravity 2.5 (Table-3). The values were plotted in Fig. 6,7.

DISCUSSION

The main uses of sandstones as construction geomaterial such as building stones, armourstones, rip-rap, road subbase road dressing aggregate and concrete aggregate are described in this paper. For each of these uses different rock properties are important. The bedding thickness and discontinuity spacing are important for building stones. Thickly bedded sandstones of Pab Range and Orangi Hills are generally more isotropic and hence produce more uniform material than thinly bedded rock masses. The sandstones from areas which have regional metamorphism may have incipient cleavage which could be detrimental to their use as geomaterials. High density (2.7) rocks from Pab Range are good for rip-rap, instead using the stone as road aggregate. The lower density (2.5) stones of Orangi Hills and Surjan Range may be advantageous for use in buildings provided this is not associated with increased porosity and strength loss (270-265MPa).

For building purposes, building industry require shape stones for which cutability may by an important factor. This is related to the tensile strength of the rocks which may be greatly influenced by the presence of clay minerals which produce a microscopic anisotropy within the rock fabric. This textural inhomogeneity can be exploited during the cutting operation, despite the rocks having high compressive strength (270MPa). The Orangi sandstone is a typical example, being frequently shaped by sawing for tombstone, paving and building stone. Different applications of the geomaterials will require different strength characteristics and it is important to consider whether the rock material will be subjected to dynamic or static load and whether wet or dry.Armour- stone will suffer repeated wave buffeting hence the dynamic strength properties are important while in the case of building stones or concrete aggregates the static strength is applicable. For aggregates used in surface dressing the tensile strength of the material is of major importance due to the particular forces exerted on it.

For armour-stone and rip-rap the angularity of blocks is vital in order to obtain interlocking framework. Shape of the stone is also important for compaction of crushed aggregates used in road subbase and for producing the maximum surface areas for bonding by concrete binders. To obtain the skid resistance, so that it does not produce a single polished surface (good-excellent). For the geomaterial of the area the durability and capability of resisting physical and chemical weathering is very important. In the case of aggregate it is essential that the material does not deteriorate with time due to either slaking or decrease in chemical soundness (0.21% to -14.32%). In the sandstone aggregates of Orangi Hills which are clayey in nature, some change in volume occur and increase the shrink and swell potential. Such stones are found only at one place (Orangi Town). It was suggested that this rock should not be used in construction as concrete aggregate. The sandstones of Manchar Formation contain some cherty material which are chemically reactive and require special consideration before use as geomaterial. The sandstones of Surjan Range contain carbonate rock fragments (about 50%) and require careful consideration in view of the possible alkali reaction. An attempt has been made to demonstrate the suitability of each sandstone type to the main six applications for which they are used as construction raw material.

CONCLUSIONS

This study has drawn attention to the wide variation in sandstone types emphasizing the significance of this when considering geomechanical properties.

Four sandstone types are reported with quartz contents varying between 50 to 60%. The other minerals are madeup of rock fragments, feldspars, clay minerals and matrix materials.

The unconfined compressive strength ranges from 38 MPa to 270 MPa. being related to the textural variations such as porosity and packing density and to the nature of the intergranular cement.

The AIV and ACV are variable, with values of 6.1% to 43.2% loss for AIV and 5.3% to 43.5% for the ACV.

The chemical soundness values also show a wide variation with five cycles producing only 0.21% loss for Pab Sandstone while the Manchar Sandstone disintegrated during fifth cycle. The Nari Sandstone performed worse than expected during soundness testing with a weight loss of 12.35%. The high value is probably related to the high percentage of sedimentary phyllitic rock fragments present and underlies the importance of mineralogy in controlling an aggregates susceptibility to freeze thaw action.

This paper highlights the necessity of exercising caution in making generalizations regarding the geomaterial properties of sandstones in view of the tremendous variation in lithologies from different areas, despite the fact they may have the same stratigraphic name.

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A NEW SPECIES OF THE GENUS LISTRIODON FROM KAMLIAL BEDS OF VASNAL, DISTRICT SARGODHA PUNJAB, PAKISTAN

By

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ABSTRACT: A new pig is described from Chinjian of the Lower Siwaliks. It was larger than Listriodon theobaldi but smaller than Listriodon pentrapotamiae. This new form is differentiated from the species Listriodon penatapotamiae in morphological features of P^3 and M^1.

INTRODUCTION

Siwalik listriodonts were reported for the first by Falconer (1868). These samples were designated as *Tapirus pentapotamiae*. Few years later, Lydekker (1876) transferred this species to the genus *Listriodon*. In 1878, Lydekker described some listriodont specimens and differentiated them from the material of the species *Listriodon pentapotamiae* at specific level. He assigned the name *Listriodon theobaldi* to this new species. In 1926 Pilgrim added a third species i.e. *Listriodon guptai* to the list from Kamlial beds of Bhagothoro, Sind. It was based upon a single upper last molar. Chen (1984) on noticing bunolophodonty in the type tooth, transferred the species to the genus *Bunolophodon*. The present material comprises a P^3, M^1, M^1 and mandibular ramus. The first three isolated teeth belongs to one individual and the last one to another individual.

SYSTEMATIC ACCOUNT

Order	ARTIODACTYLA	Owen
Suborder	SUIFORMES	Gray
Superfamily	SUOIDEA	Cope
Family	SUIDAE	Gray
Subfamily	LISTRIODONTINAE	Simpson
Genus	LISTRIODON	Meyer

LISTRIODON VASNALENSIS new species
(Figs. 1-4)

HOLOTYPE

Type: P.U.P.C. 68/387, a P^3, M^1 and M^2 of the left side.

LOCALITY

Vasnal, District Sarghoda, Punjab, Pakistan.

HORIZON

Chinjian of the Lower Siwaliks.

HYPODIGM

1. Type specimen.
2. P.U.P.C.* 68/305, a right mandibular ramus from Vasnal, District Chakwal, Punjab, Pakistan.

DIAGNOSIS

A form smaller than *Listriodon pentapotamiae*. P^3 with well defined internal cusp and wide deep valley separating it from the outer cusp. M^1 squared. Oblique ridge connecting the two plates absent. Cingula stronger. Oblique ridges connecting fore and aft cingula with the main cusp present.

DESCRIPTION

P^3 (Fig. 1) is a well preserved triangular tooth. It is essentially an unworn third upper premolar of the left side. It is moderately high. It is longer than wider. Cingulum is well-developed and is crenulated. It can be seen all around the crown. Protocone is low and transversely thin. It is an elongated low pyramidal ridge with an anterior and a posterior slope. The anterior

*Fossil collection stored in the Zoology Department, Punjab University, Lahore Pakistan.

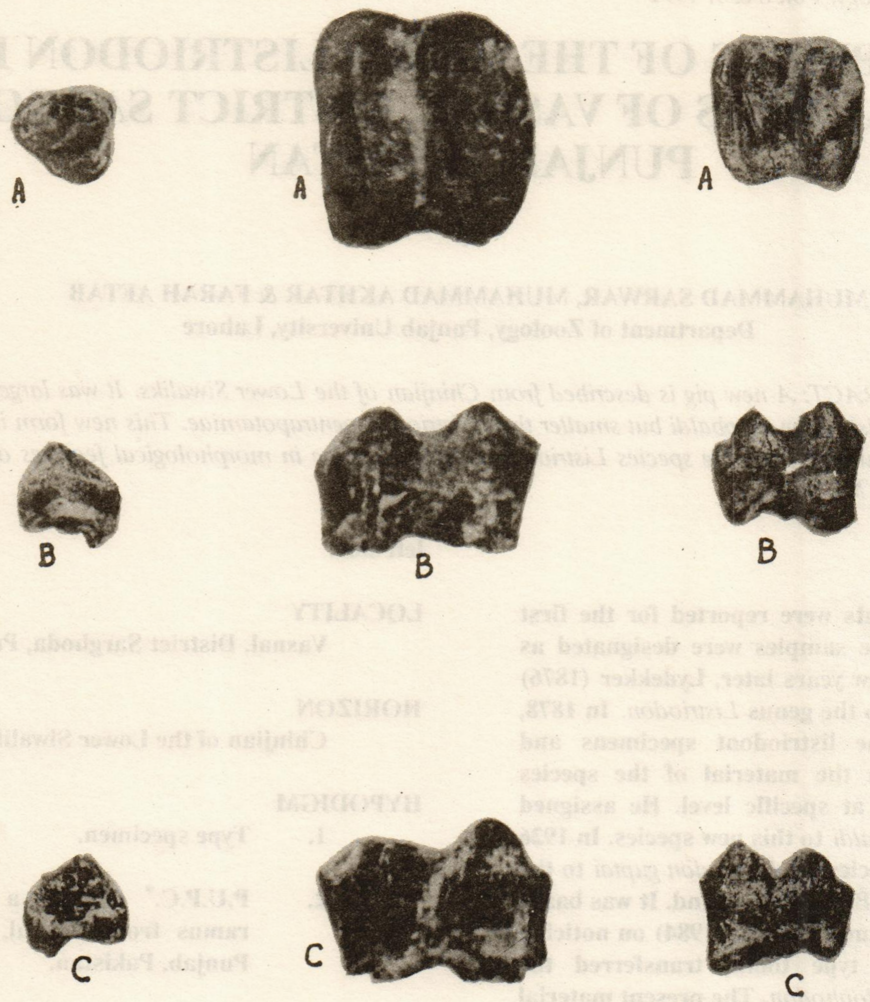

Fig. 1 **Fig. 2** **Fig. 3**

Fig. 1. Type P^3 (P.U.P.C. 68/387) of *Listriodon vasnalensis* n. sp. x .75 A. Crown view; B Lingual view; C. Buccal view.

Fig. 2. Type M^1 (P.U.P.C. 68/387) of *Listridon vasnalensis* n. sp. x .75 A Crown view; B. Lingual view; C. Buecal view.

Fig. 3. Type M^2 (P.U.P.C. 68/387) of *Listriodon vansalensis* n. sp. x .75 A. Corwn view; B. Lingual view; C. Buccal view.

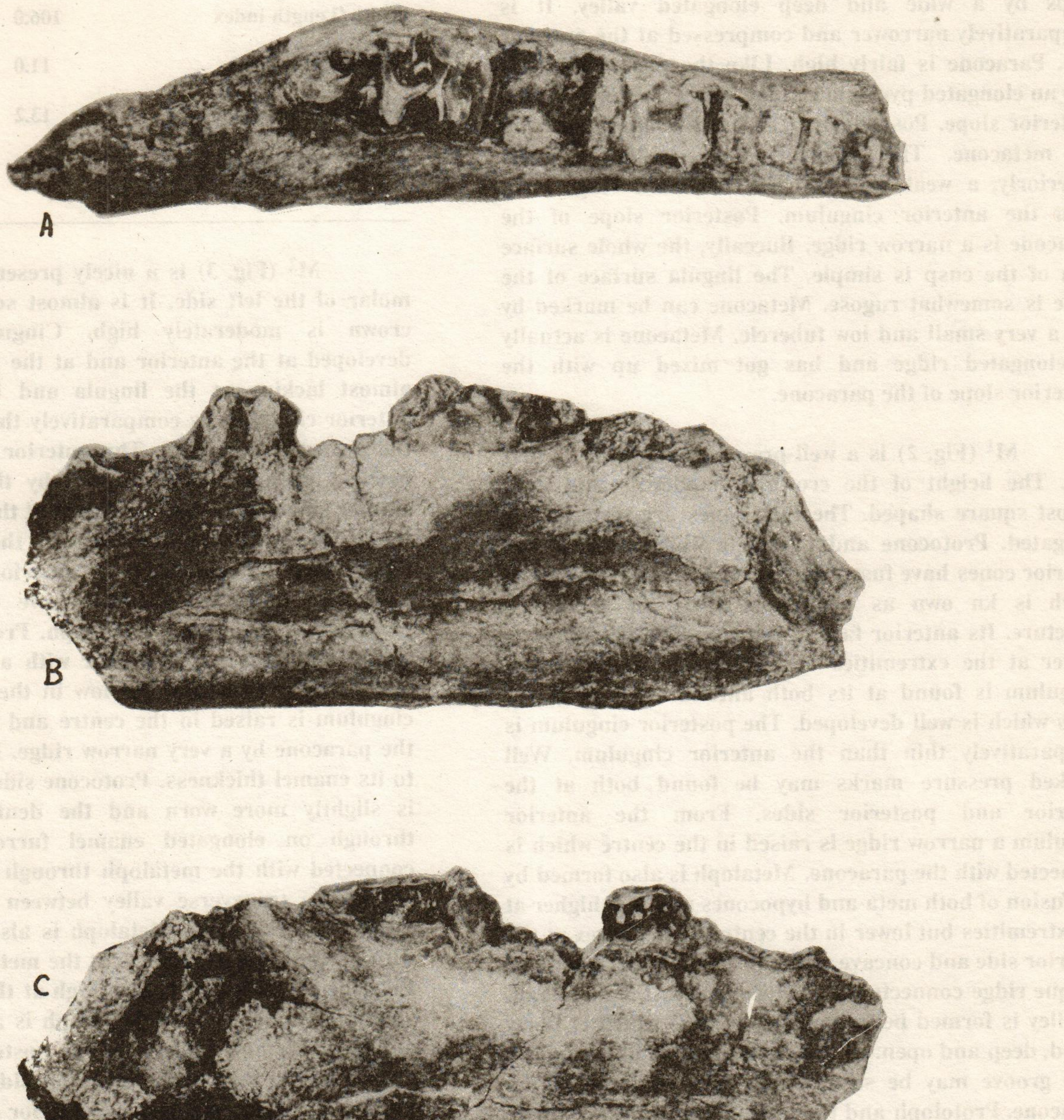

Fig. 4. Referred mandibular ramus (P.U.P.C. 68/305) of *Listriodon vansalensis* n. sp. x.75 A. Crown view; B. Lingual view; C. Buccal view.

ridge is simple whereas the posterior one is crenulated. Peak of the cusp is continuous with the internal cingulum. Protocone is widely separated from the outer cusps by a wide and deep elongated valley. It is comparatively narrower and compressed at the anterior side. Paracone is fairly high. Like the protocone, it is also an elongated pyramidal ridge with an anterior and a posterior slope. Posteriorly, it is hardly separated from the metacone. The anterior slope is fairly thick. Anteriorly, a weak but well differenciated ridge rises from the anterior cingulum. Posterior slope of the paracone is a narrow ridge. Buccally, the whole surface area of the cusp is simple. The lingula surface of the same is somewhat rugose. Metacone can be marked by just a very small and low tubercle. Metacone is actually an elongated ridge and has got mixed up with the posterior slope of the paracone.

M^1 (Fig. 2) is a well-preserved tooth of the left side. The height of the crown is moderate and it is almost square shaped. The four cones are transversely elongated. Protocone and paracone which are the two anterior cones have fused and formed a transverse ridge which is kn own as protoloph. It is an arcshaped structure. Its anterior face is concave. The protoloph is higher at the extremities but shallower in the centre. Cingulum is found at its both anterior and posterior sides which is well developed. The posterior cingulum is comparatively thin than the anterior cingulum. Well marked pressure marks may be found both at the anterior and posterior sides. From the anterior cingulum a narrow ridge is raised in the centre which is connected with the paracone. Metaloph is also formed by the fusion of both meta-and hypocones and it is higher at its extremities but lower in the centre. It is convex at the anterior side and concave at the posterior side. A narrow oblique ridge connects the protocone with the metaloph. A valley is formed between the two lophs which is fairly broad, deep and open. At the posterior side of the loph a deep groove may be seen, which is more close to the metacone. Protoloph and the metaloph are worn to their dentinal thickness.

TABLE - 1 Measurements (in mm) of lp^3, $1m^1$, $1m^2$ (P.U.P.C. 68/387) of *Listriodon vasnalensis* new species.

	$1P^3$	$1M^1$	$1m^3$
Anteroposterior length	12.3	14.5	18.6
Transverse width of anterior half	10.0	15.0	18.4
Transverse width of posterior half	13.0	14.7	18.4
Width/Length index	106.0	103.0	99.0
Height (preserved)	11.0	7.5	11.0
Height (reconstructed)	13.2	14.3	15.5
Height/Width index	102.0	94.0	84.0

M^2 (Fig. 3) is a nicely preserved second upper molar of the left side. It is almost square-shaped. The crown is moderately high. Cingulum is strongly developed at the anterior and at the posterior side but almost lacking at the lingula and buccal sides. The anterior cingulum is comparatively thicker than that of the posterior cingulum. The anterior face bears a well marked pressure mark caused by the first molar. A similar structure has been caused at the posterior face of the tooth by the last molar. All the four cusps are transversely elongated. The anterior two cusps i.e. protocone and the paracone have fused to form a transverse ridge or the protoloph. Protoloph is an arc-shaped structure. It is higher with a concave anterior face at the extremities but low in the middle. Anterior cingulum is raised in the centre and is connected with the paracone by a very narrow ridge. Protoloph is worn to its enamel thickness. Protocone side of the protoloph is slightly more worn and the dentine is appearing through on elongated enamel furrow. Protocone is connected with the metaloph through a narrow oblique ridge. The transverse valley between the two lophs is fairly wide and open. Metaloph is also somewhat worn with an exposure of dentine at the meta- and hypocones. Like the protoloph, it is also high at the extremities and shallower in the middle. Metoloph is also convex at the anterior side and concave at the posterior side. A deep groove may be seen at the posterior side of the loph. It is more close to the metacone. Posterior cingulum is fairly raised in the median longitudinal line of the tooth and is connected with the hypocone through a narrow ridge.

P_3 (Fig. 4) is completely missing. However, its preserved root base indicates that the tooth was not much elongated.

P_4 (Fig. 4) is completely missing. The preserved root base shows that the naterior half was narrower than the posterior half and the tooth was moderately elongated.

M_1 (Fig. 4) is deeply worn leaving behind no boundary mark for the individual conids. However, the boundary between protolophid and entolophid still can be marked. Like the premolars, the entolophid is somewhat more in transverse demension than the anterior half. The overall tooth contour is nearly squarish.

M_2 (Fig. 4) is completely missing leaving behind the root basis only. The root basis suggest that the tooth was almost squarish and that the protolophid and entolophid were equally wide.

The lower last molar (Fig. 4) is partly damaged. However, it still provides all the essential tooth morphology required for the specific identification of the specimen. Protolophid is much damaged and only a part of its posterior enamel figure is preserved. Entolophid is as wide as the protolophid. It is almost completely preserved. Entoconid is transversely linear cusp whereas the hypoconid is connected with the protolphid through a strong well-developed oblique ridge obliterating the transverse valley. The valley posterior to the entolophid is shallow. Talonid or heel is angular posteriorly with a large forward ridge and a week ridge on each lateral side.

Table - 2 Measurements (in mm) of rM_1 and rM_3 (P.U.P.C. 68/305) of *Listriodon vasnalensis* new species.

	rM_1	rM_3
Anteroposterior length (preserved)	13	28.2
Anteroposterior length (reconstructed)	14	29.2
Transverse width of anterior half (preserved)	10.8	14.2
Transverse width of anterior half (reconstructed)	11.8	15.2
Transverse width of posterior half (preserved)	11.5	13.8
Transverse width of posterior half (reconstructed)	13.0	14.6
Width/Length index	93	52
Height (preserved)	4.2	7.7
Height (reconstructed)	10.0	13
Height/Width index	82	86

Table - 3 Measurements (in mm) of (P.U.P.C. 68/305) of *Listriodon vasnalensis* new species.

Mandibular thickness below P_3	19.0
Mandibular thickness below P_4	17.5
Mandibular thickness between M_2 and M_3	21.5
Mandibular depth below P_3	34.5
Mandibular depth below P_4	35.8
Mandibular depth below M_1	35.0
Mandibular depth below M_2	35.0
Mandibular depth below M_3	35.5
Length of P_3-M_3	82.0

DISCUSSION

Three types of listriodont pigs are hitherto known from the Siwaliks. These are:

1. *Listriodon pentapotamiae* described by Falconer (1868).
2. *Listriodon theobaldi* founded by Lydekker (1878).
3. *Listriodon guptai* erected by Pilgrim (1926).

Of these, the first two species are true lophodont types whereas the last one is partially bunodont. Bunolophodonty has been regarded as the generic distinction of the genus *Bunolophodon* by Arambourg (1933). Due to this feature, Chen (1984) has treated the species *Listriodon guptai* as *Bunolistriodon guptai* which is justified. The species *Listriodon theobaldi* was comparatively a smaller form than the species, *Listriodon pentapotamiae* (Colbert, 1935). As regards the material under study, it is smaller than that of the species, *Listriodon pentapotamiae.* However, its P^3 is comparatively broader. P^3 shows a well-defined internal cusp separated from the outer cusp by a wide deep valley. In P^3 of *Listriodon pentapotamiae,* the internal cusp is neither well-defined nor well separated. Both upper as well as the lower first molars are squared in the material under study. In *Listriodon pentapotamiae,* the first upper molar is longer than wider (Table-4). Oblique ridge connecting the two cross-crests are lacking in the specimens under study. These oblique ridges may be seen in the molar teeth of the species, *Listriodon pentapotamiae.* These dental features clearly indicate that the material under discussion represents some new species of the genus *Listriodon.* the name *Listriodon vasnalensis* is being proposed to lable this new species, which is after the name of the type locality.

Table - 4 Comparative measurements (in mm) of M^1 and M_1 in *Listriodon vasnalensis* new species and *Listriodon pentapotamiae.*

	M^1			M_1		
	L	W	W/L index	L	W	W/L index
L. *vasnalensis* new species	14.5	15	103	14	13	93
L. pentapotamiae*	17	16	94	15.8	14	89

*From Colbert, 1935.

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A NEW ANTHRACOTHERIID GENUS FROM VASNAL PUNJAB PAKISTAN

By

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ABSTRACT: A small anthracothere has been described from Lower Chinji beds of the Siwaliks. A comparison with the known members of the family anthracotheriidae has revealed that it is a new genus. It appears to be one of the most primitive members of the family and the name **Vasnalina primitivus** *n.g. et n.sp. has been suggested for this new form.*

INTRODUCTION

This Siwalik anthracotheres are known since 1836 when Falconer and Cautley described the species *Merycopotamus dissimilis* as *Hippopotamus dissimilis*. Since that seven genera have been recorded from the area by the subsequent workers. These are *Choeromeryx, Rhagatherium, Anthracotherium, Hyoboops, Hemimeryx, Merycopotamus* and *Telmatodon*. These forms of the family anthracotheriidae range from Chinjian (as termed by Romer, 1974) to the pinjorian. Of these, the species *Anthracotherium punjabiense* is considered to be the most primitive.

In the year 1988, a posterior half of right mandibular ramus bearing two last molars (P.U.P.C.* No. 88/379) was collected during a field trip to the village Vasnal, Punjab. It was procured from the Lower Chinjian shale and is probably the oldest of the Siwalik forms. It is the smallest of the known Siwalik anthracotherids and is highly different from all the known Siwalik species of the family in morphology. It is even smaller than the species *Anyhracotherium punjabiense*. The name *Vasnalina primitivus* n.g. et n.sp. is being assigned to this new form.

SYSTEMATIC ACCOUNT

Order	ARTIODACTYLA	Owen
Suborder	SUIFORMES	Jaeckel
Infraorder	ANCODONTA	Matthew
Superfamily	ANTHRACOTHERIOIDEA	Gill
Family	ANTHRACOTHERIIDAE	Gill
Genus	*VASNALINA* n.g.	
Genotype	*VASNALINA PRIMITIVUS* n.sp.	

DIAGNOSIS

Molars extremely brachyodont, outer cusps of the lower molars highly simple and conical, rounded and thick. Cingulum lacking at the lateral sides. Transverse valleys shallow. Cement fairly developed.

VASNALINA PRIMITIVUS n.g. et n.sp.
(Fig. 1)

HOLOTYPE

P.U.P.C*.No. 88/379, a posterior fragment of the right mandibular ramus bearing second and third molar.

HYPODIGM

Type only.

LOCALITY

Vasnal, district Khushab, Punjab, Pakistan.

HORIZON

Lower Chinjian.

*Fossil Collection stored in the Zoology Department, Punjab University, Lahore Pakistan.

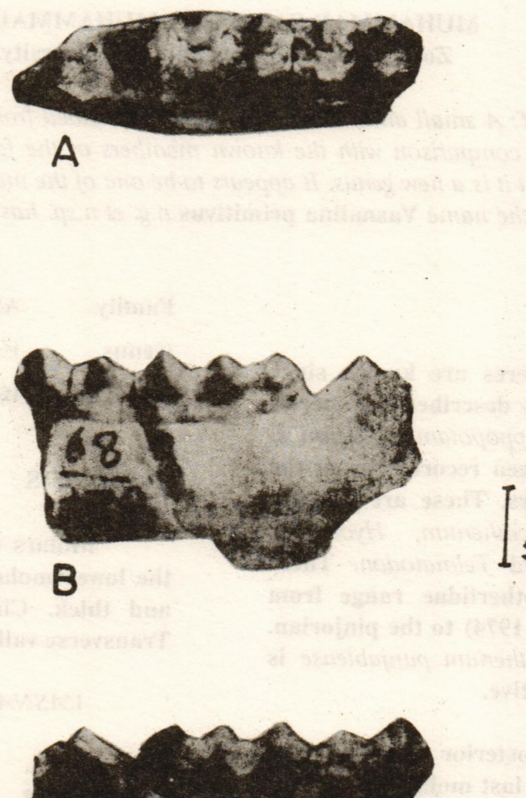

Fig. 1. Right mandibular fragment of *Vasnalina primitivus* n.g. et n.sp.
A. Top view; B, Inner view;
C. Outer view.

DIAGNOSIS

As for the genus.

DESCRIPTION

Dentary is thin below the second and third molars. Roots of the teeth indicate that the jaw bone was fairly deep.

Second lower molar is a quadrangular structure. It is a low crowned tooth with a fair development of cement in the transverse valleys. The cusps are rounded and comparatively simple. The tooth is elongated and transversely narrow. Although the crown is low, yet the root fangs are fairly deep and the depth may be seen from the lingual side. Enamel is simple all around the crown. A strong pressure mark may be seen at the anterior face of the tooth. The pressure mark is also indicated in the crown view. It suggests that the preceding tooth was approximately like the second molar in transverse width. Cingulum may be seen anteriorly as well as posteriorly. The two halves of the tooth are quite similar. Proto- and hypoconids resemble very much. Similarly the inner cusps also resemble in general contours. The outer cusps are V-shaped. In both the tubercles, base of the "A" i.e. the outer angle is very acute. The anterior limb remains almost horizontal and show a little slope. It is comparatively more worn and thick. The posterior limb is comparatively narrow and sloping. A vertical groove may be seen at the posterior face of the hypoconid. The valley between the anterior cusps is very shallow and somewhat crescentic. A small amount of cement may be seen at the antero-outer corner of the tooth. Metachonid is an elongated spindle-shaped cusp. The anterior limb is comparatively thick than the posterior one. The wear is more confined to the anterior limb than the posterior limb. The inner half of the transverse valley is partially blocked by the cement. The entoconid is also a spindle-shaped structure. The anterior limb of the cusp is thick and worn which indicates that it was almost horizontal is unworn condition. The posterior limb is comparatively thin and much inclined. As a result the valley between the posterior cusps is open at the postero-inner side. The posterior cingulum is so well developed that it may be considered as the hind talon. The postero-outer side of the tooth is covered by a small amount of cement.

The last molar resembles the second molar in general contours. The only difference lies in their degree of wear and the presence of hind talon. Cement is comparatively more developed in this tooth which however may be attributed to the degree of wear. The anterior limb of the inner cusps is somewhat bifurcated due to the presence of a shallow anterior groove. Because of the wear, this morphological feature could not be noticed in case of the second molar. The hind talon is very well developed. It is a crescentic structure with the valley facing forward. A narrow ridge arises from the middle of the crescent and slopes anteriorly on the mid-longitudinal axis of the tooth. The transverse valley present between the hind talon and the posterior major cusps is fairly blocked by the cement.

Table-1 Comparative Measurements (in mm) of M_2 and M_3 in *Vasnalina Primitivus* new genus and new species and *Anthracotherium Punjabiense*.

		Crown length	Crown width	Crown height	Width/ length index
M_2	*Vasnalian primitivus* n.g. et n. sp. (P.U.P.C. No. 88.37)	16	9.5	6.5	59
	Anthracotherium punjabiense (A.M. No. 19444)+	17	12.5	9	74
M_3	Vasnalina primitivus n.g. et n. sp. (P.U.P.C. No. 88/379)	21	10.5	7.5	50
	Anthracotherium punjabiense (A.M. No. 19444)	24.5	14	11	58

+A.M. - American Museum of Natural History.

DISCUSSION

The molar teeth of the specimen under study show bunoselenodoty. The outer cusps are crescentic and the inner cusps are conical at their apices. It has been regarded as the family character of the anthracotheres by Zittel (1925). A number of genera are known in the family anthracotheriidae. Of these, only seven are known from the Siwaliks (Colbert, 1935). These are the genera *Choeromeryx, Rhagatherium, Anthracotherium, Hyoboops, Hemimeryx,* *Merycopotamus* and *Telmatodon*. The specimen under study may very clearly be differentiated from the Siwalik anthracotherid material described by Lydekker (1877, 1978), Pilgrim (1910, 1913), Bakr and Akhtar (1987-88) in its molar morphology i.e. extreme brachyodonty, simple and rounded inner cusps and the presence of cement. The specimen under study (Fig. 1) shows some superficial resemblance with the Siwalik genus *Anthracotherium* but the former is smaller and morphologically different from the non-Siwalik forms. In size it approaches the genus *Brachyodus*. The measurements given by Dineur and Ginsburg (1986) indicate that the specimen under study is very close to the species *Brachyodus onoideus*. However, the two differ in their molar structure,

Anthracotheres were abundant in Europe, but were sparingly distributed in North America, northern Africa and India. In the Sub-Continent of Pakistan and India, the first anthracothere appeared in upper Oligocene beds of Bugti deposits, Baluchistan (Pilgrim, 1915). In the Siwaliks, they appeared for the first in Chinji beds. The youngest chronological record has been cited by Falconer and Cautley (1936) from Pinjor beds of the Siwaliks.

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FIRST DESCRIPTION OF THE LOWER MOLAR IN THE CLAWED HORSE *MACROTHERIUM SALINUM* COOPER (Perissodactyla: Mammalia)

By

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ABSTRACT: A posterior chalicothere mandibular fragment bearing the partially erupted last molar is described. A comparison with the known Siwalik forms has indicated that it belongs to the species Macrotherium Salinum Cooper. It is the first description of the lower last molar in the said species.

INTRODUCTION

Chalicotheres are rare in the Siwalik deposits. They are known only by two genera and two species. The first record of the Siwalik chalicothere was made by Falconer and Cautley in 1843. It was the report of fragments of the skull with upper dentition. The present description is based upon a posterior portion of the right mandibular fragment (P.U. P.C. No. 68/26) bearing molar alveolus of the second molar and the erupting last molar. It was collected during a field trip to Chinji and its surroundings. After a careful examination, it turned out to be conspecific with the species *Macrotherium Salinum*.

SYSTEMATIC ACCOUNT

Order	**PERISSODACTYLA**	**Owen**
Suborder	**HIPPOMORPHA**	**Wood**
Superfamily	**CHALICOTHERIOIDEA**	**Gill**
Family	**CHALICOTHERIIDAE**	**Gill**
Subfamily	**CHALICOTHERIINAE**	**Matthew**
Genus	***MACROTHERIUM***	**Lartet**

MACROTHERIIUM SALINUM Cooper
(Fig. 1)

HOLOTYPE

B.M. No. M 12239, a left third superior molar.

LOCALITY

Near Chinji, Salt Range, district Chakwal, Punjab, Pakistan.

HORIZON

Chinjian.

DIAGNOSIS

A typical *Macrotherium,* closely to *M. grande,* but smaller than this latter species. Upper molars quadrate and brachyodont, and protoconule more distinct than in the other species of the genus (Colbert, 1935).

SPECIMEN EXAMINED

P.U.P.C*. No. 68/26, a posterior portion of the right mandibular ramus bearing alveolus of the second molar and the erupting last molar from Bhelomar, district Chekwal, Punjab, Pakistan.

DESCRIPTION

Dentary is typical of the horses. It is moderately thick and the thickness remains almost equal from the base of the ascending ramus to the molar alveolus of the first molar. The ventral line is straight. The alveolus of the second molar and the calcitic casts of the pulp cavities indicate that the tooth was rectangular, much longer than wider.

The crown of the last molar is finely preserved. Enamel is somewhat rugose and cement is essentially lacking. It is doubly crescented structure with five apices representing protoconid, metaconid, metastylid, entoconid and the hypoconid. Of these the metaconid and the hypoconid are nearly of equal height whereas the entoconid is the lowest. Front limb of the anterior

Fig. 1. A right mandibular fragment of *Macrotherium salinum*.
A. Top view; B. Inner view; C. Outer view.

crescent slopes inwardly and ends at the metastylid. Metastyplid is so low that the anterior crescent fails to enclose the valley as does the posterior crescent. Apex of the protoconid forms an acute angle for the crescent. A low and weak transverse ridge may be seen in centre of the crescent. No such ridge is seen in case of the posterior crescent. Metaconid is somewhat elongated and bears two weakly developed vertical ridge. These ridges are antero-posterior in position. The posterior crescent is elongated than the anterior one. The enclosed valley is comparatively shallower than the anterior one.

DISCUSSION

The molar tooth (Fig. 1) shows two 'V'-shaped crescents and it is without any third lobe. These are the characteristics of the family chalicotheriidae (Zittel, 1925). According to Simpson (1945) the family comprises 12 genera. Different genera have been reported by different workers. The genus *Circotherium* was described by Holland and Peterson (1914) and the genus *Macrotherium* was reported by Cooper (1922). According to Matthew (1929), the Siwalik challicotheres either belongs to the genus *Macrotherium* or *Chalicotherium*. In Colbert's opinion (1935) there exists two genera and two species in the Siwaliks. These are the species *Nestoritherium sivalense* and *Macrotheriurn salinum*. The specimen under study (Amer. Mus. No. 19437) figured by Colbert (1935). In both the anterior crest is equally developed and the metaconid is transversely elongated. Last lower molar was hitherto unknown in the species *Macrotherium salinum*. The specimen under study provides the first description of the last lower molar and thus adds to the known dental morphology of the species.

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GEOLOGICAL, MINERALOGICAL AND GEOTECHNICAL INVESTIGATIONS OF LATERITE FROM CHANGLAGALI AREA OF HAZARA DIVISION

By

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ABSTRACT: Indian plate movement after the deposition of Cretaceous Kawagarh Formation and prior to the Paleogene deposition created conditions suitable for the formation of Hangu Formation which is the product of lateritization of old limestone surfaces. The laterite beds exposed near Changlagali, on Murree-Abbottabad road were measured and sampled for this study. The samples dominantly consist of grey coloured pisoliths embedded in a grey to creamish brown matrix. Mineralogically, goethite and boehmite are the two distinct phases in laterite. Geochemical analyses show that the percentage of alumina decreases in the upper parts of the beds, whereas, the percentage of iron increases with the decrease of alumina in the beds. The general trend is desilicification in the middle of the beds. In the upper parts of the beds the percentage of silica is increasing because of leaching out of the elements due to weathering phenomenon. The firing of samples at above 900°C produces beautiful red colours. It is deduced that materials are suitable for the manufacturing of surface tiles.

INTRODUCTION

Laterite deposits are reported from Azad Kashmir, Hyderabad, Sargodha, Rawalpindi and Quetta divisions (Ahmed, 1969).

Occurrence of laterite in Hazara was reported at the top of the upper Cretaceous limestone (Latif, 1962), that was later mapped as the basal part of the Mari limestone (Latif, 1970). It was identified as the part of the Hangu Formation (Latif, 1976). No detailed geochemical and petrological work on laterite is available in the current literature of Hazara. The laterite exposures are widespread in the area. Changlagali (Fig. 1) was chosen initially for qualitative studies because of the easy access on the Murree-Nathiagali Road, 17 kilometers north of Murree. The laterite of the area is dominantly pisolitic with pisoliths attaining a maximum size of 5mm. The grey coloured pisoliths are embedded in a grey to creamish-brown matrix. The laterite from the lower parts of the Hangu Formation has been collected for this study with the following objectives: (a) to collect field information about the nature and extent of the deposits, (b) to assess the variation in chemical and mineralogical composition and (c) to make an attempt to interpret the geological, chemical and mineralogical data for the utilization of this deposit.

GEOLOGICAL SETTING

The detailed geological map of the area is shown in fig. 2 (Latif, 1970). The exposed rock units (Latif, 1976) in the vicinity of the sample locations are as follows:

Group	Formation	Age
Rawalpindi	Murree Formation	Miocene
	———Unconformity———	
	Kuldana Formation	
	Chorgali Formation	Eocene
Galis	Margala Hill Limestone	
	Patala Formation	
	Lockhart Limestone	Paleocene
	Hangu Formation	

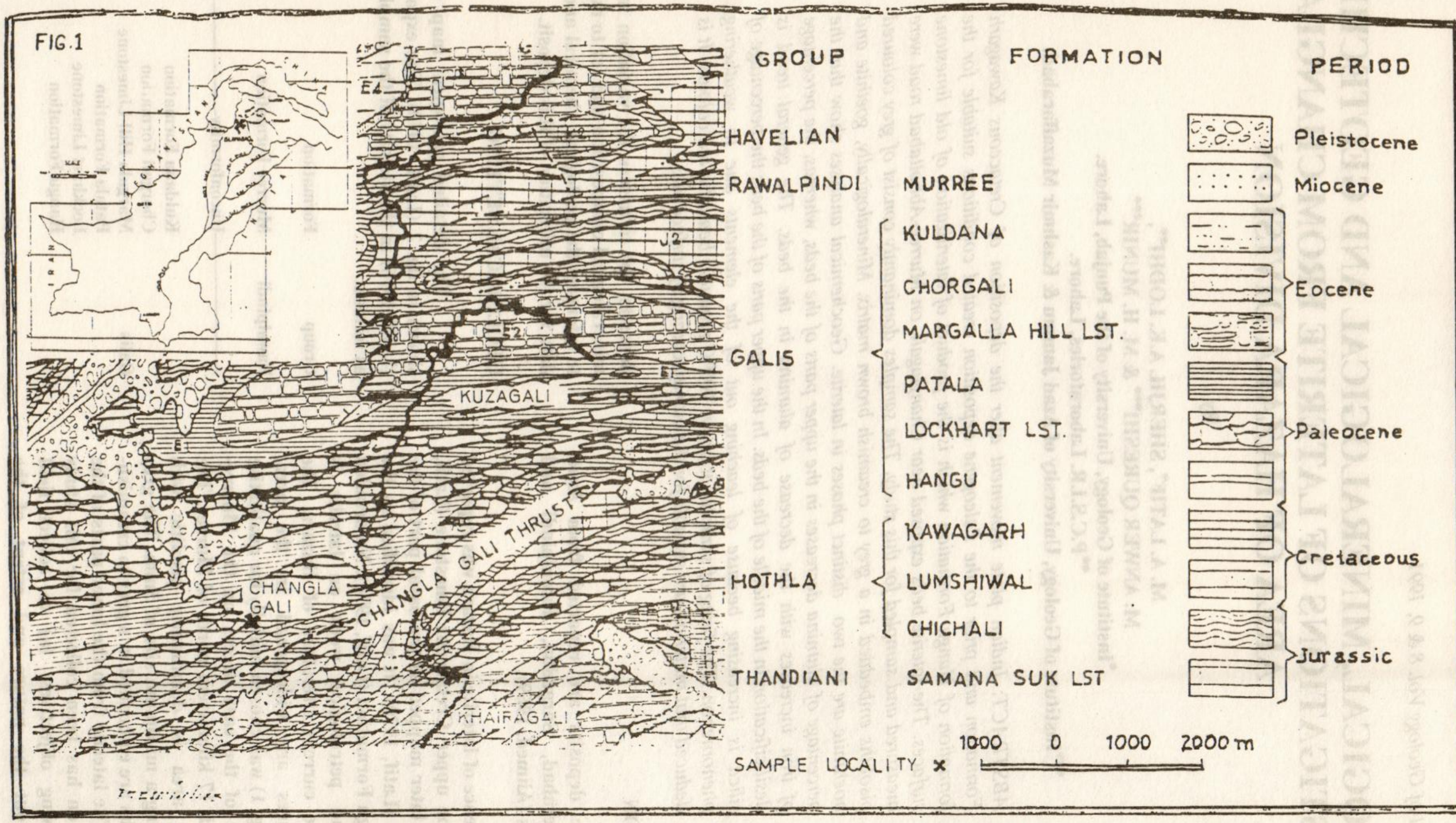

FIG. 2 GEOLOGICAL MAP OF THE CHANGLA GALI AREA.

———————Unconformity———————

Hothla	Kawagarh Formation	Cretaceous
	Lumshiwal Formation	
	Chichali Formation	Cretaceous

———————Unconformity———————

Thandiani --	Samana Suk Formation --	Jurassic

After the deposition of the Late Cretaceous Kawagarh Formation the Indian plate was at such a position to create conditions suitable for lateritization of exposed Kawagarh Formation. The Kawagarh Formation consists of limestone, marls and marly limestone. The lateritization varies in the area due to the affects of the Paleocene unconformity.

SAMPLING AND FIELD INVESTIGATIONS

The representative samples of the laterite were collected from Changlagali (longtitude 73°23'N, latitude 34°00'E) that is 16 kilometers north of Murree on Murree-Nathiagali road, located at the cliffy face of the Changlagali Bazar (Fig. 2). The Hangu Formation was sampled from the bottom to top and numbered in ascending order as given below:

Formation	Sample No.	Characteristic	Thickness
Hangu Formation		Black carbonaceous shale.	0.40 m
	8	Yellow ocherous limonitized laterite with pisolites.	0.40 m
	5	Pisolitic greyish green laterite.	0.70 m
	4	Compact, massive and grey laterite with pisolites (upper part)	1.70 m
	3	Sample as above (lower part)	
	2	Highly pisolitic greyish green laterite with high specific gravity.	1.10 m
		Ash grey to khaki coloured clays.	0.20 m

Another section situated one kilometer east-southeast of the above section on the Changlagali-Khairagali road was also sampled for the sake of comparison. It may be pointed out that the two exposures are situated on either side of the Changlagali Thrust (Fig. 2). The sequence is as follows:

Lithology	Thickness	Correlation with upper section
Black carbonaceous shales	0.60 m	Carbonaceous shales.
Orange-yellow weathering, Soft greyish and greenish lateritic material.	0.50 m	samples 5 & 8
Less pisolitic, compact, dark grey with high specific gravity lateritic material	2 m	Samples 2,3 & 4
and shales.	Very thin	Ash-grey Khaki shales.

GEOCHEMICAL BEHAVIOUR

The analyses were carried out by wet geochemical methods (Table-1). The major geochemical trend is shown in figure 3, as the samples were taken stratigraphically in ascending order. It shows that Al_2O_3 is decreasing whereas Fe_2O_3 is increasing gradually upwards in the sequence that may be due to leaching and weathering effects. Diagenesis may also be a cause of lower percentage of Fe_2O_3. The general trend of desilicification is that SiO_2 is high in ochre type laterite, as it is confirmed from the field evidence, that the top of the formation shows yellow ocherous limonitized laterite. The oolitic and pisolitic part of the laterite is rich in Al_2O_3 and TiO_2 especially at the bottom and in the middle parts of the sequence. Due to diagenetic processes the top of the laterite is deficient in Al_2O_3 and TiO_2.

Table-1 Chemical Analyses of Changlagali Laterite.

Sample No.	2	3	4	5	6
I/L	11.50	10.40	11.30	10.10	15.14
SiO_2	30.40	24.88	19.50	24.50	27.10
Al_2O_3	41.10	40.40	37.00	31.00	28.80

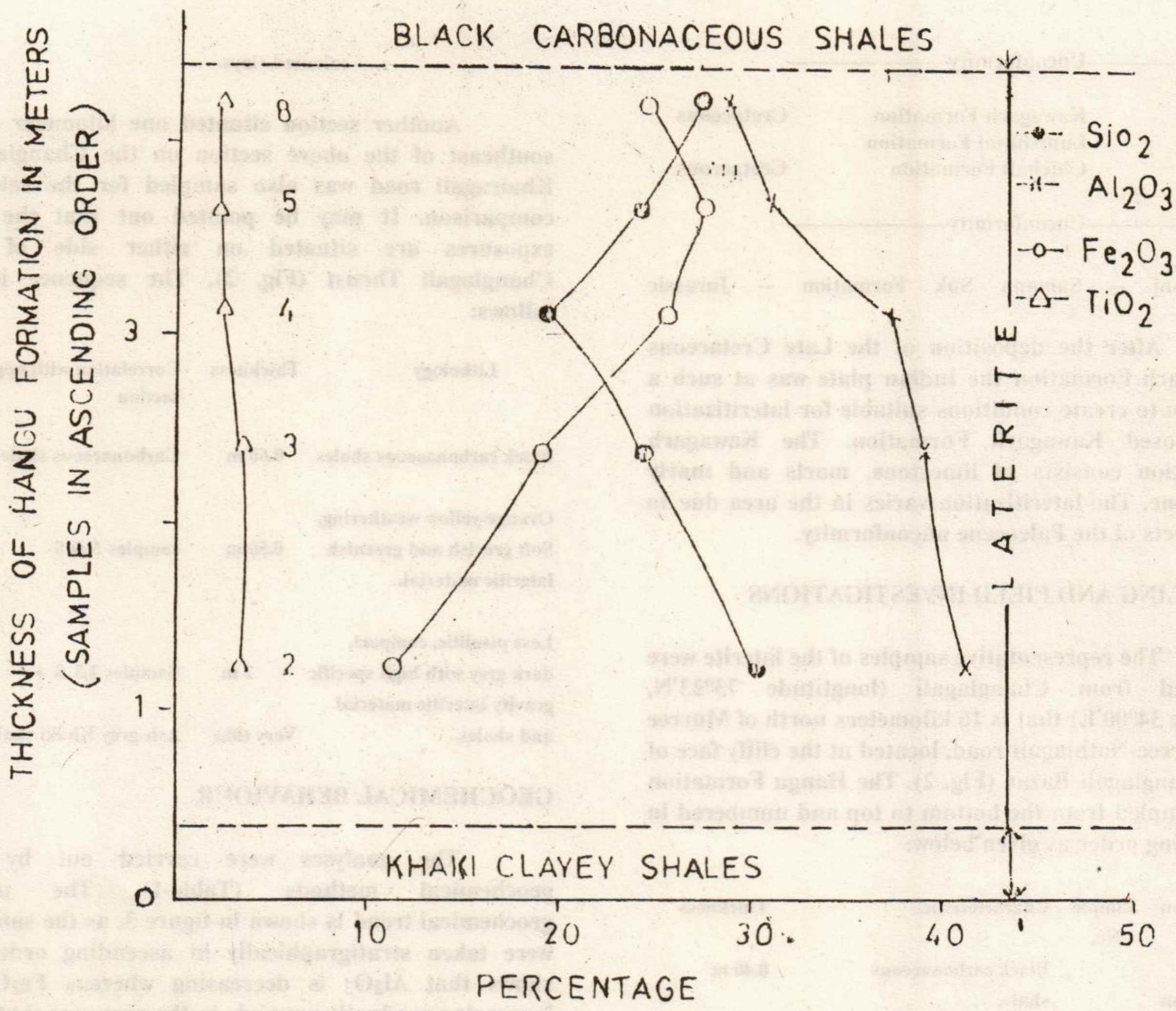

Figure 3 Distribution of major oxides in Changlagali laterite.

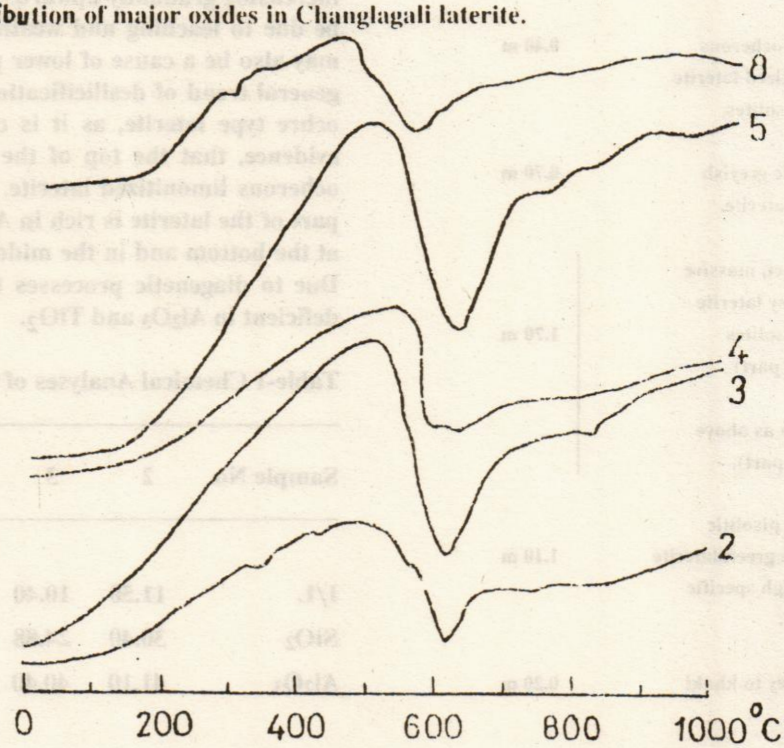

Figure 4 DTA of Changlagali laterite. For explanation see Table-2.

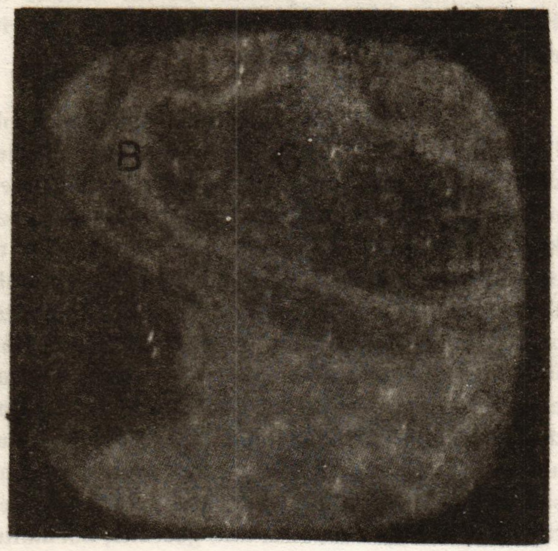

Fig. 5 **Sample No. 3 shows Oolites with Goethite (G) in the centre and Boehimite (B) in the outer rim, Clay minerals are seen in the darker part. (Pol. X4).**

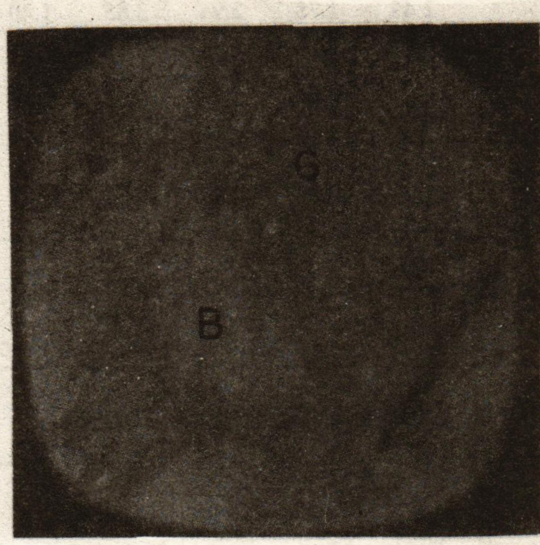

Fig. 6 **Sample No. 4, Two phases of Boehmite (B) Goethite (G) are visible. (Pol. XS).**

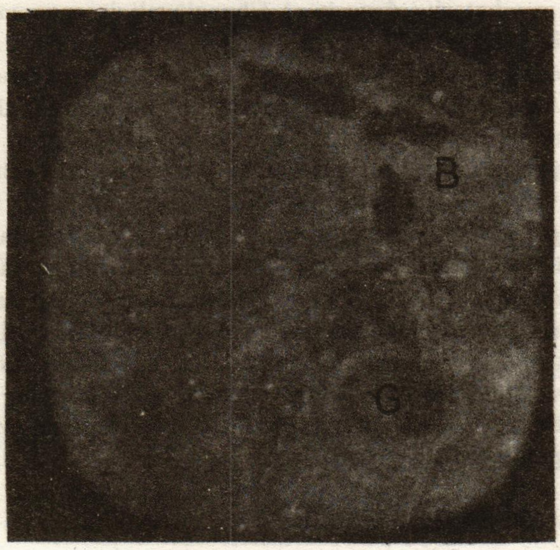

Fig. 7 **Sample No. 5, Boehmite (B) and Goethitic Oolites (G) in the Laterite. (Pol. X4).**

Fig. 8 **Sample No. 2, Boehmite (B) with Limonite (L). The cracks are filled with Calcite. (Pol. X4).**

Fe_2O_3	11.20	19.10	25.50	27.50	24.70
CaO	2.45	1.75	2.94	3.85	1.40
MgO	0.19	0.27	0.19	0.15	0.11
TiO_2	3.07	3.27	2.56	2.57	2.56
TOTAL	99.91	99.87	98.99	99.67	99.81

Table-2 Differential Thermal Analyses of Changlagali Laterite.

Sample No.	Peak Temperature °C	Minerals
2.	350°C Endo	Geothite
	450°C Exo	
	550°C Endo	Boehmite
	620°C Endo	Kaolinite
3.	620°C Endo	Kaolinite
	820°C Endo	Calcite
4.	585°C Endo	Boehmite
	620°C Endo	Kaolinite
5.	620°C Endo	Kaolinite
	770°C Endo	Dolomite
	820°C Endo	Calcite
8.	280°C Endo	Boehmite
	552°C Endo	Limonite

MINERALOGICAL AND CHEMICAL VARIATION

The study of the thin and polished sections has revealed that two phases of the minerals like goethite and boehmite are present (Fig. 6). Boehmite as the major mineral of the laterite which was confirmed by DTA studies (Table-2). However, goethite is not a stable mineral. Cracks of these minerals are filled with limonite (mixtures of Fe-hydroxide). Oolites normally show goethitic composition in the middle, whereas, the rims are composed of dark grey boehmite (Fig. 5 and 7). The dark cloudy parts seen under incident light are of clay minerals (Fig. 5). Calcite and quartz veins are very thin. Some dolomite is also seen in sample no. 5 (Fig. 7). The pisolitic trend of the laterite decreases towards the top of the formation. Clay minerals are present at the top of the formation (Fig. 8) Al_2O_3 varies from 11.20 to 27.50 percent in the reverse sampling order (Table-2). TiO_2 remains relatively constant from 2.5 to 3 percent. SiO_2 shows a range of 19.50 to 30.50 percent. Magnesium is deficient while calcium is a leached product in the laterite of the Hangu Formation. The mineralogy of laterite in different samples is variable.

The percentage of goethite, boehmite, kaolinite, limonite, calcite, dolomite and quartz varies in different samples. In sample number 2, the percentage of boehmite is in major amount whereas goethite, kaolinite, limonite, calcite and quartz in minor amount. Dolomite almost is nil. In sample number 3, boehmite is in major amount, goethite, kaolinite and calcite in minor amount whereas the percentage of limonite, dolomite and quartz is zero. In sample number 4, the percentage of boehmite and kaolinite is dominant and goethite, limonite and calcite in minor amount whereas dolomite and quartz absent. In sample member 5, the percentage of kaolinite and calcite is in major amount and goethite, boehmite and dolomite in minor amount whereas limonite and quartz are absent. In sample number 8, the percentage of limonite is in major amount and goethite, boehmite, kaolinite, calcite and quartz in minor amount whereas percentage of dolimite is zero.

CONCLUSIONS

Laterite deposit at Changlagali is economically important due to its chemical and mineralogical composition. The laterite has moderate contents of Al_2O_3 and TiO_2. The presence of boehmite makes it more significant by hydrometallurgical or pyrometallurgical extraction methods. The value of SiO_2 is apparently high and ranges from 20 to 30 percent. Therefore, it was thought to use this laterite in brick manufacturing industry. On firing at 900°C it imparts a beautiful red colour. Therefore, it can be used in the manufacturing of surface bricks. Studies are also underway to use this laterite for making all weather more resistant bricks, without going into firing process. This work is in progress and will be published shortly.

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CHARACTERISTICS OF AQUIFER SITUATED NORTH OF THE BRIDGE ON MASU WAH AT MIRPUR-MATHELO SIND

By

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ABSTRACT: Tube well hydraulic data of Gudu left bank command area, situated north of the bridge on Masu Wah at Mirpur-Mathelo were analyized for the quantitative characteristics of aquifer. Storage Co-efficient and Transmissibility have been estimated by different standard methods given by Theis, Jacob and Chow.

INTRODUCTION

Ever since the implementation of Indus Basin irrigation Treaty under which India stopped Pakistan's three rivers, resulting into apportionment of Indus waters and construction of gigantic net work of artificial channels which eventually has lead to creation of two main problems i.e. (a) the quantum of already available waters has decreased and (b) below the soil, water table has been elevated considerably.

The shortage of surface water has necessitated to look for and exploit every available aquifer in order to meet the ever increasing demand of water for our agriculture.

For this purpose hydraulic data was collected for tubewell no. 40 situated in Gudu left bank Command area, north of the bridge on Masu Wah at Mirpur Mathelo, Sind (Map. 1). The data has been analyized to investigate quantitative characteristics of the acquifer determining its Transmissibility and Storage Co-efficient.

Geologically the alluvial soil of Pakistan as a whole is adequately porous and permeable to store and convey water. In this context it may be mentioned that many tubewells drilled by government or private agencies are under observation. The ground water observations pertaining to pumping wells and observation wells holes are available with these agencies.

In this connection a spontaneous effort was to collect data (Table-B) and analysize has been made to investigate quantitative characteristics of the aquifer by different standard methods given by Theis (1935), Jacob (1951), and Chow (1952).

LITHOLOGY

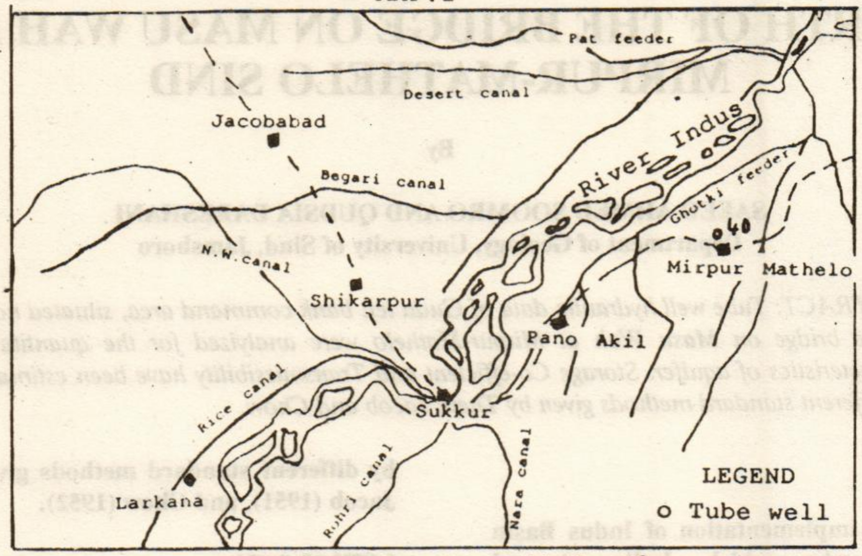
The lithology of the tubewell and observation hole (O, H.) is described in Table-A. The formation consists of layers of mainly fine to very fine sand with occasional thin bands of clay between 10-200 feet. The 10 feet surface consists mainly of clay.

Table - A Lithology of Tubewell and Observation Hole. Tube Well 40

O.H	Depth (feet)	Description of Strata
T.W.	0-10	clay
	10-200	Sand, fine, with small proportions of very fine sand and some thin bands of clay.
S 400	0-21	Clay
	21-66	Sand

Well Hydraulics with Standard Methods: Well hydraulics and methods employed in determining aquifer characteristics are fairly well known and standard procedures have been out-lined in many texts and manuals e.g. Todd (1959), Sharma and Chawla

MAP.1



Location of Tube well No.40

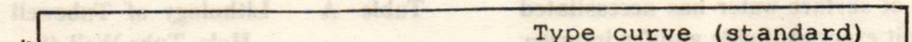


Fig.1 Solution of the non-equilibrium equation
(After Theis)

(1977), Edward and Johnson's Report 1972.

Differential equation for continuity for Depuits assumption cloud be written as:

$$\frac{d^2h}{dX^2} + \frac{d^2h}{d y^2} + \frac{d^2h}{d z^2} = \frac{S.\ dh}{kb\ dt} \text{ ..... (i)}$$

The above continuity equation transformed to polar coordinates and rewritten as:

$$\frac{d^2h}{d r^2} + \frac{1}{r'} \cdot \frac{d h}{d r'} = \frac{S.\ d h}{T'\ dt} \text{ ..... (ii)}$$

Where k = permeability
b = Aquifer thickness
h = Piezometric head
r = Radial distance
t = Time since pumping started

x,y,z = Coordinates along x,y and z axis respectively.

Three popular formulae for solution of above continuity equation (polar coordinates) are those given by Theis, Jacob and Chow which though based on slightly variable premises give the comparable and desired aquifer characteristics.

Assuming that acquifer is homogeneous, uniform isotopic of infinite volume unaided by extra inflow recharge and the well being fully penetrated. Theis derived a condensed equation consisting of a popular parameter known as well function w (u).

$$s = \frac{114.6\ Q}{T\ t} \quad w\ (u)$$

$$u = \frac{1.87\ s\ r^2}{T\ t}$$

Where s = $(h_o - h)$ = Drawdown in ft.
Q = Well discharge in gal/min.
T = Transmissibility Coefficient in gpd/ft.
W(u) = Well function.
S = Storage Coefficient.
r = Distance between pumping and observation wells in ft.
t = Time since pumping started.

Parameter (u) is directly proportional to square of distance and indirectly proportional to time, the value of (u) tends to be very small compared to $\log_e$ u. Considering that 0.5772 = $\log_e$ u 1.78, equation becomes:

$$s = \frac{Q}{4\ \pi\ T\ u} (\log_e 1 - \log_e 1.78)$$

or, in decimal logarithms

$$s = \frac{2.3\ Q}{4\ \pi\ T} \log \frac{2.25\ T\ t}{r^2\ S}$$

It is evident that semi-logarithmic plot of drawdown versus time will follow linear law. Therefore the value of T in the above equation can be determined by

$$T = \frac{264\ Q}{\Delta\ s}$$

Chow using Theis and Jacob formulae for the solution of problem, developed a simplified method for elimination of super imposition matching process, and introduced a function F (u), which is

$$F(u) = \frac{\text{Drawdown at the arbitrary point of tangency}}{\text{Drawdown difference per log cycle}}$$

He also plotted a general curve governing the relationship between the function F(u), and parameter u.

Table-B. Hydraulic data of tubewell No. 40 of Gudu Left Bank Command Area, about 700 yards north of the bridge on Masu Wah at Mirpur Mathelo, Sind. Aquifer depth = 170 ft. Distance between pumping and observation well (r) 400 and Q = 1.9 cfs.

Time since pumping started (t) day	Drawdown in observation well (s) = h_o-h, ft.	$r^2/t = ft^2/day$
6.95×10^{-2}	0.11	2.3×10^{6}
8.33×10^{-2}	0.11	1.9×10^{6}
1.04×10^{-2}	0.12	1.5×10^{6}
1.25×10^{-1}	0.15	1.2×10^{6}
1.66×10^{-1}	0.18	9.6×10^{5}
2.08×10^{-1}	0.21	7.6×10^{5}
2.50×10^{-1}	0.26	6.4×10^{5}

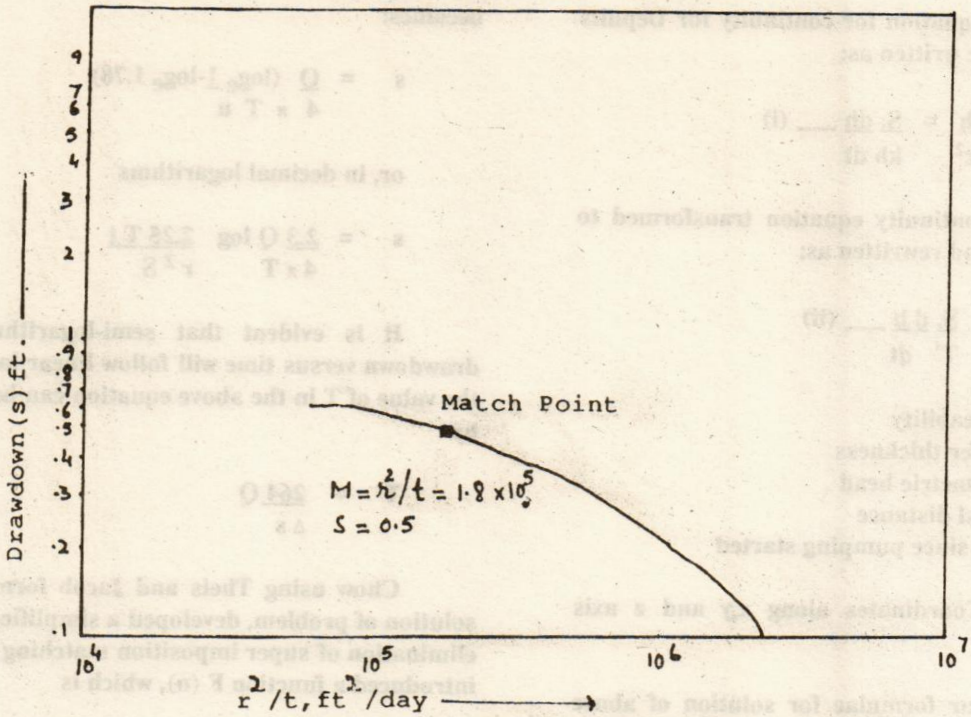


Fig.2 Solution of the non-equilibrium equation
(After Theis)

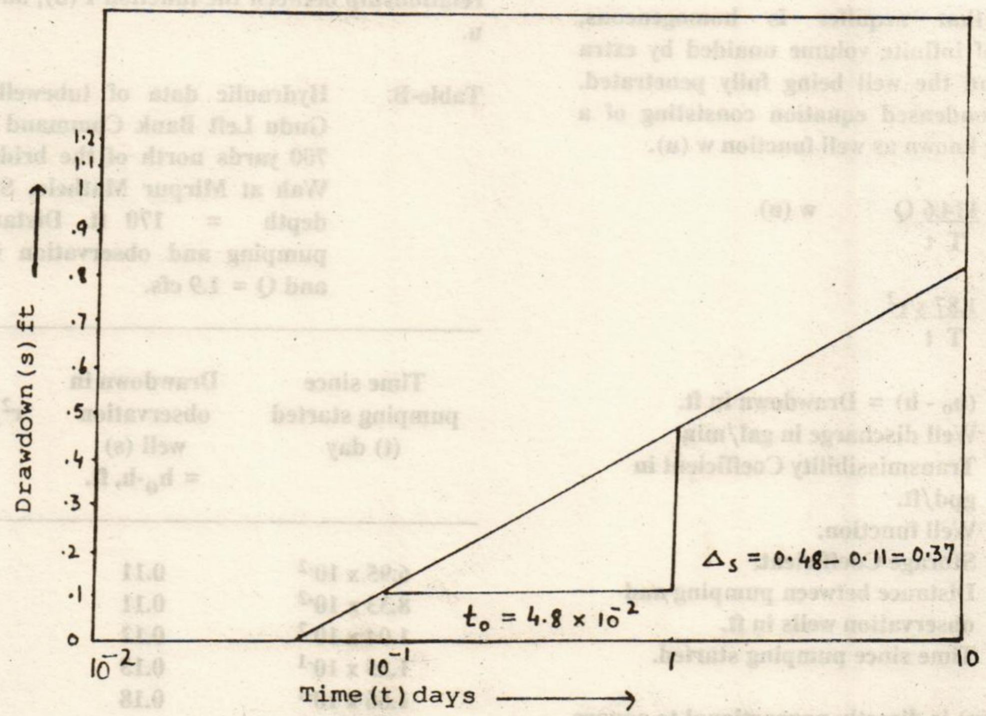


Fig.3. Solution of the non-equilibrium equation
(After Jacob)

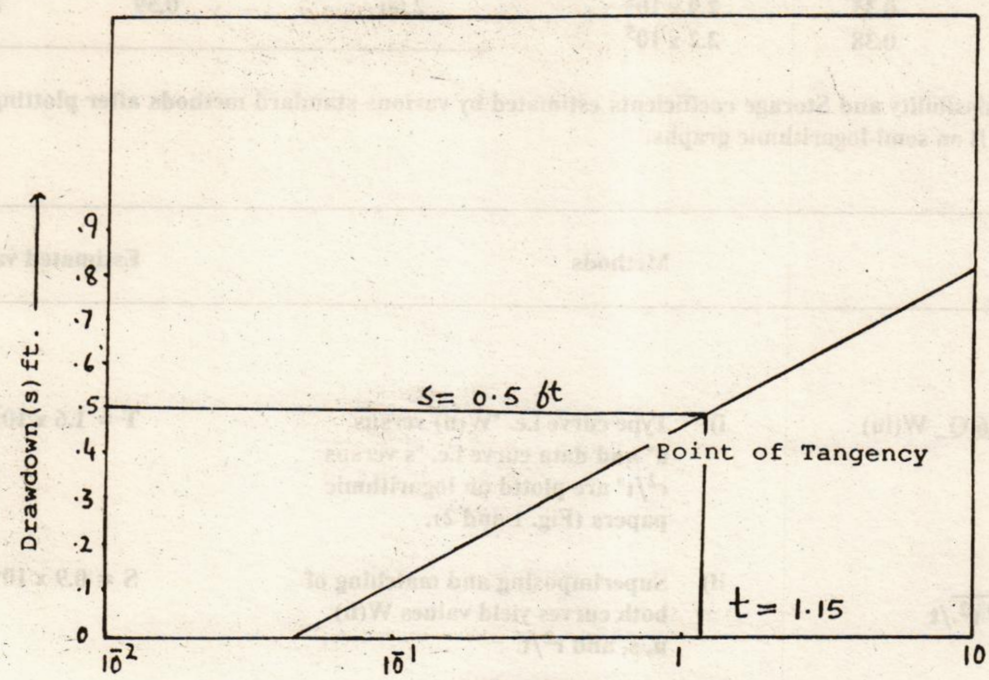


Fig.4. Solution of the non-equilibrium equation
(After Chow)

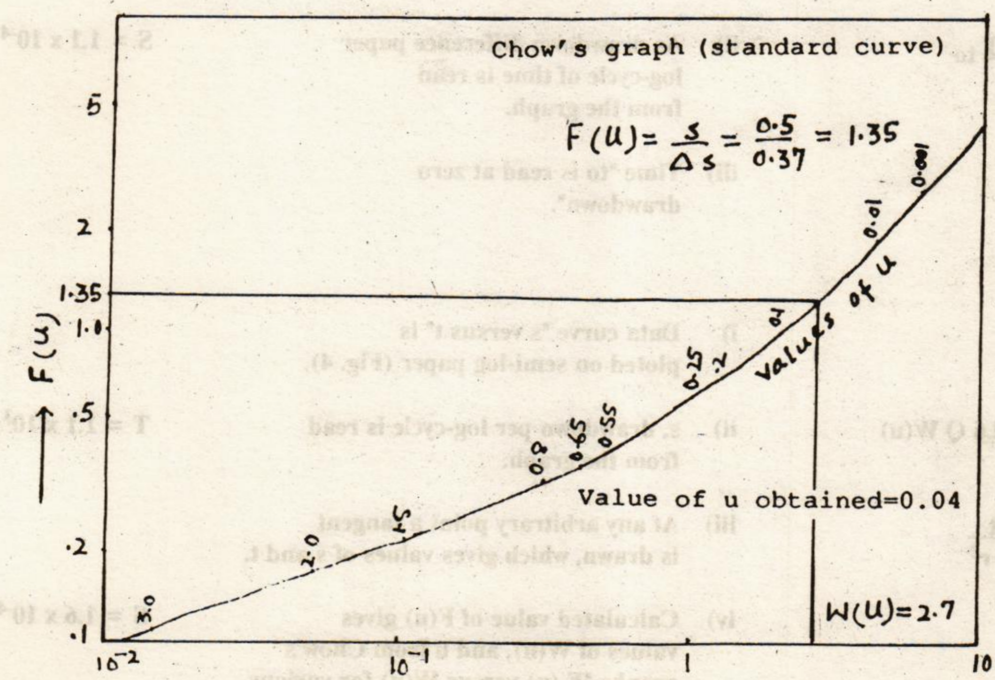


Fig.5 Relation among F(u), W(u) and u
(After Chow)

2.92×10^{-1}	0.28	5.4×10^5	8.75×10^{-1}	0.42	1.8×10^5
3.34×10^{-1}	0.31	4.7×10^5	1.00	0.46	1.6×10^5
4.58×10^{-1}	0.33	3.5×10^5	1.62	0.58	9.8×10^4
5.41×10^{-1}	0.35	2.9×10^5	2.00	0.59	8.0×10^4
7.11×10^{-1}	0.38	2.2×10^5			

Table-C. Transmissibility and Storage coefficients estimated by various standard methods after plotting data from Table - B on semi-logarithmic graphs.

S. No. Formula		Methods	Estimated values
1. THEIS			
i) T	$= \frac{114.6\,Q}{s} W(iu)$	i) Type curve i.e. "W(u) versus u" and data curve i.e. "s versus r^2/t" are plottd on logarithmic papers (Fig. 1 and 2).	$T = 1.6 \times 10^3$ gpd/ft.
ii) S	$= \frac{u\,T}{1.87\, r^2./t}$	ii) Superimposing and matching of both curves yield values W(u) u, s, and r^2/t.	$S = 0.9 \times 10^{-4}$
2. JACOB			
i) T	$= \frac{264\,Q}{s}$	i) Data curve "s sersus t" is plotted on semi log paper (Fig. 3).	$T = 1.3 \times 10^3$ gpd/ft.
ii) S	$= \frac{0.3\,T}{r^2}$ to	ii) As drawdown difference paper log-cycle of time is read from the graph.	$S = 1.1 \times 10^{-4}$
		iii) Time "to is read at zero drawdown".	
3. CHOW			
i) F(U)	$= \frac{S}{\Delta s}$	i) Data curve "s versus t" is ploted on semi-log paper (Fig. 4).	
ii) T	$= \frac{1114.6}{s} Q\, W(u)$	ii) s, drawdown per log-cycle is read from the graph.	$T = 1.1 \times 10^3$ gpd/ft.
iii) S	$= \frac{uTt}{1.87\, r^2}$	iii) At any arbitrary point a tangent is drawn, which gives values of s and t.	
		iv) Calculated value of F(u) gives values of W(u), and u from Chow's graphs "F (u) versus W(u) for various values of u" (Fig. 5).	$S = 1.6 \times 10^{-4}$

CONCLUSIONS

Keeping in view the heterogeneous characteristics of aquifer, it may be pointed out that parameters pertaining to groundwater potential are of unsteady and of varied nature. Hence, there would be enormous variation in estimation of groundwater potential. The conclusions drawn are:

(i) Maximum, average and minimum storage co-efficients calculated by standard methods are of the order of 1.60×10^{-4}, 1.10×10^{-4} and 0.90×10^{-4} respectively.

(ii) Maximum, average and minimum trans-missibility obtained by standard formulae are approximately 1.60×10^{-3}, 1.30×10^{-3} and 1.10×10^{-3} respectively.

(iii) Results obtained by standard methods are found relatively satisfactory.

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A GEOLOGIC STUDY OF BASHA DAM AND ITS APPURTENANCES IN DIAMIR DISTRICT, NORTHERN AREA, PAKISTAN

By

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ABSTRACT: The Basha dam site is situated on the Indus river about 45 km downstream of the town of Chilas. This is purely meant for hydel power. Rocks exposed at the dam site are predominantly igneous complex, comprised of norite with subordinate peridotite, hornblendite and quaternary deposits. Geological map is presented with the possible location of main dam and its essential appurtenances. The locations of appurtenances are essentially examined and discussed.

INTRODUCTION

The Indus river is the main source of hydel power in Pakistan. The drop along Indus river at places shows attractive locations for hydroelectric power. Basha is a site which is selected by WAPDA and the foreign consultants, about 45 km downstream from the town of Chilas, near the Basha village along the Karakorum Highway. The Basha reservoir will be a newly created storage reservoir in the Kohistan (Khan, 1982). It could be partly used to substitute the existing reservoir at Tarbela Dam during drought period. Millions of cubic feet of water can be utilized for production of electricity by construction of Basha dam.

GENERAL GEOLOGY

The proposed dam site is located on the Kohistan island arc (Tahirkheli, 1979; Bard *et al.*, 1980; Ghazanfar *et al.*, this volume), a huge igneous and metamorphic complex, sandwiched between the Indian plate to the south and the Asian plate to the north. This island arc is divided into a southern amphibolite, diorite mass and a northern granite-granodiorite mass (Jan and Howie, 1981) separated by a huge east-west trending belt of norite. This norite belt starts from near Chilas and extends westwards through Dir into Afghanistan. A Cretaceous to Eocene age has been proposed for the Kohistan island arc (Patriot and Acheche, 1984; Coward *et al.*, 1987).

GEOLOGY OF THE DAM SITE AREA

The rocks exposed at the dam site are mainly peridotite, hornblendite, norite and quaternary deposits (Fig. 1 and Table-1).

Table-1 Geology of the Basha Dam Area.

SCREE	**About 4% of the total area. They are colluvial deposits. Angular coarse grained material is normally at the base and relatively fine at the top.**
SAND	**About 10% of the total area. At some places pure sand and also include silty sand. It is unconsolidated and normally washed during flood time.**
MORAINE DEPOSITS	**About 15% of the total area. Angular boulder and gravel material with fines in compacted form. Heterogeneous material available in deposit.**

CLAYEY SILT	About 2% of the total area. It is a fine grained, hard and compact deposits. Normally found on left and right ridges. Shows lacustrine deposits.
SANDY SILT	About 3% of the total area. Origin is uncertain. Low plasticity index found at left ridge downstream of the main axis.
GRAVELLY SAND	Very nominal quantity of gravelly sand present at the outlet area of tunnels. Gravels range from 20-25% in the medium to fine grained sand.
HORNBLENDITE	About 3% of total area. Blackish hard and coarse grained. Composed mainly of hornblende and plagioclase with some biotite. About 400 m upstream of dam axis.
PERIDOTITE	About 3% of total area. Light brown and fine to medium grained. Mainly composed of olivine and pyroxene. Located at 400 m to 500 m upstream of the main dam axis.
NORITE	About 60% of total area. Light grey and fine to medium grained. It gives massive appearance. It constitutes plagioclase,hornblende and pyroxene (ortho/clino pyroxene).

Note: percentages given are for the mapped area.

SALIENT FEATURES AND ASSOCIATED PROBLEMS

Basha dam consists of main embankment, coffer dam, diversion tunnels, spillway, power tunnels and power house.

Coffer Dam and Diversion Tunnels: Coffer dam may be defined as temporary structure made up of earth, rock and timbers or sheet piling, across the river to keep the proposed area dry and to divert its path. Straight 15 m dia diversion tunnels about 1 km long can be aligned easily on the right abutment. These tunnels will provide sufficient room to pass maximum flood during summer and monsoon time. The excavation may be started at the same time from upstream portals at elevation 960 m and 950 m respectively. Tunnels are straight, horizontal and are in the uniform lithology of norite. Slopes facing to intake area of diversion tunnels, must be stabilized by rock bolting and guniting the face. Blockage in the intake area of diversion tunnels may cause the flood in the main construction area (Fig. 1).

Embankment: There are three different proposed sites for the dam on the Indus river near Basha. In the text, only the suitable one is discussed and shown on the map (Fig. 1). The axis on the river loop is considered to be the best because it provides maximum space, which helps in reducing the current and exerts less concentric pressure on the embankment. The dam site is situated in a river section with steep rock slopes, in a V-shaped valley, covered locally with talus and scree. River section widens to U-shape both upstream and downstream of the dam axis. The left abutment is mainly a steeply dipping rock slope which rises sub-vertically from the river bed level of 950 m to over 2000 m elevation. The bed rock lies at the depth of about 48 m below the alluvium (MECO, 1983).

Spillway and Power Tunnels: Spillway is a structure which allows extra water from the reservoir to pass safely downstream of a river. Controlled chute spillway has been proposed at the Basha dam. Right abutment is suitable and possibility of building power house and tunnels can also be considered at this abutment. S-loop provides the most suitable topography for placing the power house downstream of the main dam axis and the intake area upstream of the main dam axis (Proposal-1; Fig. 1).

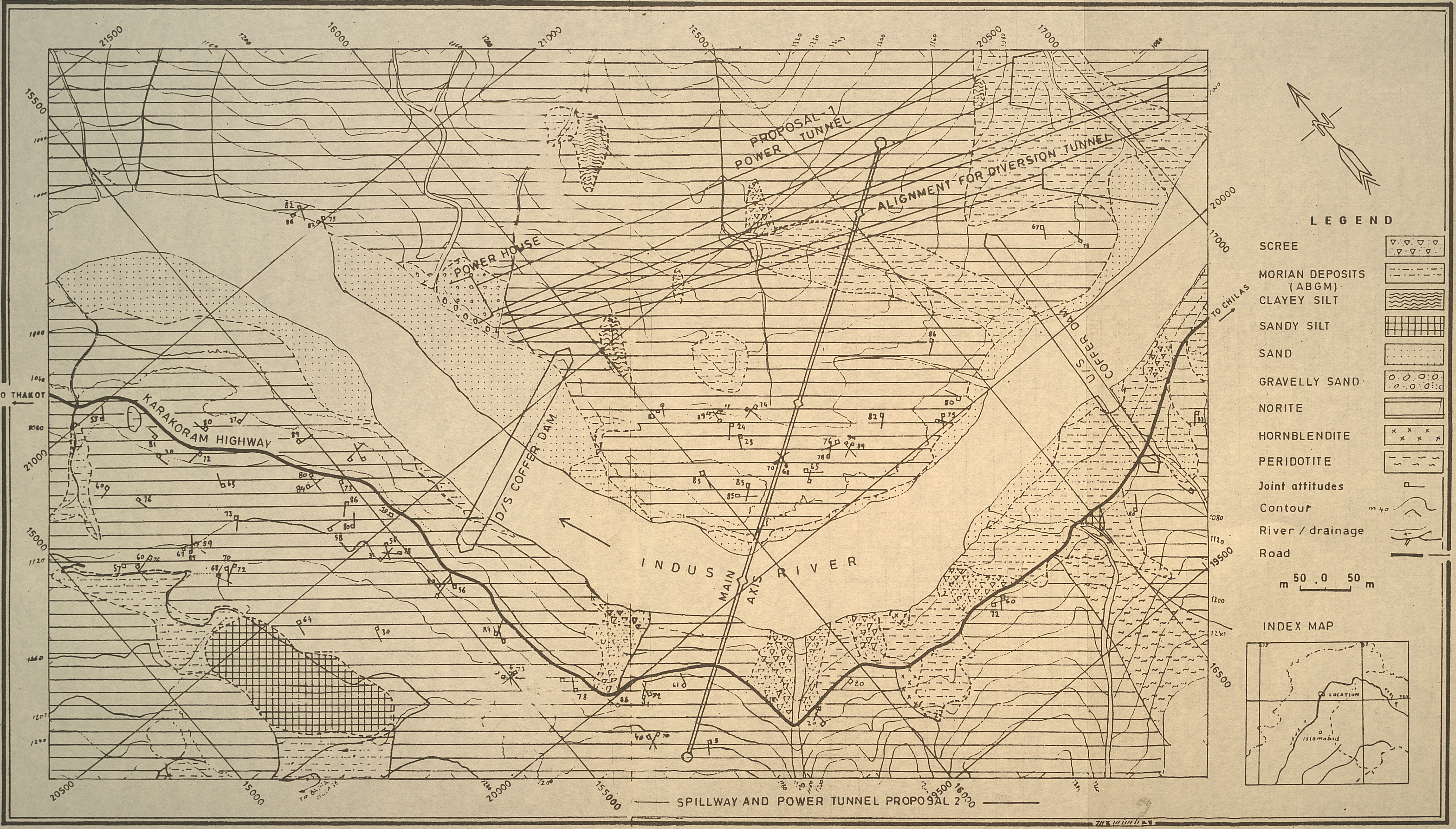

Fig.1 Geology and salient features of Basha Dam

The left abutment of the valley near the dam axis is also suitable for power tunnels and spillway. Power tunnels are the outlet of water which carry the water from reservoir to power house to generate the hydel energy. At left slope, rocks are massive and hard, and shows high rock mass strength, even though rocks are shattered at the surface due to blasting for the KKH. Six tunnels may be constructed and intake area may be at 400 m or 500 m upstream of main dam axis. Tunnels may be curved and taken out in the downstream region for power house (Proposal-2; Fig. 1).

Controlled gated spillway is proposed for the Basha Dam. It may have 6 or 7 gates, about 20 m wide and 20 m high, anchored to 5 m thick piers by system of post tensioning anchors. The spillway will consist of chute channel, flip bucket and plunge pool. Emergency spillway can be constructed at the rim of reservoir for an extraordinary flood.

DISCUSSION

In general, the dam site is ideally good for reservoir. Coffer dams, at Basha may be constructed by earth and rock material obtained from the excavation of diversion tunnels. Material excavated at downstream and upstream portals may directly be placed at 500 meters and 800 meters down and upstream of the main dam axis. The height of coffer dam may range from 25-30 meters. Good quality riprap will also be needed to protect the downstream and upstream slopes of the coffer dam.

At the dam site, the bed rock lies at the depth of about 48 m below the alluvium (MECO, 1983). A concrete dam is not feasible due to great depth of the bed rock. Earth-fill dam is also not advisable due to the limited quantity of impervious material in the vicinity of the area. Earth-rock fill dam will be the suitable type. Because, the plentiful supply of rock fill and sufficient earth for core is available in the localities of Thor and Thurly areas.

The Karakorum Highway is aligned on the left side of the Indus valley. The blasting has caused extensive overbreak and loosened rock mass at lower elevation of the Karakorum Highway. Both abutments need complete removal of the scree and weathered materials from the slopes. Concrete cut-off and curtain may be constructed in the foundation all along the axis of the embankment to minimize the possibilities of seepage. Filters and series of relief wells must be designed along the toe of the main embankment.

There are two proposals for the power tunnels (Fig. 1). Right abutment is suitable and possibility of building power house and tunnels can also be considered at this abutment. S-loop provides the most suitable topography for placing the power-house downstream of the main dam axis and the intake area upstream of the main dam axis (Proposal-1; Fig. 1). At left slope, rocks are massive and hard and show high rock mass strength (Proposal-2; Fig.1). In this case, the tunnels will be long and curved and power house may be placed somewhere three or four kilometer downstream of the main dam axis. Intake area of power tunnels should be very carefully cleaned and properly treated for all sorts of problems like rock fall, sliding, erosion of material and development of pore water pressure.

The spillway should consist of chute channel connected with flip bucket. The water should finally discharge in a pre-excavated plunge pool. Emergency spillway can also be constructed at the rim of reservoir for an extraordinary flood.

It is essential to bear in mind that the proposed dam site though suitable from the design and storage point of view is nevertheless located in a seismically active zone of the Himalayas. Numerous faults and shear zones are present in the area to the east (Coward *et al.*, 1987). The area also has a seismic history. Construction of dam and filling of reservoir lake could provide stimulus to local seismic affects. Apart from the local seismic activity and other faults, the Main Mantle thrust which forms the northern boundary of Indian plate, is located at a distance of about 35 km to the south of Basha and dips towards dam. The tectonics and associated problems could possibly affect the design of the dam. A detailed seismic study should be an essential part of any future feasibility works.

CONCLUSIONS

The preliminary study shows that the proposed dam site is proper and calls for detailed feasibility report. The shortage of impervious material in the vicinity of the dam site and the great depth of the bedrock constraint the choice to be an earth rock fill dam. The relief is high which can allow 200 m plus height of the dam. If the dam axis is placed at the middle of the meander loop, ample room would be available for the fitting and placement of other structures. The right abutment is considered more suitable for the location of power tunnels. However, to avoid concentration of structures, the left abutment can also be selected, though it would increase the overall cost of construction. The right abutment allows for the location of short and straight power tunnels. Karakorum Highway will be completely under water after accumulation of reservoir of Basha dam, so a new alignment may be investigated for the Karakorum Highway.

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ENGINEERING GEOLOGICAL AND PETROGRAPHIC EVALUATION OF META-DOLERITES OF BULAND HILL AND CHAK-123 QUARRIES OF KIRANA HILLS, DISTRICT SARGODHA, PAKISTAN

By

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ABSTRACT: A new source for concrete aggregate from Buland Hill and Chak-123 quarries of Kirana Hills has been studied for the first time. A geological map from the engineering point of view related to active quarry zone is presented. A study of engineering geological properties such as unconfined compressive strength, aggregate grading, dry unit weight, apparent specific gravity, water absorption, flakiness and elongation index has been carried out and discussed critically with reference to its suitability and stability in the text. Petrographic evaluation of meta-dolerites has been carried out from Alkali-Silica-Reaction (ASR) point of view. It has been found that grey to dark grey meta-dolerites are non-deleterious whereas greenish varieties of meta-dolerites deeply weathered or hydrothermally altered are potentially deleterious with respect to Alkali-Silica-Reaction. The deleterious constituent is hydromica produced by the alteration of feldspar. The expected reaction will be of Alkali-Silicate type.

INTRODUCTION

The American Society for Testing Materials (1986) defines the term "Aggregate" as in the case of material of construction, designates inert material, when bound together into a conglomerated mass by a matrix, forms concrete. It is a man made composite, the major constituents of which are natural aggregate such as crushed rock, gravel, sand and cement. About 70% of the concrete consists of aggregate, therefore, aggregates properties have a significant effect on concrete after setting.

Kirana Hills are the important source rocks of aggregate in Central and Northern Punjab. The hills in the Kirana, Chiniot, Shahkot and Sangla areas are the only outcrops of Precambrian rocks exposed in the plains of Punjab. The Shahkot rock exposures are almost quarried while there is a limited quarrying activity in the Sangla Hill area. The main quarry activities of aggregates are within the isolated hills of Chiniot, Rabwa, Sikhanwali and Shaheenabad. Here Buland Hill and Chak-123 quarries are specially taken into account because these are well known in the market for crushed stones. Millions of tons of aggregates have been quarried and supplied to different parts of the Punjab for concrete aggregate and civil engineering structures.

Buland Hill and Chak-123 quarries provide various types of aggregates. These aggregates vary with respect to their petrography, physical appearance and engineering geological parameters. Many rocks which are being used are deleterious and result, after use, in the deterioration of the structures through Alkali-Silica-Reaction (ASR) and low strength. Since, the deterioration is gradual, therefore, losses incurred as a result run into billions of rupees. Concrete aggregate for the Runway of Lahore International Airport was also supplied from this area. Aggregate supplied was of low strength and deleterious with respect to ASR which caused cracks and deterioration in the concrete slab.

GEOLOGY OF THE AREA

The geology of Kirana Hills have been studied by Davies and Crawford (1971), Gee (1935), Heron (1923) and Shah (1973). The rocks of Kirana area have been described under Kirana Group (Shah, 1973). The rocks of Kirana are further divided into five lithostratigraphic units (Fig. 1). Three units namely

Hachi volcanics, Asianwala quartzite and Taguwali slates have been included in the Kirana Group. An other new Sharaban group except Kirana Group has been proposed by Sarwar (1987; Table - 1). It comprises two units of calcareous conglomerates and calcareous sandstone. The contact relationship is uncertain and yet to be worked out (Sarwar, 1987). These units are exposed only in isolated hill called Sharaban. These units are considered to be younger than the Kirana Group.

The most conspicuous intrusive rocks are represented by basic sills which are present throughout the area. These rocks are green to dark green and at places greyish in shades. The general trend of the intrusive sills is NW-SE, normally parallel to the strike of the metasediments. These sills are called meta-dolerites.

Table - 1 Stratigraphy of the Kirana Hills, District Sargodha, Pakistan (Sarwar, 1987).

GROUP	FORMATION	DESCRIPTION
	Sharaban Conglomerate	**Conglomerate is dull rusty brown, contains pebbles of quartzite, slate and limestone embedded in calcareous matrix. Thickness 119 m.**
Sharaban group	**Hadda quartzites**	**Quartzites are dull rusty brown, fine grained and calcareous. These are typical of shallow marine or deltaic in origin; containing minor conglomerate beds and rare lava flows. Thickness 372 m.**
	Asianwala quartzites	**Quartzites are light grey to dirty white, mottled brown, medium to coarse grained, cross bedded, ripple marked and contains minor interclations of slate. Thickness 248 m.**
Kirana Group	**Taguwali phyllites**	**Phyllites are light grey with minor interclations of quartzites. Lower part is fine grained quartzite and cross bedded. Thickness 1190 m.**
	Hachi volcanics	**Slates, minor quartzites with abundant tuff and lava flow of acidic composition. Thickness 440 m.**

METHODOLOGY

Buland Hill and Chak-123 quarries are remapped specially from engineering point of view related to active quarries as well as the intensity of operational crushers.

The meta-dolerite samples are either dark grey or green to greyish green. Samples of both types were taken in order to find out the possible differences between the two colour groups (Tables- 2-5). A total of eighteen samples of meta-dolerite, 12 from Buland Hill and 6 from Chak-123 quarries have been collected by Mr. Khan in October, 1988 for their physical, petrographic and engineering geological studies. Samples of Buland Hill and Chak- 123 quarries are represented by BH and CH prefixes (Tables 3 - 5). Cores and crushed samples from both quarries were collected from different localities and processed through crusher separately to see the crushing behavior of the rocks (Table - 3). The engineering geological properties have been determined in accordance with ASTM specifications. The petrographical studies have been carried out in accordance with ASTM-295.

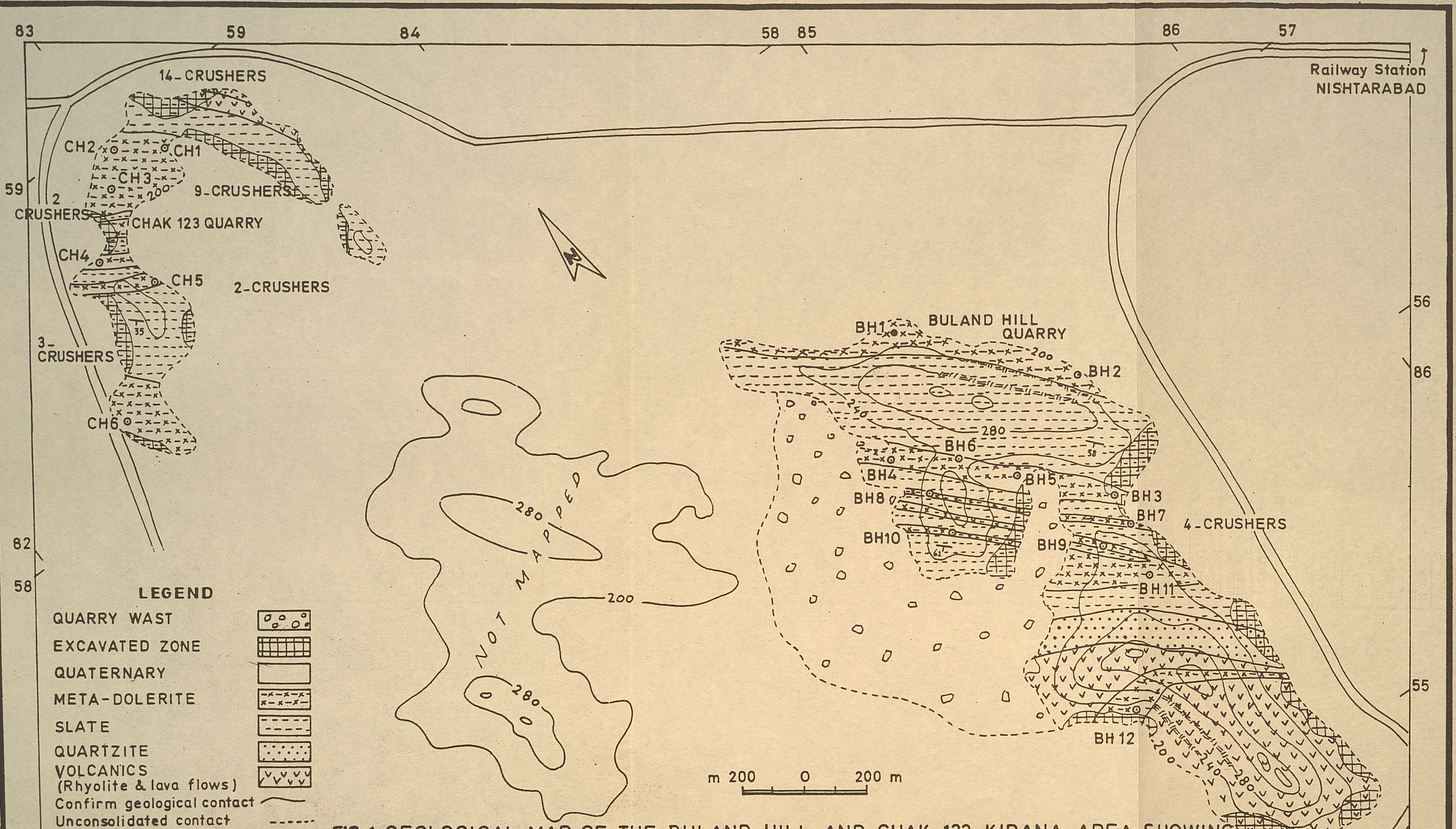

FIG. 1 GEOLOGICAL MAP OF THE BULAND HILL AND CHAK-123, KIRANA AREA SHOWING ACTIVE SITES OF QUARRIES

Table - 2 Physical Properties of Meta-dolerites from Buland Hill and Chak-123 Quarries.

SAMPLE	FRESH COLOUR	WEATHERED COLOUR	TEXTURE	SHAPE OF AGGREGATE WHILE BROKEN	JOINTS	FINES AND COATING
Meta-dolerite	Dark grey or greenish	Dull green to greenish	Medium to coarse	Sub-angular to angular	Relatively tight joints as compared to other lithologies	No coating No washing required

Table - 3 Engineering Geological Properties of Buland Hill and Chak- 123 Quarries.

S. No.	Apparent Sp. Gr.	Water Absorption %	Dry Unit Weight lb/cft.	Los Angeles Abrasion	Flakiness %	Elongation %	U.C.S. after crushing psi	Retained on seive 4 %
BH$_1$	2.84	0.17	184.8	15.0	13.25	18.0	25250	> 50 %
BH$_5$	2.81	0.17	184.0	15.0	14.0	18.9	25813	< 50 %
BH$_6$	2.95	0.12	180.2	16.0	--	--	26110	56 %
BH$_{10}$	2.89	0.16	182.0	15.5	--	--	> 24000	55 %
CH$_1$	2.90	0.11	170.8	16.0	13.0	19.0	20308	> 50 %
CH$_3$	2.87	0.17	184.5	16.0	12.5	20.0	25800	> 50 %
CH$_4$	2.95	0.13	183.0	16.5	12.0	20.5	--	> 50 %
CH$_6$	2.92	0.12	180.8	15.5	--	--	--	> 50 %

Table -4 Petrographic Composition of Meta-dolerites of Buland Hill Ouarry, Kirana Hill.

	BH-1	BH-2	BH-3	BH-4	BH-5	BH-6	BH-7	BH-8	BH-9	BH10-	BH-11	BH-12
Plagioclase	55.0	53.0	52.0	52.0	45.0	43.0	41.0	30.0	24.0	21.0	20.5	18.0
Pyroxene	--	--	--	18.0	25.0	--	--	--	--	3.0	--	--
Amphibole	26.5	38.5	40.0	6.0	5.0	38.0	--	--	--	5.0	--	5.0
Epidote	3.0	--		3.0	4.0	4.0	8.0	20.0	14.0	12.0	29.0	18.5
Chlorite	5.0	0.5	0.4	--	--	4.0	16.0	35.5	40.0	29.0	29.0	29.5
Quartz	1.0	1.3	1.0	--	--	--	12.0	--	07.0	6.8	11.5	7.5
Sphene/ Leucoxene	4.0	5.0	4.1	5.0	5.0	6.0	1.0	5.5	3.0	4.7	3.0	4.0
Olivine	--	--	--	12.0	8.0	--	--	--	--	--	--	--
Magnetite/ Ilmenite	2.0	1.0	2.1	--	--	--	5.0	1.0	3.0	2.0	--	6.0
Limonite/ Hematite	--	Tr.	Tr.	Tr.	Tr.	Tr.	--	0.5	2.0	--	1.5	--
K-feldspar	--	Tr.	--	Tr.	--	--	0.5	--	--	--	--	--
Hydromuscovite or illite	0.5	0.7	0.4	4.0	8.0	1.0	2.0	5.0	5.4	4.5	5.5	5.3
Calcite	3.0	--	Tr.		--	3.0	16.0	2.0	1.6	12.0	--	6.2
Pyrite	Tr.	--	--	Tr.	--	1.0	--	--	--	Tr.	--	--
Apatite	Tr.	--	Tr.	--	--	--	0.5	0.5	--	--	--	--

Table - 5 Petrographic Composition of Meta-dolerites of Chak-123, Ouarry, Kirana Hill.

	CH-1	CH-2	CH-3	CH-4	CH-5	CH-6
Plagioclase	48.0	40.0	34.0	30.0	5.2	3.0
Pyroxene	20.0	--	--	--	--	--
Amphibole	7.0	32.2	29.0	--	34.0	32.5
Epidote	5.0	8.0	10.5	3.5	31.0	31.0
Chlorite	--	4.3	5.3	36.0	6.5	8.5
Quartz	--	2.0	4.5	12.0	13.3	13.5
Sphene/Leucoxene	6.0	5.0	6.5	5.0	5.2	7.0
Olivine	10.0	--	--	--	--	--
Magnetite/Ilmenite	--	3.0	3.3	--	3.0	3.3

Limonite/Hematite	--	--	--	0.5	--	--
K-feldspar	--	Tr.	2.0	--	Tr.	--
Hydromuscovite or Illite	4.0	4.5	3.9	1.0	0.8	0.7
Calcite	--	1.0	1.0	12.0	1.0	0.5
Apatite	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.

DISCUSSION

The samples from Buland Hill and Chak-123 quarries were tested on the basis of their physical appearance, engineering properties and petrography. Meta-dolerites exhibit the characteristics of a good quality rock.

About 50% coarse aggregate can be obtained after crushing the meta-dolerites. The shape of the crushed aggregate are sub-angular to angular which helps in getting a good bonding and interlocking of aggregates in concrete. Flaky and elongated particles are within the limits of ASTM-295 specifications (Table - 3). The rocks show high unconfined compressive strength ranging from 24,000 psi - 26,000 psi while weathered samples show low strength. Abrasion from 15.5% - 16.5% show that the rocks are sound and have good cementation. Quarries are running mostly in slates, rhyolite and at the contact of meta-dolerite (Fig. 1). The owners of the crushers do not like to crush the meta-dolerite because of its high strength. It is quite hard and badly effects the machines and gives low progress.

Most of the rocks, quartzite, slate, rhyolite and portion of meta-dolerite of Kirana have deleterious and reactive constituents (M. N. Chaudhry verbal commun., 1987). Due to the reaction of caustic alkali solution and reactive silica, the alkali gels of varied composition are produced. The absorbed water and resulting osmotic pressure may fracture the concrete (Callson, 1944; Diamond, 1975).

Detailed petrographic studies in accordance with ASTM-295 were carried out of 18 samples of meta-dolerites from Buland Hill and Chak-123 area. The petrographic composition of these rocks is given in (Tables- 4 and 5).

Both grey as well as greenish varieties of meta-dolerites were studied petrographically and in the field. The field and petrographic studies show that the greenish samples are mainly from weathered parts of the meta-dolerites.

The only deleterious constituent in these rocks is hydromica which is formed due to alteration at the expense of plagioclase. A careful comparison of greenish samples which are weathered and greyish parts which are fresh, shows that, the former are generally much higher in hydromica than the latter.

However, it may be pointed out that some areas with greenish colour are in fact hydrothermally altered and may be encountered even at depth. Whether the alteration is due to hydrothermal activity or weathering, the resultant greenish colour indicates deleteriously high amount of hydromica, associated with the alteration of feldspar. It may be concluded that grey outcrops are non-deleterious with respect to ASR while greenish outcrops are generally deleterious.

The reaction between deleterious parts of meta-dolerite is dependent upon hydromica. This reaction will be of Alkali-Silicate type. It is likely to be slow and may not be noticed for quite sometime, in a concrete fabricated with ordinary portland cement.

It may be pointed out that some of the green meta-dolerite samples have hydromica slightly below the higher limit of ASTM specifications, yet as a rule of thumb these may be excluded from quarrying (Tables - 4 and 5).

CONCLUSIONS

On the basis of physical, engineering geological and petrographical properties, it may be concluded that meta-dolerites in general, can be used safely in concrete according to ASTM-295 specifications. Meta-dolerites exhibit highly appreciable engineering properties for concrete aggregates. Los Angeles Abrasion ranges from 15 to 16 percent which is good indication for its bonding characteristics. Unconfined compressive strength also quite high ranging from 20,000 to 26,000 psi. More than 50 percent material is produced as coarse aggregates after crushing.

ACKNOWLEDGEMENTS

The authors greatly acknowledge the owners of the crushers of the project area specially Mr. Ghazanfar Ali and Mr. Muzaffar Ali of Chak 120 who co-operated throughout the field trip and during sampling. Critical review of manuscript by M.S. Baig is acknowledged.

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kashmir Journal of Geology, Vol. 8 & 9, 1991

GEOLOGY OF RESHIAN-NAUSERI AREA, AZAD JAMMU AND KASHMIR, PAKISTAN

By

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The 307 square km area between Reshian and Nauseri has been geologically mapped on toposheet Nos. 43 F/11 and 43 F/15. This communication presents a summary of this study. Detailed work will be published elsewhere.

The Reshian-Nauseri area lies in the Pir Panjal Range of the Lesser Himalaya. A Precambrian to Late Paleozoic sequence of the northern margin of Gondwana is imbricated by northeast dipping thrust faults. The major thrust faults from south to north are; the Murree Thrust and the Panjal Thrust (Wadia, 1931). The Murree Thrust emplaces the rocks of Late Paleozoic Panjal formation onto the Oligocene to Miocene Himalayan molasse of the Murree Formation. Whereas, the Panjal Thrust emplaces the Precambrian Tanol formation and intrusive early Paleozoic granites onto the rocks of the Panjal formation.

The Precambrian Tanol formation is dominantly psammatic and pelitic in nature. It is composed of quartz-mica schist, chlorite-biotite-quartz schist and garnet-quartz-mica schist. The petrography of the Tanol formation is presented as follows:

Quartz-Mica Schist: **Quartz (70-80%), muscovite (2-6%), plagioclase (2-6%) and epidote (2-5%).**

Chlorite-Biotite-Quartz Schist: **Quartz (40-67%), chlorite (20-35%), biotite (10-12%), plagioclase (2-6%) and epidote (2-3%).**

Garnet-Quartz-Mica Schist: **Quartz (62-63%), biotite (12-23%), muscovite (4-16%), garnet (4-8%) and epidote (2-3%).**

The Precambrian Tanol formation (Ghazanfar *et al.,* 1983) is intruded by the Jura and Reshian-Nauseri granite gneisses. These granites do not intrude the Late Paleozoic Panjal formation. The Jura granite is a two mica porphyritic granite gneiss. It is mainly composed of quartz (30-60%), plagioclase (10-35%), orthoclase (10-25%), microcline perthite (8-20%), muscovite/sericite (7-10%), biotite (2-8%), garnet (1-4%), sphene (1-2%), tourmaline (1-2.5%), epidote (1-3%), apatite (1-1.5%) and iron ore (1-2%). The Reshian-Nauseri granite gneiss is a two mica flaser granite gneiss. It is composed of quartz (25-75%), plagioclase (5-35%), orthoclase (5-10%), microcline perthite (10-30%), muscovite/sericite (5-15%), biotite (3-15%), epidote (2-15%), opaque minerals (1-5%), chlorite (1-2%), apatite (1-2%), sphene (1-2%), garnet (1-2%) and zircon (0-0.5%).

These granite gneisses are similar in lithology to the Early Paleozoic Lesser Himalayan peraluminous granites. The Early Paleozoic peraluminous granites (Baig and Lawrence, 1987; Baig *et al.,* 1988) and associated metamorphism in northern Pakistan have been interpreted by Baig *et al.* (1989) related to the Early Paleozoic orogeny. We interpret that the Reshian-Nauseri and Jura granites may have intruded during the Early Paleozoic orogeny. However, in the Reshian and Jura areas, yet no geochronologic evidence for pre-Himalayan metamorphism and deformation has been documented to confirm the Early Paleozoic orogeny.

The Early Paleozoic orogeny may relate to the amalgamation of Gondwana as a supper continent (Baig and Lawrence, 1987; Baig *et al.,* 1988). This tectonic event occurred before the Permo-Triassic breakup of Gondwana (Baig and Lawrence, 1987; Baig *et al.,* 1989).

During the Permo-Triassic, The Panjal formation was deposited on the northern margin of Gondwana. The Panjal formation constitutes tuffs, agglomerates, greenstones and marbles (Wadia, 1934).

Tuffs: **Tuffs are composed of angular fragments of basic volcanics, white quartz, grey slate and brown** dolomite in fine to medium grained matrix of quartz and muscovite. Tuffs are composed of quartz (60-70%), potash feldspar (1-5%), hydro-mica (10-15%), pyrite (2-5%), magnetite (2-5%), chlorite (2-6%) and cherty rock fragments (5-10%).

Agglomerates: Agglomerates are composed of agglomeratic sandstone, conglomeratic sandstone, quartz-mica schists, graphitic schists and fragments of volcanic material, phyllites and tuffs.

Quartz-Mica Schist: It comprises quartz (65-70%), biotite (5-25%), chlorite (2-20%), muscovite/sericite (5-10%), plagioclase (1-5%), iron ore (1-5%) and garnet (0-1%).

Graphitic Schist: It consists of quartz (20-40%), carbonaceous material (30-60%), plagioclase (5-8%), muscovite/sericite (5-10%), iron ore (2.5-5%) and epidote (0.5-1%).

Greenstones: The greenstones alternate with marble bands. These are lavas of intermediate to mafic composition. The colour varies from light green to brown and bright green. Texture is fine to medium grained. Pillow structures are present. At outcrop epidote, chlorite and feldspar can be recognized. The randomly oriented chlorite flakes give spotted appearance to the rock. At places contain amygdules and vesicles filled with quartz and chalcedony. Greenstones are composed of quartz (3-6%), actinolite (5-10%), plagioclase (10-20%), epidote (8-25%), chlorite (10-25%), biotite (5-25%), chalcedony (3-10%), muscovite/sercite (2-5%), sphene (1-2%), iron ore (1-2%) and clay (2-8%).

Marbles: These consist of calcite (85-95%), quartz (3-5%), chert (1-2%), dolomite (1-2%), muscovite/sericite (1-1.5%), magnetite (0-0.2%) and clay (1-1.5%).

The tuffs and agglomerates mark the initial phase of Panjal volcanism. Whereas, the greenstones represent the main phase of mafic Panjal volcanism. The presence of bands of marble and pillow structures in greenstones shows that these were deposited under rift-related shallow water conditions. Thus, the Panjal formation records evidence for the Panjal volcanism and associated sedimentation. The Panjal volcanism occurred during the Permo-Triassic rifting of Gondwana to form the Cimmerian microcontinents (Baig *et al.*, 1989).

The major metamorphism and deformation in this area is related to the Himalayan orogeny. The metamorphic mineral assemblages of the Tanol formation, Jura granite gneiss, Reshian-Nauseri granite gneiss and Panjal formation suggest that these units have been metamorphosed upto greenschist facies. Generally, in the Reshian-Nauseri area, the grade of metamorphism shows metamorphic inversion i.e. chlorite-grade in the south and garnet-grade in the north. The metamorphic inversion is due to the south-directed Himalayan thrusting.

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GEOLOGY AND PETROLOGY OF JIJAL AND PATTAN LAYERED ULTRAMAFIC-MAFIC COMPLEXES IN THE VICINITY OF JIJAL, DUBER AND PASHTO, NWFP, PAKISTAN

By

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ABSTRACT: The project area covers about 300 sq. km. located in the vicinity of Jijal, Duber and Pashto (Fig. 1) in districts of Kohistan and Mansehra. Geological mapping was carried out of the area on a scale of 1:50.000 of toposheet nos.43 A/12, 43A/16, 43 E/4 and 43 F/1 of Survey of Pakistan.

The geological sequence of Jijal complex consists of ultramafic and mafic cumulates. The ultramafic cumulates are divided into dunite, wehrlite, websterite, garnet-pyroxenite and garnet-hornblendite whereas mafic cumulates are garnet gabbro. The geological sequence of Pattan complex also consists of ultramafic and mafic cumulates, the ultramafic cumulates are chromite,dunite and (meta)-wehrlite, whereas mafic cumulates are divided into two pyroxene gabbronorite and two pyroxene quartz-diorite.

Previously, the metamorphosed mafic complexes of the Kohistan island arc have been lumped together as an undifferentiatd mass called Kamila amphibolite. Now, the Kamila amphibolite has been divided into three complexes i.e, Dassu complex, Kayal complex and Pattan complex. The Dassu complex is the oldest pluton which is polymetamorphosed, isoclinally folded and banded amphibolite augen gneiss that grades from metatonalite at its top downward to melanocratic garnet amphibolite at its base some 5 to 6 km down section. Dassu complex is underplated by the Kayal complex, has a metamorphosed agmatitic intrusive breccia at its roof and grades downward from moderately banded metadiorite gneiss in its upper part to melanocratic garnet-amphibolite at its base. Again Kayal complex is being underplated by the Pattan complex which is least metamorphosed partly to greenschist facies. The Pattan complex is underplated by Jijal complex.

Field evidences suggest that the Pattan complex was emplaced along the pre-existing metamorphosed Kayal cumulate complex. The top of the Pattan complex is marked by a spectacular, intrusive, polymict agmatite breccia. In Duber and NW of Duber the Pattan complex is overthrust on to the Jilal complex. While in Pattan area and SE of Pattan, there is a faulted (strike slip) contact between Pattan complex and Jijal complex.

The Jijal complex is the southern most, layered ultramafic-mafic cumulate complex of the Kohistan tectonic province, the Main Mantle Thrust (MMT) is the southern boundary of the Jijal complex, which in turn is the southern boundary of Kohistan arc complex. The Main Mantle Thrust (MMT) and Duber thrust wedges out Jijal complex NW of Duber near Charri, on the other hand Main Mantle Thrust and Pattan fault (strike slip fault) wedges out the Jijal complex on the eastern side near Pashto.

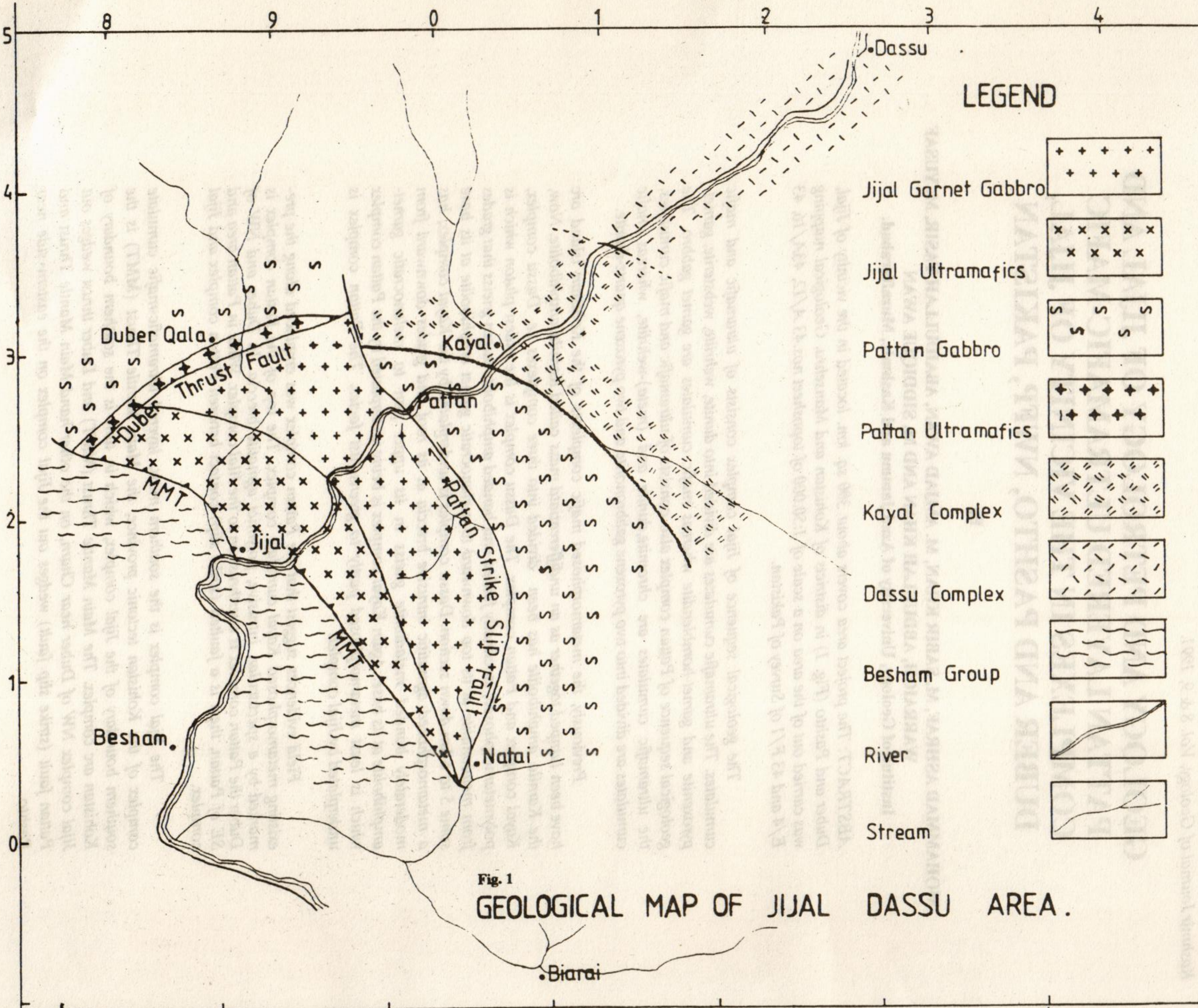

Fig. 1

GEOLOGICAL MAP OF JIJAL DASSU AREA.

The Jijal and Pattan complexes are generated by precipitation from subduction-generated, hydrous, low K, picritic-high Mg tholeiitic magmas and there is a strong possibility of finding economic metallic mineral deposits within these layered cumulate complexes.

So far chromite, chalcopyrite, chalcocite, covellite, pentlandite and platinum group minerals like sperrylite, atheneite etc., have been found by Ashraf et al. (1990) and Miller et al., (1991).

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GEOCHRONOLOGY OF PRE-HIMALAYAN AND HIMALAYAN TECTONIC EVENTS, NORTHWEST HIMALAYA, PAKISTAN

By

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ABSTRACT: In the northwest Himalaya of Pakistan, metamorphism, deformation and plutonism are the result of collision between the Indo-Pakistan and Asian plates. The timing of pre-Himalayan orogenic events remains uncertain, due to strong, pervasive Himalayan overprinting.

This study presents new field, structural and metamorphic data together with $^{40}Ar/^{39}Ar$ isotopic age data on hornblende, muscovite, biotite and K-feldspar for Besham, Mansehra, Swat, and Hazara areas of northern Pakistan. These data provide the first detailed record of Early Proterozoic to Late Paleozoic events in the northwest Himalaya and combine with prior U/Pb, Rb/Sr, and fission track data record an orogenic history from the Early Proterozoic to Cenozoic.

The Early Proterozoic orogenic events in the Besham basement complex occurred at (A) 2,031 $\pm$ 6 to 1,997, $\pm$ 8 Ma, (B) 1,950 $\pm$ 3 Ma, and (C) 1,887 $\pm$ 5 to 1,865 $\pm$ 3 Ma. These were followed by sodic granite intrusion at 1,517 $\pm$ 3 Ma.

Subsequently, flysch of the Kurmang, Gondaf, Manki, Hazara, Dakhner, Dogra, and Simla formations was deposited unconformably on the basement rocks of the Indo-Pakistan plate. These units are unconformably overlain by the molasse of the Tanawal and Manglaur formations. The area underwent metamorphism and deformation at 664 to 625 Ma, and volcanism and plutonism at 850 to 600 Ma (Hazaran orogeny or Pan-African orogeny). Later metamorphism and deformation at > 466 $\pm$ 3 Ma and plutionism at 550 to 450 Ma record an Early Paleozoic orogeny. This tectonic event is marked by the development of cambro-ordovician unconformity in the Himalaya.

Alkaline magmatism (315 $\pm$ 15 to 297 $\pm$ 4 Ma), sodic granites (> 272 $\pm$ 1 Ma), mafic Panjal volcanism (284 $\pm$ 4 to 262 $\pm$ 1 Ma) and metamorphism (333 $\pm$ 1 Ma), occurred during early rifting of the Cimmerian microcontinent from Gondwana.

The early Himalayan metamorphism and deformation in northern Pakistan occurred between 70 to 64 Ma. The Late Cretaceous to Early Paleocene deformation and metamorphism is related to melange emplacement along the northwestern margin of the Indo-Pakistan plate. This tectonic event is marked by the widespread development of Paleocene unconformity in the Himalaya.

$^{40}Ar/^{39}Ar$ dates of 51 to 36 Ma, 36 to 30 Ma, and 30 to 24 Ma from shear zones, date successive shearing and thrusting, and 24 to 5 Ma fission track dates show unroofing and tectonic erosion, during the development of the Indus syntaxis. The presence of active faults, seismicity, and newly recognized 1600 m of uplifted Indus river terraces, show that the Indus syntaxis is an active feature, which has an uplift rate of about 1 mm/yr since 5.2 Ma.

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STRUCTURAL EVENTS IN THE SUB-HIMALAYA OF NIKIAL-KHUIRATTA AREA, KOTLI DISTRICT, AZAD KASHMIR, PAKISTAN

By

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ABSTRACT: To the southeast of the Hazara-Kashmir syntaxis, the Nikial-Khuiratta area lies in the Sub-Himalaya of Pakistan. A sequence of Precambrian to Quarternary rocks has been deformed during the pre-Himalayan and Himalayan orogenesis. Initially, the Precambrian Dogra Formation was deposited and was later affected by the late Proterozoic lower greenschist facies metamorphism and deformation related to the Hazaran orogeny. Subsequently, the lower Cambrian Sirban formation was unconformably deposited on the Dogra Formation. A basal conglomerate is present in Nail nala at the base of the Sirban formation. The lower Cambrian basal conglomerate contains the clasts of slates of the Precambrian Dogra Formation. The presence of slate clasts in the basal conglomerate indicates that the low-grade metamorphism and deformation in the Dogra Formation occurred before the Lower Cambrian deposition of the basal conglomerate.

The Middle Cambrian to Mesozoic rocks have been eroded or have not been deposited before the Paleocene deposition of the Patala Formation. The base of the Patala Formation is marked by an unconformity. The unconformity is marked by laterite, bauxite and fireclay. This break in deposition is the result of pre-Paleocene or early Paleocene orogenic movements. After the Paleocene deposition of the Patala Formation, the Eocene Margala Hill Limestone was deposited under shallow water marine conditions. There is no evidence of Oligocene deposition in Nikial-Khuiratta area. The absence of Oligocene deposition indicates the initial uplift of Sub-Himalaya during Himalayan orogeny. Subsequently, Miocene Murree Formation and Pliocene to Pleistocene Siwaliks were deposited as molasse in the southward migrating Himalayan foredeep. These rocks have been deformed during the Himalayan orogeny.

The structural study shows that at least three phases of Himalayan deformation can be recognized in the area. These deformational phases are D1, D2 and D3. D1 deformation is the major deformational event in the area. It is marked by F1 south-vergent folds and related thrusts. The folds and thrusts trend southeast-northwest. This deformation phase is common in the Higher, Lesser and Sub-Himalayas. F1 folds in the area are Khuiratta-Kohali anticline, Devigarh-Palana anticline, Tattapani-Krela anticline, Khad-Balmi syncline and Shisetar syncline. These are south-vergent, open to tight and doubly plunging anticlines and synclines. The general trend of folds is northwest-southeast and plunge varies from 2° to 10° to the southeast or northwest. The interlimb angle varies from 50° to 112°. The variation in interlimb angle shows that the folds are tight to open in nature. These folds were formed due to northeast-southwest main Himalayan compression.

D1 thrusts in the area are the Himalayan Frontal Thrust, Khad thrust and Gala thrust. These thrusts show an imbricate style of geometry and are syn-to post-F1 folds. During the uplift and migration of the thrust front to the south, the Patala Formation, Margala Hill Limestone, Murree Formation and Siwaliks have been eroded from the crests and exposed the Sirban formation in the cores of the Devigarh-Palana and Tattapani-Krela anticlines to form inliers. Similar inliers are also present near Jammu, Muzaffarabad and Balakot areas. At places, the remnants of Patala Formation, Margala Hill Limestone and Murree Formation are preserved in the cores of the Khad-Balmi and Shisetar synclines.

The D2 deformation forms F2 folds. The F2 folds are only recognized by the change in plunge of F1 folds from southeast to northwest. These folds are gentle and open and trend northeast-southwest. During D3 deformation, earlier thrusts, fold axes and outcrops have been broadly folded into map scale north-plunging F3 folds. The F3 folds are synchronus with the development of north-plunging antiformal structure of the Hazara-Kashmir syntaxis.

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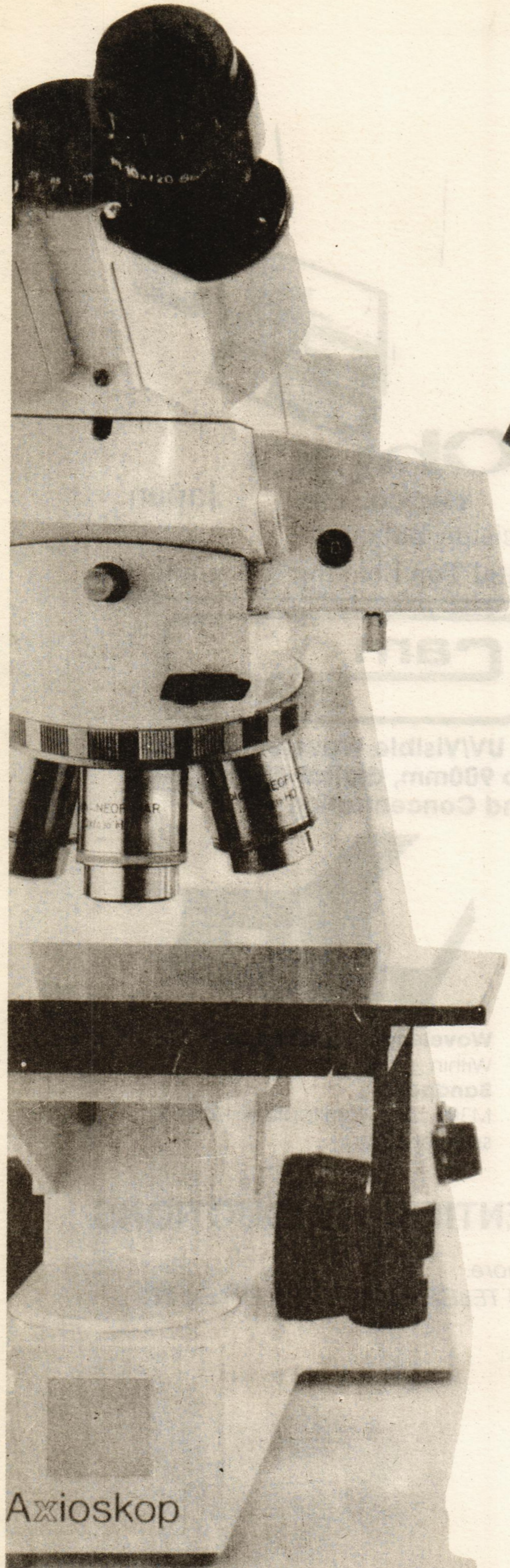

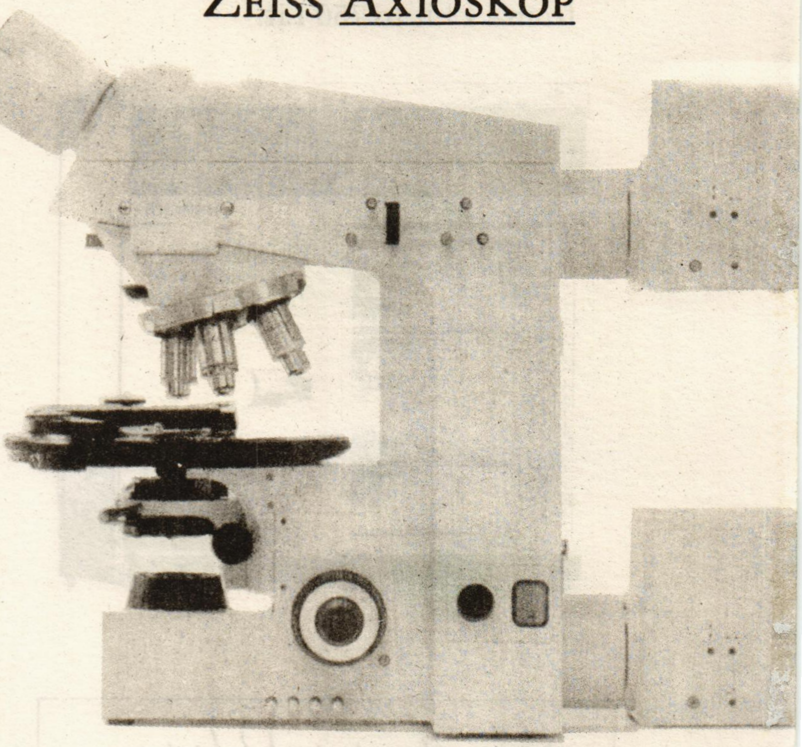

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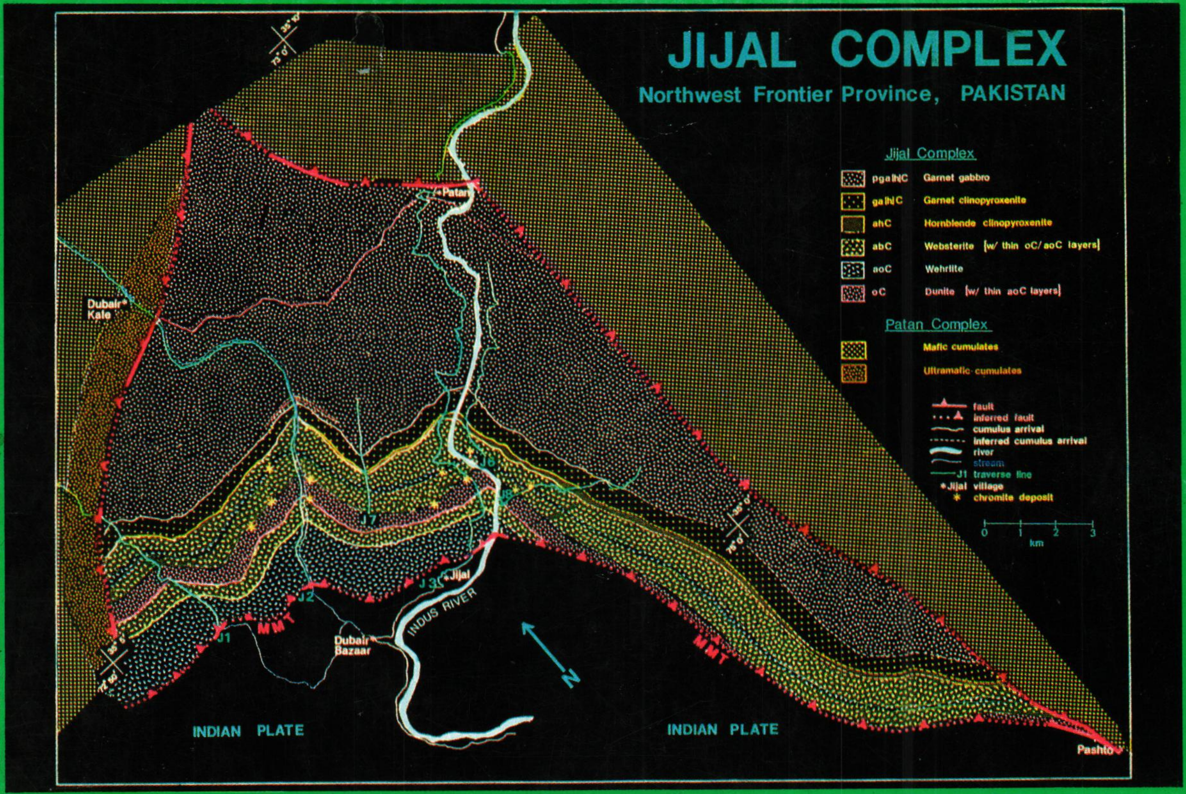

A NEW GEOLOGICAL MAP OF JIJAL LAYERED COMPLEX (MILLER, LOUCKS & ASHRAF 1991)

AGMATITIC ROOF OF PATTAN COMPLEX