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CONTENTS

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GEOCHEMICAL CHARACTERIZATION AND ORIGIN OF THE KARAI -GABBRO FROM THE NEOPROTEROZOIC NAGARPARKAR COMPLEX, PAKISTAN

BY

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Abstract: *The Neoproterozoic magmatism associated with continental rifting to the West of the Aravallis at the NW margin of the Indian Shield, is represented by the Nagarparkar, and Kirana Complexes which constitute a distinct anorogenic igneous cratonic rift assemblage of widespread magmatic activity and which is a part of widespread Late Proterozoic Malani Igneous suites extending from western Rajasthan to Sindh Province in Pakistan.*

Geochemistry of the Karai gabbros and associated mafics of the Nagarparkar complex, Pakistani part of the Indian Shield (Kirana-Malani-Nagar Basin) is present. The rocks are characterized by ring shaped outcrops of "within plate" tholeiitic alkali dolerite and gabbro. The Karai gabbro and dolerite are the representative mafic rocks of the Nagarparkar Complex. Geochemically the gabbro and dolerite are alkaline to subalkaline. The alkaline character is confirmed by the appearance of nepheline in the norms. Various discrimination diagrams confirm the "within plate" character of gabbro and dolerite. The gabbro contain 4.48 to 10.05% MgO and their Mg# ranges from 35 to 68 (generally remains above 54). They show depletion of Ni and Cr (ranges from 11 to 160 ppm and 56 to 306 ppm respectively). The total alkali contents generally range for 5% to 8%. The gabbros with normative nepheline are generally enriched in alkalis. The relatively high Ti/V values indicate that these rocks are not subduction related (Ti/V varies from 33.7 to 121.8). The tholeiitic nature is evident from Nb-Zr-Y plot. The Chondrite normalized spider diagram shows that the LREE are enriched as compared with HREE having slightly fractionated HREE. A slight Nb anomaly is present indicating characteristic continental tholeiite.

"Within plate" character of the gabbro and dolerite is suggested by discriminations diagrams. The dolerite contains 5.65 to 12.18% MgO and their Mg# ranges from 45 to 62 (generally remains above 55). Dolerite generally shows depletion of Ni and Cr (ranges from 34 to 172 ppm and 205 to 680 ppm respectively). The total alkali contents generally range from 1.51% to 3.98%. The relatively high Ti/V values indicate that these rocks are not related to subduction processes (Ti/V varies from 31.7 to 40.7%). The tholeiitic nature of these rocks is evident from Nb-Zr-Y diagram. The Chondrite normalized spider diagram shows that the LREE are enriched as compared with HREE having slightly fractionated HREE. A slight negative Nb anomaly is present indicating characteristic continental tholeiite.

This study suggests hot spot magmatism responsible for the generation of continental rifting leading to generation of A- type peraluminous to peralkaline granites alongwith within plate nature of tholeiitic dolerites/gabbros, characterized by ring structures for the Nagarparkar Complex alongwith its counterparts within Nagar-Malani-Kirana Basin in the Indian part of Rajasthan. The stresses released after Aravalli-Delhi orogenic cycles gave rise to linear zones of crustal weakness and high heat flow and along these northeastern-southwestern-trending weak zones, the magmatism of Nagarparkar suite was triggered by mantle plume. Fixed mantle plumes are considered to burn through lithospheric plate giving rise to localized igneous activity. Where lithosphere is continental, the activity is represented by alkaline magmatism including subalkaline sub volcanic complexes.

INTRODUCTION

The Karai gabbros and mafic rocks are associated with Nagarparkar Complex, situated at the extreme southeast of Thar desert of Sindh near the Runn of Kutch (24° 15' 00" to 24° 30' 00" latitude, 70° 37'00" to 71° 07'00" longitude and covers an area of about 450 sq km (Fig. 1) which crops out at the extreme southeast of the Great Thar Desert near the Runn of Kutch, is a part of widespread Late Proterozoic Kirana-Malani-Nagar Basin extending from western Rajasthan to Sindh Province in Pakistan (Chaudhry, et. al., 1999). The Complex is characterized by a major period of anorogenic (A-type), "Within Plate" magmatism equivalent to Nagarparkar, Kirana, Malani, Siwana, Jaswantpura, Tusham, Mount Abu and Gurapratapsingh, complexes, part of the Basin (Kochhar: 1973, 1974, 1984; Naqvi: 1987: Bushan: 1985; Eby: 1990; Rathore et al: 1991; Bhushan and Chittora: 1999; Bhushan: 1989; Butt et al 1992: Maheshwari et al: 2001, 2002: Chaudhary et al: 1999; Ahmad et al: 2000; Ahmad: 2004 and Ahmad and Chaudhary: present study. The igneous rocks of the Nagarparkar Complex fall into two distinct magma associations. The older sequence represents plutonic sub alkaline tholeiitic magma associations of gabbro, diorite, granodiorite, adamellite and granites, while the younger magma series form an alkaline bimodal volcano plutonic association, comprising mafic suite of alkali basalt, trachybasalt and K-phonoteprite and felsic members comprising alkali rhyolite and alkali granites. Such a variation in composition can occur only in major rift systems (Stern, 1985, 1995; Leat and Thorpe, 1986; Currie, 1989; Rathore et al., 1999; Bhushan and Chittora, 1999 and Kochhar, 2000). This paper belongs to the geochemistry and genesis of the mafic rocks of the Complex. Geochemical data is plotted on the tectonic discrimination diagrams in order to find out magmatic environment. REE data is plotted on the various spider diagrams to evaluate origin and evolution of different rock suites from the Nagarparkar Complex.

Geology and Stratigraphy

Kazmi and Khan (1973) presented a Geological map of the area describing different units of the complex based on field relationships. Muslim et al (1989, 1997) partially amended the stratigraphy. The granites and gabbro are the main exposed rocks, occupying 90% volume of the crystalline rocks of the complex. These exposed units are present as scattered hillocks jutting out of the Thar Desert and extend in to the Southeast towards Rajasthan, India. The complex is generally covered by Quaternary Bar-tala formation, comprising basal conglomerates and sandstone, marking an unconformity. Dhedvero gabbros are the oldest exposed rock unit, intruded by Karai dolerite and Nagarparkar Granite. Both these units are placed in early Proterozoic period. Stratigraphically, granites are comparatively younger phases and are placed in the late Proterozoic age (Table.1). Nagarparkar Granite postdates the Grey Granite (Fig. 1). Churio Granite and Grey Granite are considered older on the basis of field relationship. Dolerite and rhyolite are the youngest crystalline units, which are present as cross cutting bodies postdating the entire complex and trending NW-SE and NE-SW directions. A brief summary of proposed phases is given below-

Group/Formation	Type	Mode	Lithology
Recent/sub recent	Sand/Marsh		Sand/evaporates/Kaolin
Bar Tala	Bar Tala		Sandstone/marl
(Sub-Recent to Recent)			
………………………………	Unconformity………………………………		
Dhedvero Dykes	Basic and Acid dykes	Intrusive dykes	Dolerite/microgabbro
(Igneous suites)	(Aplite and dolerite)	(Phase-4)	Rhyolite
Nagarparkar Granite	Granites/microgranite	(Phase-3)	Granites/microgranite
Grey Granite	Granite/adamellite	(Phase-2)	Granite/adamellite
Churio Granite	Off white granite	(Phase 2)	Granite/aplites
Dhedvero Gabbros	Gabbro/dolerite	(Phase-1)	Gabbro/dolerite
Neoproterozoic (Phase-1 to Phase-4)			
………………………………	Unconformity………………………………		
Aravalli-Delhi Super Group (Middle to Lower Proterozoic)……………(not exposed)			

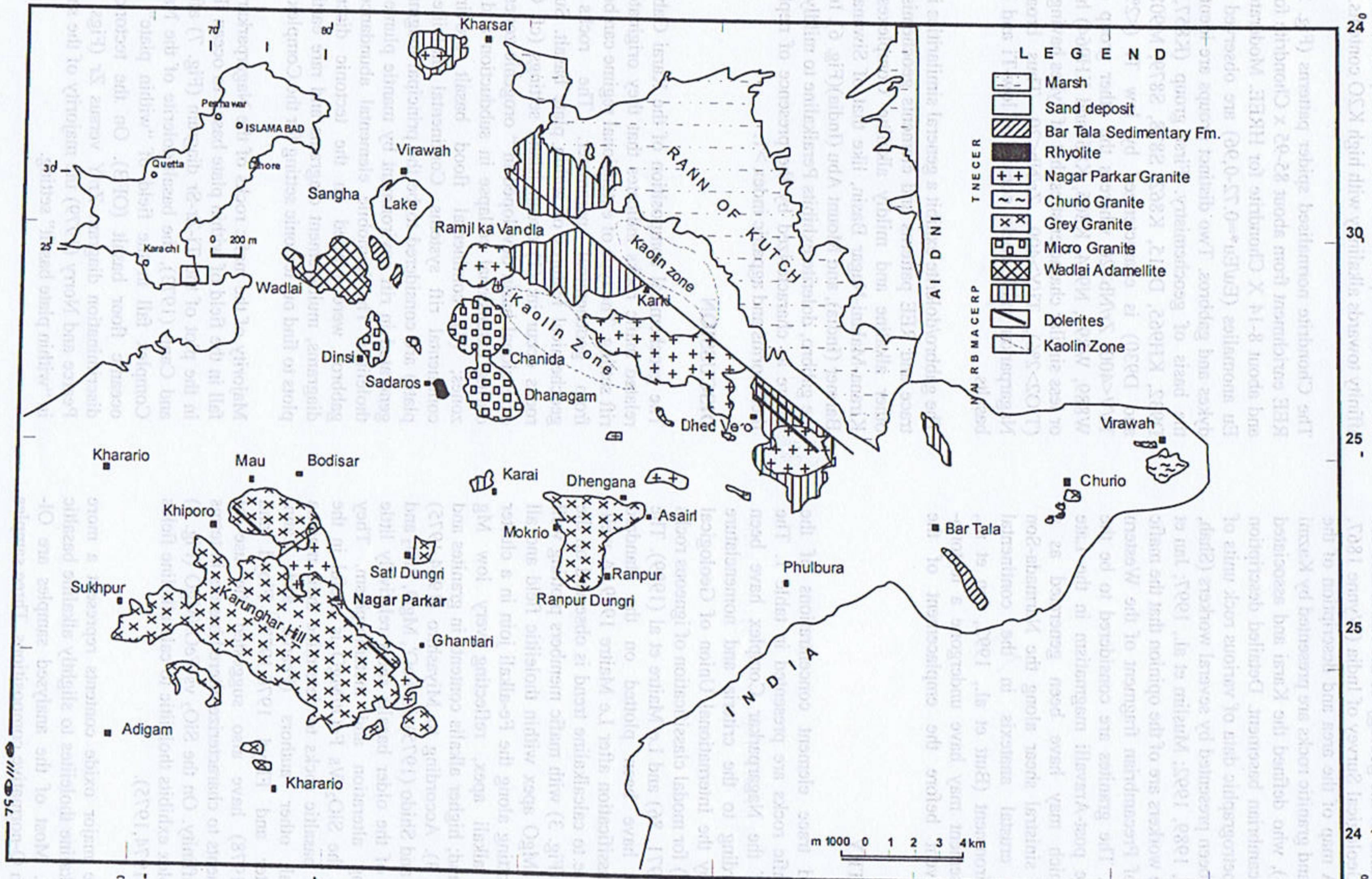


Fig. 1: Geological Map of the Nagarparkar Complex (After Ahmad, 2003)

The earliest accounts of the geology of the Karai area are recorded in the Geological Survey of India (Wynne 1867, Fermor 1932). A map of the area and description of the basic intrusions and granitic rocks are presented by Kazmi and Khan (1973), who defined the Karai and associated Complex as Precambrian basement. Detailed description of geology and petrographic data of various rock units of Karai area have been presented by several workers (Shah, 1977, Butt et al., 1989, 1992; Muslim et al., 1997; Jan et al., 1997). These workers are of the opinion that the mafic rocks are part of Precambrian fragment of the Western "Indian Shield". The granites are considered to be the extension of the post-Aravalli magmatism in the Late Proterozoic, which may have been generated as a consequence of sinistral shear along the Narmada-Son lineament and crustal anatexis in the continental anorogenic environment (Butt et al., 1992, Jan et al., 1997). The basement may have undergone a tectono-metamorphic event before the emplacement of the granites.

GEOCHEMISTRY

The major and trace element concentrations of the Nagarparkar mafic rocks are presented in table 1. The mafic rocks of the Nagarparkar Complex have been classified according to the criteria and nomenclature recommended by the International Union of Geological Sciences (IUGS) for modal classification of igneous rocks after Le Bas (1971, 86) and Le Maitre et al (1989). The analytical data have been plotted on the standard geochemical classification after Le Maitre 1989. A well-defined tholeiitic to calcalkaline trend is observed on the AFM diagram (Fig. 3) with mafic members plotting well away from the MgO apex within tholeiitic field and all felsic rocks plotting along the Fe-alkali join in a cluster close to the alkali apex, reflecting very low Mg concentration and; higher alkalis contents in granites and rhyolites (Fig. 3). According to Miyashiro (1974,1975) and Miyashiro and Shido (1975) the FeO^t, MgO, SiO_2 and TiO_2 contents of the older basalts show relatively little changes during alteration and metamorphism. They suggested that the SiO_2 Vs FeOt/MgO is useful in the study of older basaltic rocks to determine their magma types. Several other authors (Pearce and Cann, 1971;Winchester and Floyd 1976,1977; Floyd and Winchester, 1978) have also suggested the use of immobile elements to characterize altered basalts in terms of magmatic affinity. On the SiO_2 vs FeOt/MgO (Fig. 4) plot, the complex exhibits tholeiitic to calc-alkaline fields of Miyashiro (1974,1975).

In general the major oxide contents represent a more evolved subalkaline tholeiites to slightly alkaline basaltic characteristics. Most of the analysed samples are Ol-normative with Q-normative compositions. Three samples however have nepheline normative compositions showing affinity towards alkalinity with high K2O contents.

The Chondrite normalised spider patterns (Fig. 5) show REE enrichment from about 85-95 x Chondrite for LREE and about 8-14 X Chondrite for HREE. Moderate to low Eu anomalies (Eu/Eu*=0.72-0,96) are observed both in dykes and gabbros. Two distinct groups are identified on the basis of geochemistry. First group (K857, M901, D932, KH965, D915, K862, S878, S879, M908, D919 and D930) is characterized by low Ti (<2%TiO2), Ti/V<400, Zr/Nb>20 whereas the other group (Dg856, W889, W891, N944, K866, K861and KH964) has more or less similar characteristics that of dykes having high Ti (TiO2>2%), Ti/Y>400, Zr/Nb<20. Thus broadly the Nagarparkar mafic rocks consist of low-Ti and high Ti-basalts.

The gabbro/dolerite exhibit a general similarities in major, trace and REE patterns and elements geochemistry with other alkaline and mildly alkaline Complexes of the Kirana-Malani-Nagar Basin, like that of Siwana (India), Barmer (India), and Mount Abu (India)(Fig. 6). In general the gabbro, dolerite exhibits Peralkaline to mildly alkaline nature as characterized by the presence of nepheline in their norms and agpaitic index >1.

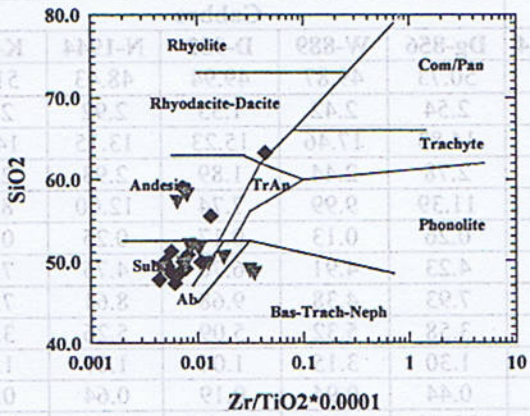
DISCUSSION

The geochemical composition of the Karai Gabbros and related mafic rocks indicates that they originated in the rift setting. The type of extensional regime can be inferred from geochemical parameter. The rocks display geochemical features of within plate basalt. Such mafic rocks occur in: (1) ocean island settings (cf. OIB); (2) extensional basin developed in " orogenic zones, such as during extensional collapse in subduction and collision zones; (3) continental flood basalt provinces and continental rift systems. Continental tholeiites (within plate) are considered to be the principal magmatic rocks generated in rift environment by mantle plume give rise tholeiites. The immobile elemental abundances of the gabbros were plotted on the tectonic discrimination diagrams, multielement diagrams and rare earth element plots to find out tectonic setting for the Complex.

Majority of the mafic rocks of the Nagarparkar Complex fall in the field of within plate basalt to ocean floor basalt in the plot of the Ti-Zr-Sr diagram (Fig. 7) after Pearce and Cann (1973), the basalt/dolerite of the Nagarparkar Complex fall in the field of "within plate" setting to oceanic floor basalt (OFB). On the tectonomagmatic discrimination diagram Zr/Y versus Zr (Figs. 8) of the Pearce and Norry (1979) the majority of the samples fall in "within plate basalt" setting.

Table-1:
Major and trace elements of Basalt/dolerite and gabbro from the Karai area.

	Basalt/dolerite					Gabbro				
Sample#	K861	S-878	S-879	D-919	KH-964	Dg-856	W-889	D-932	N-1944	K-866
SiO2	51.27	51.43	49.76	50.49	49.67	50.73	49.87	49.94	48.43	51.94
TiO2	2.91	1.41	1.95	0.93	2.20	2.54	2.42	1.33	2.92	2.01
Al2O3	12.30	17.51	16.80	16.65	16.03	14.83	17.46	15.23	13.15	14.93
Fe2O3	3.25	1.95	2.36	1.98	2.47	2.78	2.44	1.89	2.93	2.16
FeO	13.31	8.01	9.67	8.10	10.13	11.39	9.99	7.74	12.00	8.87
MnO	0.25	0.16	0.19	0.10	0.20	0.26	0.13	0.17	0.25	0.16
MgO	4.48	7.21	6.80	8.68	6.61	4.23	4.91	6.70	4.75	7.20
CaO	8.50	8.91	8.93	10.27	9.50	7.93	4.38	9.68	8.61	7.65
Na2O	2.86	2.20	2.37	1.82	2.26	3.58	5.32	5.09	5.26	3.45
K2O	0.47	0.99	0.56	0.84	0.53	1.30	3.15	1.04	1.07	1.15
P2O5	0.39	0.24	0.62	0.14	0.40	0.44	0.94	0.19	0.64	0.47
Mg. No.	32.98	56.82	50.67	61.04	48.83	35.16	41.82	55.86	36.63	54.27
CaO/Al2O3	0.691	0.509	0.532	0.617	0.593	0.535	0.251	0.636	0.655	0.512
P.I.	0.42	0.27	0.27	0.23	0.27	0.49	0.70	0.62	0.75	0.46
Al/CNK	0.59	0.84	0.81	0.74	0.74	0.68	0.87	0.56	0.52	0.72
Al/NK	2.36	3.74	3.73	4.26	3.73	2.03	1.44	1.60	1.34	2.15
Pk No.	2.97	3.46	3.61	4.78	4.03	1.98	0.66	1.86	1.60	2.01
Cs (ppm)	0.35	0.38	0.33	0.24	3.28	1.15	1.28	1.24	3.29	0.55
Rb	27	29	28	28	23	37	48	22	26	29
Sr	278	398	441	437	347	407	897	286	330	579
Ba	162	476	271	273	291	606	360	154	274	455
V	481	204	244	255	305	358	119	237	390	240
Cr	16	92	141	443	124	56	5	271	58	276
Co	34	49	46	40	40	33	32	57	35	38
Ni	22	146	101	140	85	78	27	157	40	113
Cu	37	49	41	86	58	26	25	66	43	34
Zn	112	90	107	93	97	110	128	87	125	86
Ga	22	17	19	17	19	20	29	17	20	19
Sc	28	24	22	38	26	43	6	35	28	28
Y	29	25	26	20	36	29	18	32	50	21
Zr	168	147	246	66	171	207	578	146	229	169
Hf	3	5	3	4	4	5	2	3	4	3
Nb	7	5	6	4	5	7	6	4	7	5
Ta	0.88	0.84	0.87	0.85	0.86	1.3	0.99	0.99	0.87	0.99
Th	0.4	0.2	0.3	0.4	0.2	0.4	0.4	0.3	0.4	0.3
U	0.12	0.13	0.11	0.09	0.08	0.09	0.12	0.06	0.03	0.13
La	16.45	19.86	18.21	13.12	15.12	18.18	22.17	18.94	18.92	19.45
Ce	38.23	36.77	35.11	36.66	35.55	36.66	38.44	27.55	35.44	35.15
Pr	2.12	2.13	1.69	2.08	2.13	1.92	2.12	1.98	1.67	1.89
Nd	23.45	16.12	32.14	19.12	21.4	23.34	27.19	24.13	26.44	22.12
Sm	5.65	5.34	6.45	5.33	5.23	6.34	7.3	5.23	6.34	6.25
Eu	1.37	1.33	1.45	1.49	1.55	1.28	1.6	1.44	1.39	1.39
Gd	4.89	4.79	4.78	4.59	4.87	4.2	4.65	5.08	4.89	5.08
Tb	0.9	0.88	0.84	0.89	0.69	0.73	0.66	0.69	0.75	0.78
Dy	3.66	3.76	3.45	3.54	3.89	3.55	3.76	3.67	3.87	3.34
Er	1.48	2.34	1.65	1.56	1.45	2.34	1.67	2.99	3.12	2.28
Yb	1.78	2.08	2.13	2.08	1.78	2.33	2.06	2.66	2.45	1.98
Lu	0.45	0.49	0.48	0.39	0.56	0.91	0.48	0.33	0.38	0.81



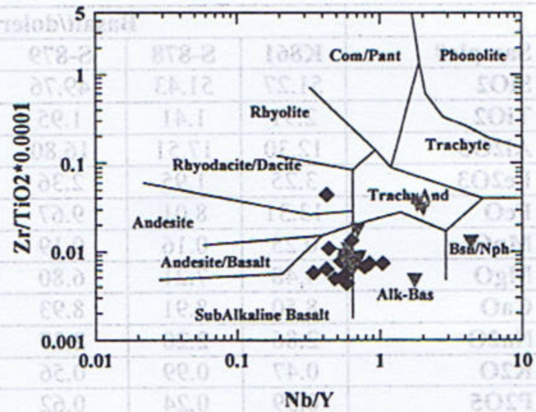
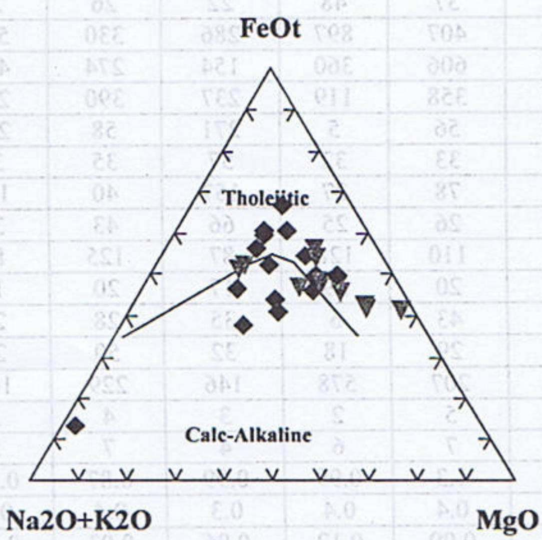


Fig.2 a. Zr/TiO2 versus Nb/Y diagram (Winchester and Floyd, 1977) of the mafic igneous rocks from the Karai area, Nagarparkar Complex.

Fig. 2b. Zr/TiO2*0.00001 vs SiO2 diagram (Winchester and Floyd, 1977) of the mafic igneous rocks, from the Karai area, Nagarparkar Complex.



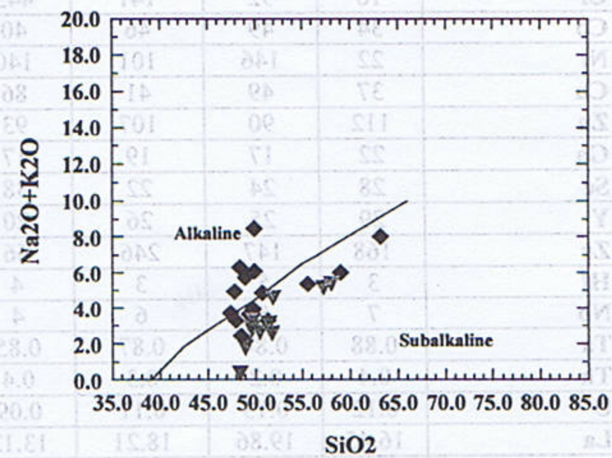


Fig. 3.a: AFM Diagram after Irvine and Baragar (1971), showing the major element compositional diversity in mafic rocks from the Karai area, Nagarparkar Complex. Gabbro (filled diamond) and dolerite (inverted filled triangle) falls within tholeiitic field.

Fig. 3.b Classification of alkaline and subalkaline igneous rocks of the Karai area, Nagarparkar Complex. The rocks represent dolerite/basalt having gabbros (filled diamond) and dolerite (inverted triangle) of the complex. The dividing line between the two series is taken from Miyashiro (1974).

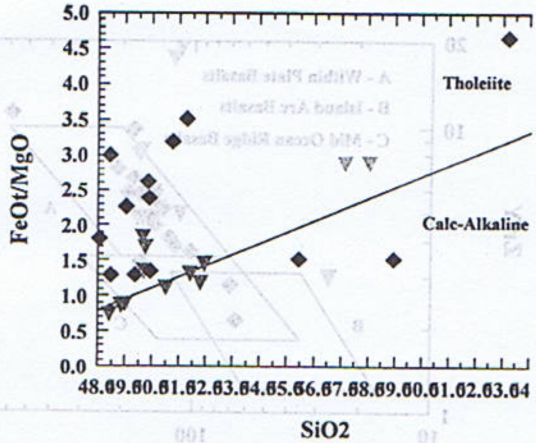


Fig. 4. Classification of Tholeiitic and Calc-alkaline series within igneous rocks of the Karai area, Nagarparkar Complex. The dividing line between the two series is taken from Miyashiro (1974).

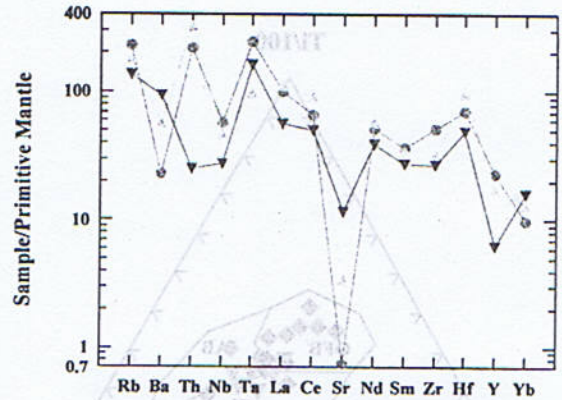


Fig. 5. Primitive mantle normalized (after McDonough and Sun 1995) trace element plots of representative gabbro from the Karai area, Nagarparkar Complex (circle), Kirana Dolerite (square) alongwith the Sankara Dolerite (Pandit and Deep, 1999) (inverted triangle).

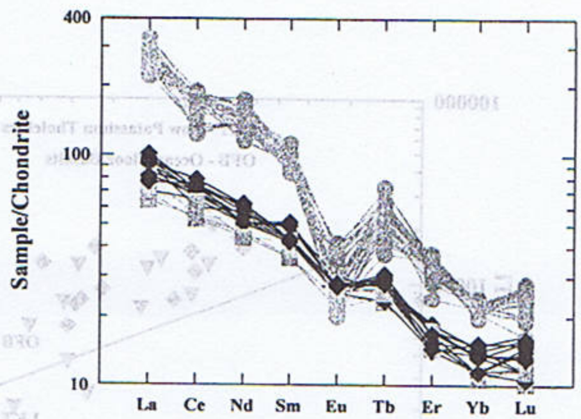


Fig. 6.a. Chondrite normalized (after McDonough and Sur 1995) REE plots of representative gabbro/dolerite (Olivine tholeiite = filled square and quartz tholeiite = filled diamond) alongwith granite (circle), from the Karai area, Nagarparkar Complex.

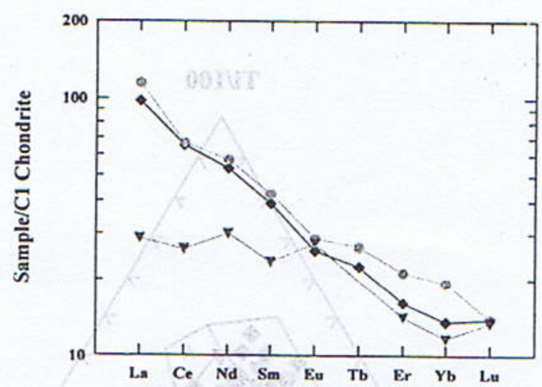


Fig. 6.b. Chondrite normalized (after McDonough and Sun, 1995) REE plots of representative gabbro/dolerite from the Karai area, Nagarparkar Complex (square) Kirana Dolerite (circle) alongwith Sankara Dolerite (inverted triangle) (Pandit and Deep, 1999).

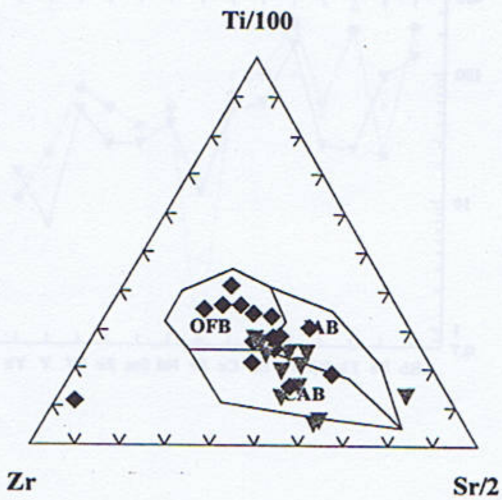


Fig.7: Plots of representative rocks of dolerite from the Karai area, Nagarparkar Complex on the Ti-Zr-Sr diagram (after Pearce and Cann, 1973). Majority of the samples cover ocean floor basalt character (OFB). IAB represents island arc and CAB is allocated for calcalkaline basalt; gabbros (filled diamond) and dolerite (inverted triangle).

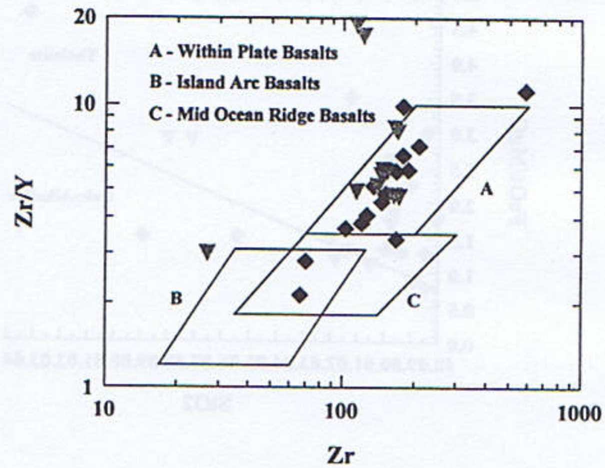


Fig .8. Plots of representative samples of dolerite from the Karai area, Nagarparkar Complex on the Zr versus Zr/Y diagram (after Pearce and Norry, 1979) exhibiting field "A" with in plate" gabbros (filled diamond) and dolerite (inverted triangle)

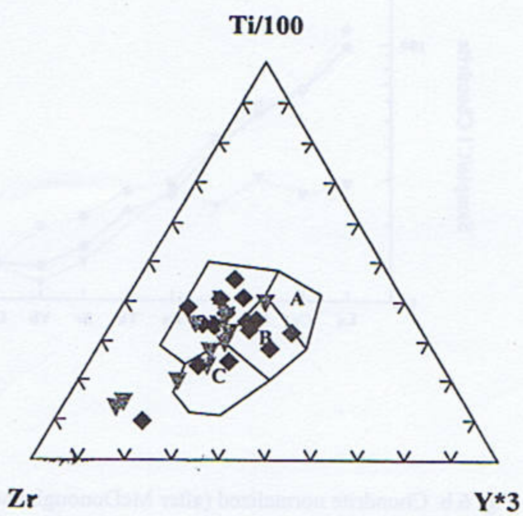


Fig.9: Plots of dolerite from the Karai area, Nagarparkar Complex in the Ti-Zr- Y diagram (after Pearce and Cann, 1973). Majority of the samples fall in "within plate basalt" field. Field "E" is allocated for island arc tholeiites, B represents MORB and C is representing calc-alkali basalt (Index is the same as in Fig. 8)

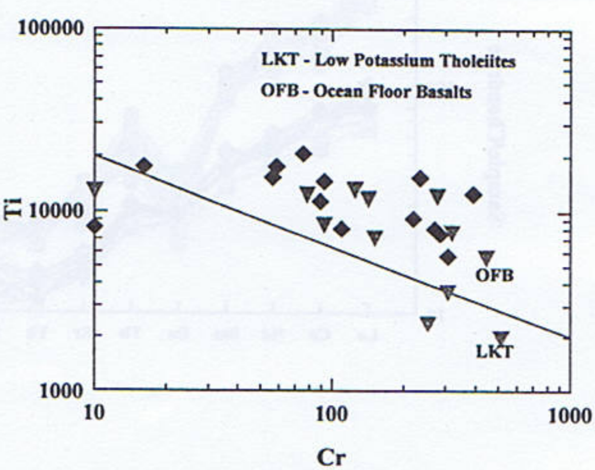


Fig.10. Plots of basalt/dolerite and gabbro from the Karai area, Nagarparkar Complex on the Cr Versus Ti diagram (after Pearce 1975), indicating "OFB" character (Gabbro = filled diamond and dolerite/basalt = inverted filled triangle).

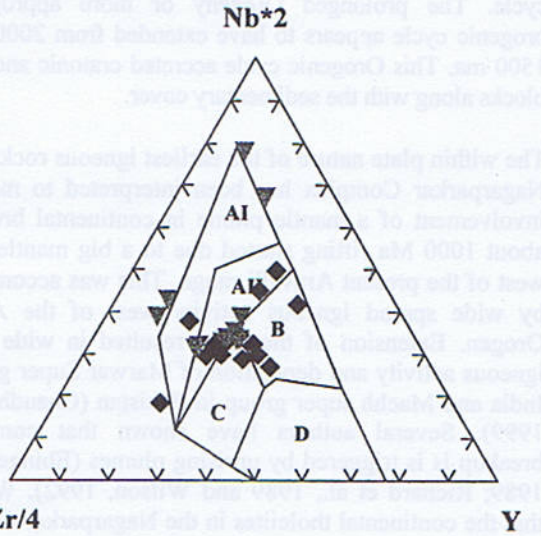


Fig.11. Zr-Nb-Y discrimination diagram for basalts (after Meschede, 1986). Majority of the samples falling in the field A11, indicating within plate character for the basalt/dolerite of the Karai area, Nagarparkar Complex. "AI" represent within plate alkali basalts, "AII" for within plate alkali basalt and within plate tholeiites, "B" is allocated for E-MORB, "C" indicates within plate tholeiites and volcanic arc basalts while "D" represents N-MORB (Index is the same as in Fig. 8).

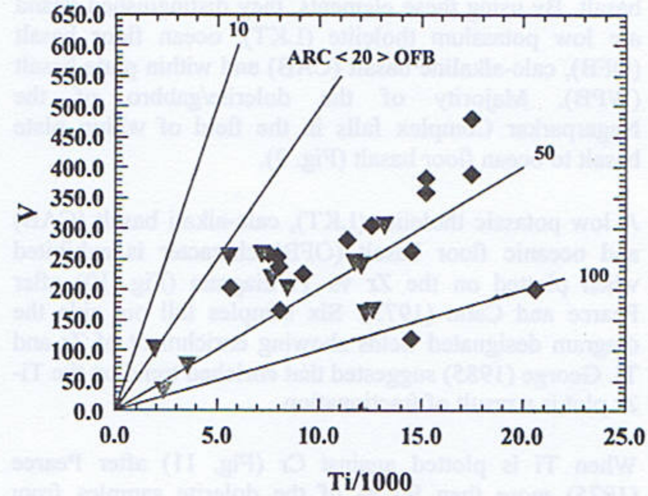


Fig. 12: Plots of mafic rocks from the Karai area, Nagarparkar Complex on the Ti/1000 versus V diagram (after Shervais, 1982), showing "OFB" character (Index is the same as in Fig. 8).

Pearce and Cann (1973) used Ti, Zr, Y and Nb ratios to determine the paleotectonic environment of the altered basalt. By using these elements, they distinguished island arc low potassium tholeiite (LKT), ocean floor basalt (OFB), calc-alkaline basalt (CAB) and within plate basalt (WPB). Majority of the dolerite/gabbro of the Nagarparkar Complex falls in the field of within plate basalt to ocean floor basalt (Fig. 9).

A low potassic tholeiite (LKT), calc-alkali basalt (CAB) and oceanic floor basalt (OFB) character is exhibited when plotted on the Zr vs Ti diagram (Fig. 10) after Pearce and Cann (1973). Six samples fall out side the diagram designated fields showing enrichment of Zr and Ti. George (1985) suggested that enriched trend on the Ti-Zr plot is a result of fractionation.

When Ti is plotted against Cr (Fig. 11) after Pearce (1975) more than 90 % of the dolerite samples from Nagarparkar Complex fall within the limits of OFB, while a few samples fall in the arc field. This may be due to the low contents of Cr observed in these rocks (Fig. 11). On 2Nb-Zr/4-Y diagram (Fig. 12) after Meschede, (1986) "within plate tholeiites" character dominates.

Rb, Th, Ta and Hf in the dolerite and gabbro of the Nagarparkar Complex show enrichment while Ba, Nb, Sr, and Y show depletion (Fig.5.b). The Chondrite normalized REE pattern of mafic flows of the Nagarparkar shows a gradual depletion and with or without Eu anomaly indicating variable role of plagioclase fractionation. Dolerite/basalt have less pronounced Eu negative anomaly. Primordial mantle normalized trace element variation spider diagram (after McDonough and Sun 1995) are given (Fig 5.a), for representative basalt/dolerite. The low Sr in mafic rocks is also due to plagioclase fractionation. The low Ti group is characterized by low Zr and Nb/La (HFSE/LFSE) values in contrast to high Ti rocks.

The research carried out by different workers on the geochemistry of the different elements of the Kirana-Malani-Nagar Basin shows that the basin evolved from a continental rift between 1000-750 Ma. The occurrence of the pre-rift continental tholeiites, extensional tholeiites, and extensional basalts emplaced in the continental rifts and mafic igneous rocks with E-MORB affinities indicates that the rift includes the different associations marking the breakup of Rodinia Supercontinent. The Kirana, Malani, Nagarparkar, Mount Abu and Tusham lie west of the Aravalli Orogen. The Aravalli Orogen formed due to Aravalli Orogeny dated by Gopalan and Choudhry (1984) Gopalan et al (1990) at 2000 Ma and Delhi Orogeny dated by Choudhry et al (1984) at 1500 to 1700 Ma and 1650 – 1700 Ma by Crawford and Compton (1970). Since Aravalli and Delhi Orogeny constitute a single Orogenic cycle therefore this cycle is termed as Aravalli–Delhi Orogenic cycle. The prolonged Orogeny or more appropriately orogenic cycle appears to have extended from 2000 ma to 1500 ma. This Orogenic cycle accreted cratonic and shield blocks along with the sedimentary cover.

The within plate nature of the earliest igneous rocks in the Nagarparkar Complex has been interpreted to mark the involvement of a mantle plume in continental break. At about 1000 Ma rifting started due to a big mantle plume west of the present Aravalli range. This was accompanied by wide spread igneous activity west of the Aravalli Orogen. Extension of the crust resulted in wide spread igneous activity and deposition of Marwar Super group in India and Machh super group in Pakistan (Chaudhry et al 1999). Several authors have shown that continental breakup is is triggered by uprising plumes (Ebinger et al., 1989; Richard et al., 1989 and Wilson, 1992). We infer that the continental tholeiites in the Nagarparkar Complex also originated from a plume. The horizontal distance between the hotspots of the Basin is around 700 km to 1500 km. This is based on the assumption that the rift related to the Kirana-Nagar-Malani Basin did not undergo major sea floor spreading as shown by the absence of true ophiolites. This distance is comparable to that of Afar and east African hotspots along the east African rift system (Schilling et al., 1992).

The hot spot activity due to which wide spread volcanism and plutonism took place appears to have started at around 950 Ma. The centers of these activities were Tusham (940 ± 20, modal age; Kochhar 1974, calculated Isochron age of 770 Ma; Eby 1990) Diri and Gurapratap Singh in Pali district (779 ± Ma, Kochhar, 1974) Kirana (873 ± 40 Ma, 870 ± 40 Ma, Davies and Crawford, 1971), Nagarparkar (800 – 750 Ma, Davies and Crawford 1971), Malani (745 ± 40 Ma, Crawford and Compston, 1970), Siwana and Jalor (750 ± 14 Ma, Rathore et.al1991)

The widespread igneous activity west of the Aravalli range has been studied geochemically by a number of authors i.e. Kochhar (1973,1974, 1984), Bushan (1985), Naqvi (1987), Butt et al (1992), Ahmad et al (2000) and Ahmad (present study). The volcanic rocks range from per-aluminous to tholeiitic as well as per-alkaline.

The distinct association of alkali dolerite/gabbro and A-type peraluminous/peralkaline rhyolite/granites is typical of anorogenic magmatism in the Nagarparkar and neighboring western Rajasthan sectors (Eby and Kochhar, 1990; Bhushan and Chittora, 1999). The strong bimodality displayed by the Nagarparkar samples and geochemical variations observed particularly among granites and rhyolite outline their complex petrogenesis.

The Nagarparkar Complex and Kirana Complex in Pakistan, felsic volcanic associations of Tusham in Haryana and Gurapratap Singh and Diri of Pali district in Rajasthan, are part of widespread volcanic activity in Kirana-Malani Basin, probably initiated by mantle plume along the western flanks of post-Delhi Trans-Aravalli belt. Subalkaline tholeiitic basaltic and rhyolitic volcanism probably commenced around 950 Ma. The centers of magmatic actively were Kirana in Pakistan (873 ± 40 – 870 ± 40 Ma, Ahmad et al., 1997), Tusham in Haryana (1940 ± 20 Ma, modal age, Kochhar 1974, calculated isochron age of 770 Ma, Eby, 1990) and Pali district of western Rajasthan (779 Ma Chaudhry et al 1984). Extensive volcanism in the region is probably linked with initial stages of rifting extension triggered by rising mantle plume with in Late Proterozoic Gondwana configuration of the Greater India.

CONCLUSIONS

The mafic igneous rocks sampled in the area are continental tholeiites and alkaline mafic rocks emplaced on a Proterozoic basement. They mark initial stage of Rodinia break up in this part of Kirana-Malani-Nagar Basin.

The dolerite dykes represent alkaline and tholeiitic magmas marking a continental rift. The maturity reached by this continental rift can be inferred using immobile trace element compositions. Our data suggest that these igneous rocks were emplaced in a Rift Basin.

Mafic igneous rock associations above the tectonic units mark a progressive opening from a pre-rift continental break-up up to a continental rift during.

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MICROFACIES ANALYSIS OF THE MIDDLE EOCENE KOHAT FORMATION, SHEKHAN NALA, KOHAT BASIN, PAKISTAN

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Abstract: *The Kohat Formation from the Shekhan Nala was sampled and measured for detailed stratigraphical and micropalentological studies to determine the age and environment of the formation. The Kohat Formation contains abundant varieties of larger foraminifera belonging to the genera Nummulites, Assilina and Alveolina. On the basis of larger foraminifera Middle Eocene age of the formation has been confirmed The microfacies studies identified the bioclastic wackestone, bioclastic packstone and bioclastic grainstone where the bioclasts are larger foraminiferal species, Nummulites beaumonti, Nummulites mamillatus, Assilina exponens and Alveolina elliptica. The Kohat Formation on the basis of larger foraminifera and micro facies analysis draws attention to the fact that it was deposited in shallow marine environments. The Kohat Formation has been identified into four lithofacies, which are from base to top, TS-l:- Calcareous shale interbedded with fossiliferous limestone. TS 2:- Nummulitic shale and limestone. TS-3:-Highly fossiliferous limestone. TS-4:* Massive *nodular limestone.*

INTRODUCTION:

The Kohat area is underlain by sedimentary sequence ranging in age from Jurassic to Pliocene. In the northeastern and northwestern corners of the Survey of Pakistan Toposheet no 38 0/6 and 380/10 between longitude 71°30'15" E and 71°31'40" E and 30°35'20" N and 30°36'50" N. (Fig. 1) The rocks are tightly folded and faulted. The northern and southern flanks are in faulted contact with younger rocks (Meissner et. al. 1974).

The Eocene and Miocene sequences lie to the south of Kohat in a belt which is 16 to 25 miles wide from north to south. The Eocene sequence consists of limestone, clay, silt and gypsum with a total exposed stratigraphic thickness of about 548 m. (Meissner et. al. 1974).

The Middle Eocene Kohat Formation is distinguished into three members. (Meissner et. al. 1974). The Kaladhand Member is composed of interbedded limestone and shale. The limestone is soft and flaggy from medium to hard and highly fossiliferous (Davies 1926).The Sadkal Member is composed of bank bed facies. The colour is light brown and limestone is soft and argillaceous. This part is almost entirely composed of larger foraminifera (the Nummulitic Shales of Pinfold 1918).The Habib Rahi Member is composed of very fine grained micritic limestone.

The Miocene sequence is composed of sandstone, siltstone, shale and clay with a Stratigraphic thickness of about 710m. (Meissner et.al. l974). South of Eocene and Miocene expose the area underlain by Pliocene strata, which mainly consist of interbedded, sandstone, siltstone and clay which contain conglomerate lenses. The objective of the detailed study of the Kohat Formation

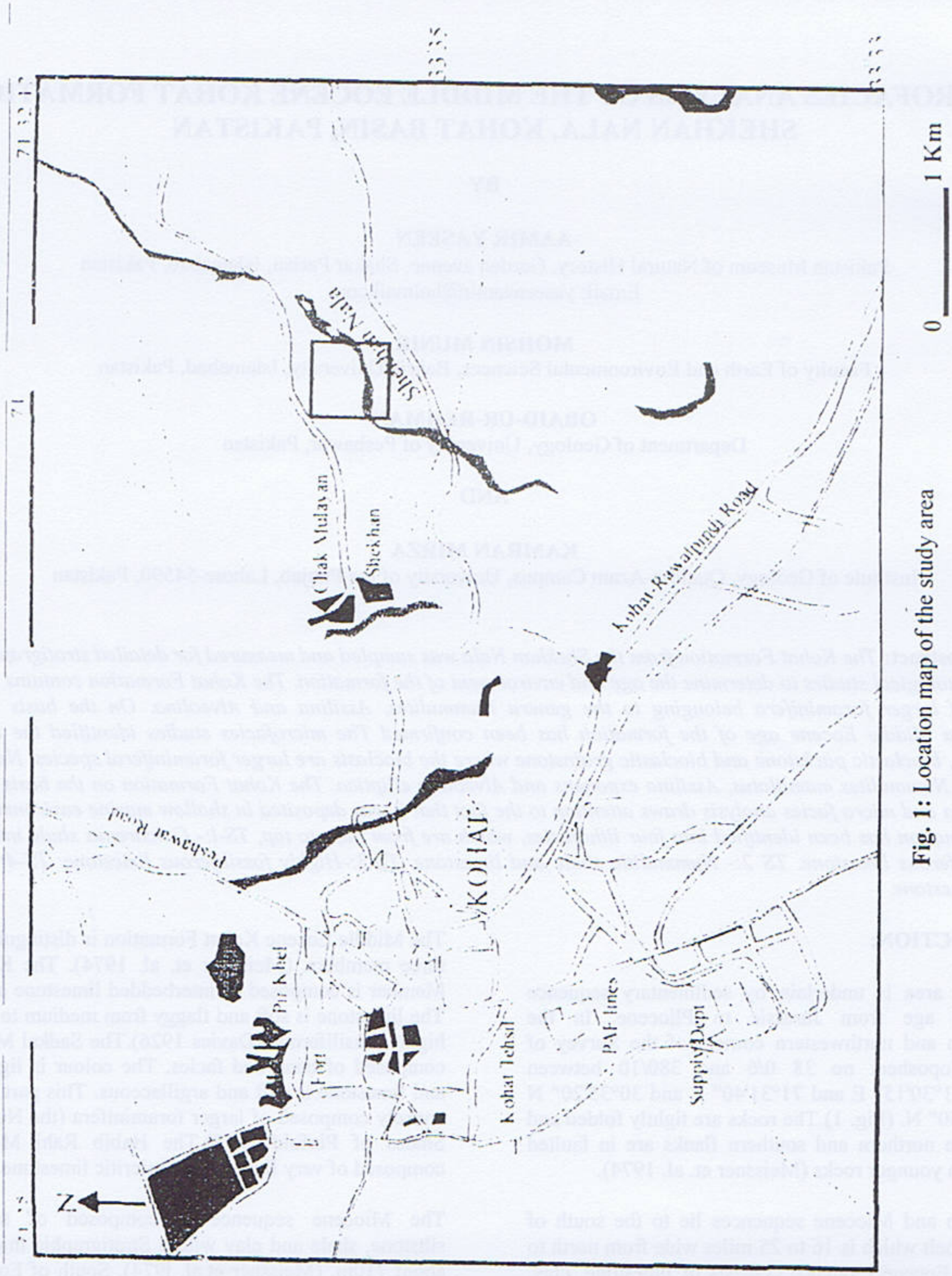

Fig. 1: Location map of the study area

exposed in Shekhan Nala is to identify the sedimentary facies, fossil contents and the environment of deposition. The present contribution is the outcome of first author's M.Sc. Field work (Yaseen, 2004).

PREVIOUS WORK

Eames (1952) described the stratigraphy of the region in greater detail and proposed various nomenclature for rock units exposed in the Kohat Quadrangle.

The first systematic geological work of the Kohat area was carried out by Meissner et. al. (1974) who prepared a geological map on a scale of 1:250,000 with the help of aerial photographs and gave a comprehensive account of the stratigraphy and structure of the area. Sameeni and Butt (1998) identified *Alveolina elliptica* (Sowerby) and *Alveolina stercusmuris* Mayer – Eymar from the Kohat Formation at Kundao Check Post, Kalabagh to Kohat Road.

MATERIAL AND METHODS

The oriented rocks specimens were collected for petrographic studies and hundred thin sections were prepared for microfacies analysis. However there were certain levels from where the free specimens of large foraminifera could be collected for systematic study.

STRATIGRAPHY OF THE SHEKHAN NALA

The stratigraphic section in the Shekhan Nala is as follows:

Miocene		Murree Formation
Eocene	Middle	Kohat Formation
		Kuldana Formation
	Lower	Shekhan Formation
		Panoba Shale
Paleocene		Patala Formation

KOHAT FORMATION

The Stratigraphic Committee of Pakistan (Fatmi, 1973) formalized the name Kohat Formation for the Kohat Shale and Kohat Limestone of Davies (1926, 1940) and for the Upper Chharat, Lower Chharat and the Kohat Limestone of Eames (1952). This also includes the Nummulitic Shales of Pinfold (1918).

The lower part of the Kohat Formation named as the "Kaladhand Member" is composed of interbedded limestone and shale. The colour of the limestone is light grey to medium grey, while the shale is of off white to medium grey colour.

The middle part of the Kohat Formation is called the "Sadkal Member" which is composed of bank bed facies due to the presence of abundant larger foraminifera. The colour of the limestone is light brown and the rock is soft and argillaceous. This corresponds to the Nummulitic Shals of Pinfold (1918).

The upper part of the Kohat Fomation is called the "Habib Rahi Member" which is medium hard to hard and is of light grey to medium grey in colour. This part is fossiliferous. The upper most part of the formation is micritic limestone. This member is also nodular.

It is interesing to note that all these three members are not exposed in a single section.

MICROFACIES

The thin section study identified three types of larger foraminifera (*Nummulites, Assilina* and *Alveolina*). Three main types of microfacies namely, Bioclastic Wackestone. (Plate 1, Figs. 1-3), Bioclastic Packstone (Plate 1, Figs. 4-5; Plate 3, Fig 1), and Bioclastic Grainstone (Plate 2, Figs. 1-2; Plate 3, Fig. 2) are identified.

The following species of larger foraminifera have been encountered during the detailed thin section study.

1. Nummulites beaumonti d'Archiac & Haime

2. *Nummulites mamillatus* (Fichtel & Moll)

3. *Assilina exponens* (Sowerby)

4. *Alveolina elliptica* (Sowerby)

Nummulites beaumonti d' Archiac & Haime
(Plate 2, Figs. 3-5)

Nummulites beaumonti d' Archiac & Haime has originally been described and illustrated by d' Archiac & Haime (1859) from the Lower Tertiary of Egypt and Indian subcontinent.

Our material from the Kohat Formation represents microspheric individuals. The outline of the species is lenticular with rounded margin. The wall is reasonably thick and shape of the chambers in the equatorial view is squarish in outline.

Nummulites mamillatus **(Fichtel & Moll)**
(Plate 3, Figs. 1-2)

Nummulites mamillatus (Fichtel & Moll) is characterized by the thick wall, narrowly spaced chambers and the presence of umbonal pillars as seen in the vertical view. The specimen is strongly biconvex.

Assilina exponens **(Sowerby)**
(Plate 3, Figs. 1-3)

Assilina exponens (Sowerby) has originally been described and illustrated from the "Nummulitic Series" of the Indian sub continent. The free specimens are of the size of coin and discoidal. The surface is provided by raised ridges. The specimens in our material are microspheric and the wall is thick. *Assilina exponens* (Sowerby) is abundantly found in the Kohat Formation.

Alveolina elliptica **(Sowerby)**
(Plate 3, Figs. 4-6)

Alveolina elliptica (Sowerby) has been described and illustrated by Hottinger (1960) from the Middle Eocene Kirthar Formation, Pakistan. Our illustrated material from the Kohat Formation closely compares with his figures. The initial portion of this species shows loose coiling and the later portion is closely spaced.

LITHOFACIES OF THE KOHAT FORMATION

For the environmental interpretation the Kohat Formation is divided into four facies in the project area on the basis of this detailed thin section study. (Fig.2)

1- TSI (Tertiary at Shekhan Nala Section-I)

This is the unit present in the base of Kohat Formation. It is composed of calcareous shale and laminated, grey, hard, fossiliferous limestone.

The petrographic studies suggest that it contains micrite as major constituent, with larger foraminifera, crinoids and echinoids. It is bioclastic wackestone.

Interpretation:

The depositional conditions represent shallow marine environments after the deposition of the Kuldana Fomation indicated by the presence of the association of *Nummulites*, *Assilina* and a1gae in a high energy environment.

2- TS2 (Tertiary at Shekhan Nala Section-2)

This unit is composed of bluish grey, fine-grained, thinly bedded, nodular and richly fossiliferous limestone with interbedded argillaceous Nummulitic shale.

The petrographic studies suggest bioclastic wackestone to bioclastic packstone Major constituents are larger benthic foraminifera and shell fragments.

Interpretation:

This depositional phase shows a stabilized condition of transgression. The bioclastic packstone indicates a relatively high energy environment and shows a shoal sequence within the shallowing upward sequence.

3- TS3 (Tertiary at Shekhan Nala Section-3)

It is an argillaceous limestone facies rich in larger benthic foraminifera having the tests of *Assilina* and *Nummulites*.

The petrographic studies show bioclastic wackestone with *Assilina* and *Nummulites* as bioclasts. Interpretation:

Interpretation:

The facies of this depositional phase show a low energy environment.

4- TS4 (Tertiary at Shekhan Nala Section-4)

This unit consists of limestone. The topmost unit of this facies consists of brownish grey massive nodular limestone, which is in contact with the overlying Murree Formation, a molasse deposit of Miocene age. The petrographic study shows that the limestone is foraminiferal packstone to foraminiferal grainstone.

Interpretation:

The basal part of the facies shows, deposition in alternating low and high energy conditions. The top unit of the facies shows high energy conditions and the dominant microfacies are the bioclastic grainstones composed of foraminiferal bioclasts. The depositional phase of this facies carried out when the agitated water conditions prevailed.

CONCLUSIONS

The Kohat Formation is a carbonate sequence containing diagnostic larger foraminifera that confirm the Middle Eocene age of the formation.

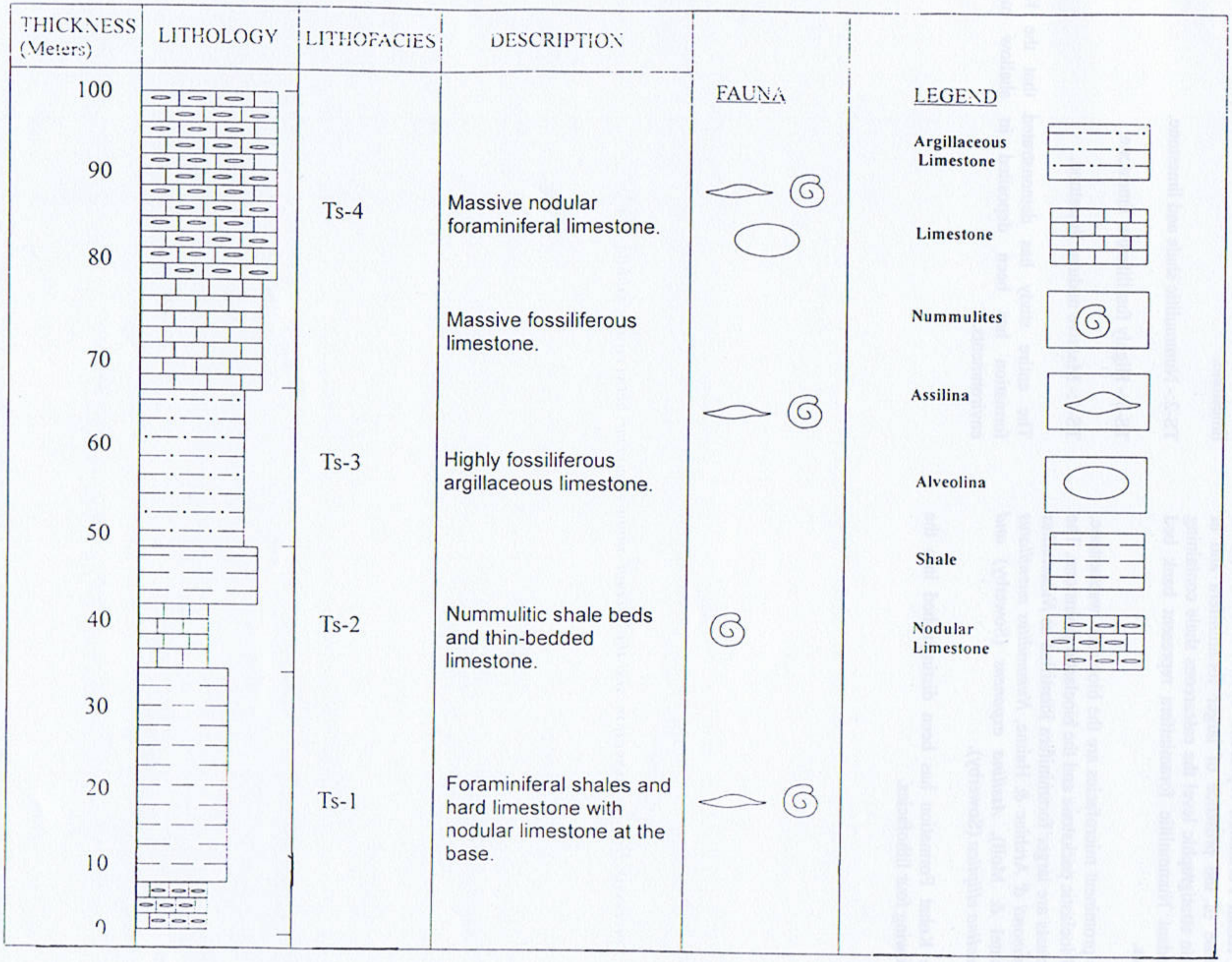

Fig 2: Lithofacies Log of the Middle Eocene Kohat Formation, Shekhan Nala, Kohat Basin

The Kohat Formation represents shallow shelf deposits because of the presence of larger foraminifera and at certain stratigraphic level the calcareous shale containing abundant Nummulitic foraminifera represent bank bed facies.

The prominent microfacies are the bioclastic wackestone, the bioclastic packstone and the bioclastic grainstone. The bioclasts are larger foraminifera identified as *Nummulites beaumonti* d' Archiac & Haime, *Nummulites mamillatus* (Fichtel & Moll), *Assilina exponens* (Sowerby) *and Alveolina elliptica* (Sowerby).

The Kohat Formation has been distinguished into the following four lithofacies.

TS-l:- Calcareous shale interbedded with fossiliferous limestone.

TS-2:- Nummulitic shale and limestone.

TS-3:- Highly fossiliferous limestone.

TS-4:- Massive nodular limestone.

The entire study has demonstrated that the Kohat formation has been deposited in shallow marine environments.

PLATE-1

Fig. 1 Bioclastic Wackestone. Nummulites beaumonti d' Archiac & Haime is the prominent bioclast

Fig, 2 Bioclastic Wackestone. Nummulites beaumonti d' Archiac & Haime is the prominent bioclast

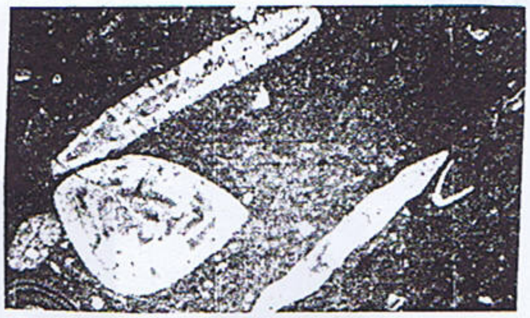

Fig. 3 Bioclastic Wackestone. Nummulites and Assilina are the prominent bioclasts

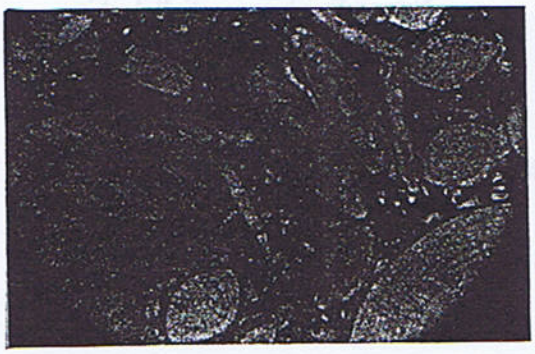

Fig. 4 Bioclastic Packstone. Assilina exponens (Sowerby) and Nummulites beaumonti d' Archiac & Haime are the dominant bioclasts

Fig. 5 Bioclastic Packstone. Assilina exponens (Sowerby) and Nummulites beaumonti d' Archiac & Haime are the dominant bioclasts

PLATE-2

Fig. 1 Bioclastic Grainstone. Nummulites beaumonti d' Archiac & Haime and Assilina exponens (Sowerby) are the prominent bioclasts

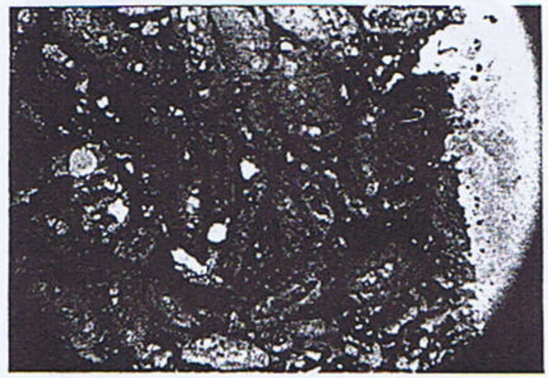

Fig. 2 Bioclastic Grainstone. Assilina sp being the dominant bioclast

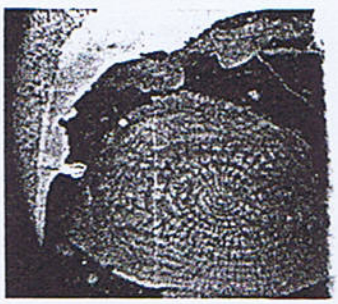

Fig. 3 Equatorial view of Nummulites beaumonti d'Archiac & Haime

Fig. 4 Axial view of the microspheric Nummulites beaumonti d' Archiac & Haime

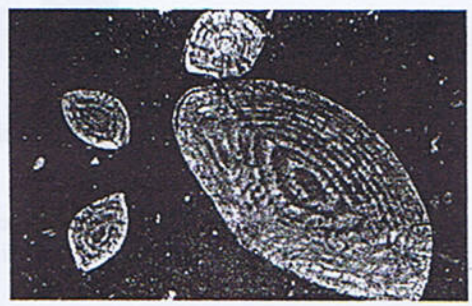

Fig. 5 Axial view of the microspheric Nummulites beaumonti d' Archiac & Haime

PLATE-3

Fig. 1 Bioclastic Packstone Assilina exponens (Sowerby) and Nummulites mamillatus (Fichtel & Moll) are the prominent bioclasts

Fig. 2 Bioclastic Grainstone Assilina exponens (Sowerby) and Nummulites mamillatus (Fichtel & Moll) are the prominent bioclasts

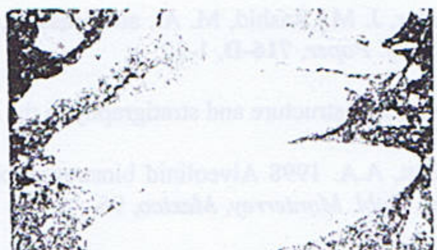

Fig. 3 Axial view of Assilina exponens (Sowerby)

Fig. 4 Equatorial view of Alveolina elliptica (Sowerby)

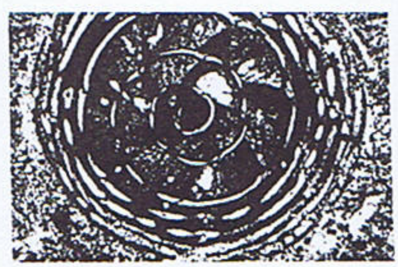

Fig. 5 Axial view of Alveolina elliptica (Sowerby)

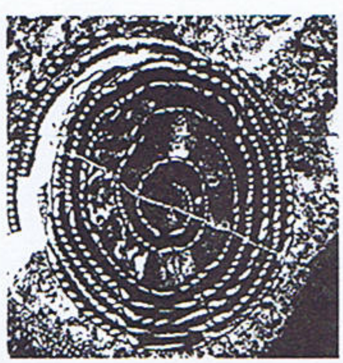

Fig. 6 Axial view of Alveolina elliptica (Sowerby)

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STRATIGRAPHIC ASPECT OF RECENT EARTHQUAKE OCCURRED ALONG THE BALAKOT-BAGH FAULT, NORTH-WEST HIMALAYAS, PAKISTAN

BY

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Abstract: *The Balakot-Bagh thrust running from Balakot through Muzaffarabad to Bagh Azad Kashmir along the eastern limb of Hazara Kashmir Syntaxis. Stratigraphically this fault occurred between the late Cambrian Abbottabad Formation and the Miocene Murree Formation from Balakot to Muzaffarabad city which is a major unconformity, while from Muzaffarabad city to Bagh through Chikar it runs within the Murree Formation.The BBT is a shallow thrust which enters upto the depth of Middle Eocene Kuldana Formation . Along the BBT, the Murree Formation thrusting over Siwalik Group due to under lying shales of the Kuldana Formation which act as a decollement. The two unconformities have been observed during this study. First major unconformity is marked between the late Cambrian Abbottabad Formation and the Paleocene Hangu Formation and the second minor oneoccur between the middle Eocene Kuldana Formation and the Miocene Murree Formation.*

INTRODUCTION

Stratigraphy in particular and tectonics of the study area are found to be very interesting during and after the occurrence of 8th October 2005, Earthquake in Hazara & Kashmir. Himalayas are extended from Burma to India and then in Kashmir and Northern Pakistan. Where it bended and formed the Nanga Perbat syntaxis and Hazara Kashmir syntaxis. The area remained uplifted at least two times. The oldest unconformity is of late Cambrian Abbottabad formation forming bauxite/laterite as part of Galdanian Formation in Hazara which merge with Cretaceous unconformity of Muzaffarabad and Kotli areas. The second unconformity is between middle Eocene Kuldana Formation and Miocene Murree Formation. The third unconformity is found between the Miocene Murree Formation and Pliocene/Pliestocene Siwalik group in Chikar towards Bagh area of Azad Kashmir (Figs. 1 & 2, Tables 1 & 2).

There might be some stratigraphic barriers due to non-continuity of certain formations in Hazara, Azad Kashmir and occupied Kashmir but they were not as they were introduced by Ghazanfar and Chaudhry (1987) that these are three stratigraphic provinces.

In my view the three provinces are as Kashmir, Muzaffarabad and Hazara. These regions had same geological environments during Precambrain times depositing Salkhala sediments overlain by Hazara/Dogra slates and Tanol qunartizite and pelites. The Cambrian conditions remained similar as well in all the three areas by depositing limestone and dolomites. In all the three stratigraphic areas during late Cambrian unconformity is seen in Hazara in form of Galdanian Formation with subsequent non-deposition till the formation of Data Formation of Jurassic.(Table 1) But there are such formations ever up to late Cretaceous in the Muzaffarabad-Kotli Basin. Where as in Kashmir Basin in Kahuta-Pir Panjal Range, Gondwana Formation of Carboniferous occurs and is not seen in other two basins. It is once again mentioned here that Hazara is the only area where we find Mesozoic rocks but after this era, rock types right from Paleocene to lower Miocene are found every where. These rocks are Paleocene Hangu Formation, Paleocene Lockhart Limestone, late Paleocene Patala Formation, Early Eocene Margala Hill Limestone, Early Eocene Chor Gali Formation Middle Eocene Kuldana Formation, Miocene Murree Formation and Pliocene to Pleistocene Siwalik Group. The occurrence of Hazara-Kashmir Systaxis of the North-Western Himalayas as around Muzaffarbad form a great

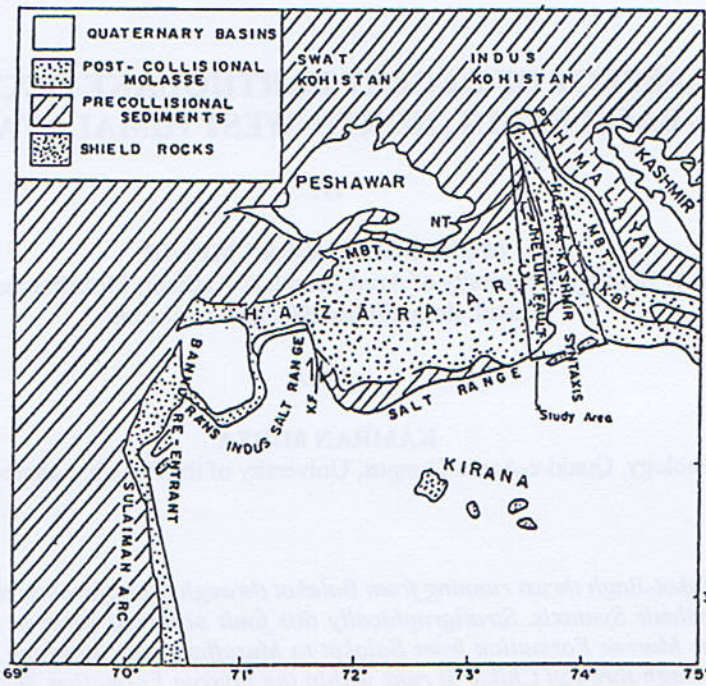

Fig. 1: Tectonic map of the Hazara Arc modified after Chaudhry & Ghazanfar (1992), Khan & Ali (1994) and Seeber et al. (1981)

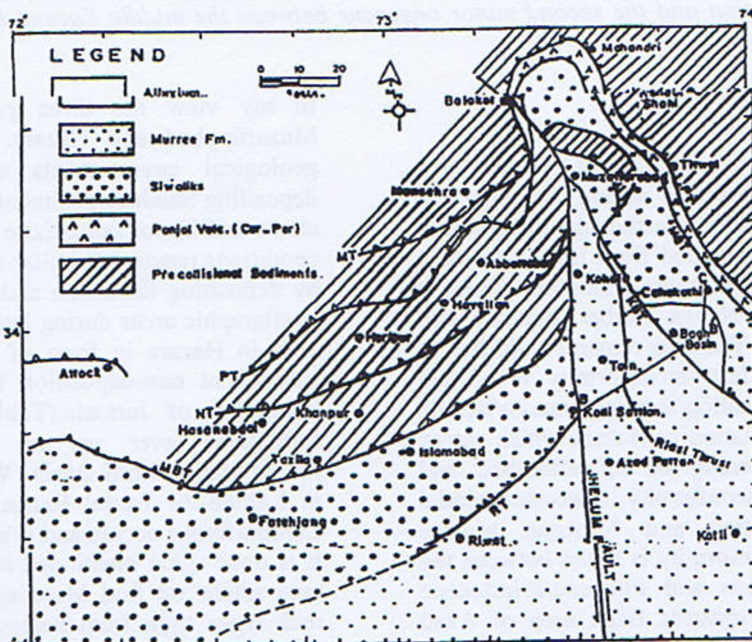

Fig.2: Generalize Tectonic map of Hazara-Kashmir Syntaxis in Northern Pakistan & Kashmir. BBT=Balakot-Bagh Thrust, PT=Panjal Thrust, MBT=Main Boundry Thrust, KBT=Kashmir Boundary Thrust, RT=Riwat Thrust, modified after Wadia (1928), Latif (1970), Calkins, et al. (1975), Baig and Lawrance (1987), Chaudhry and Ghazanfar (1992).

anticlinal structure with a lot of imbricate and nappe blocks (Fig.1).The rock units exposed in the area are given in table 1 & 2.

In recent publications Bossart et. al. (1984) and Greco (1986 & 1989) have misidentified the Kuldana Formation as Murree Formation. The Murree Formation is everywhere of the Miocene age as this identification by them is erroneous.

Table-1
Stratigraphic Sequence of Hazara Kashmir Syntaxis.

Rock type	Age
Alluvium	Recent to sub-Recent
Siwalik Group	Pliocene to Pleistocene
--------------Unconformity--------------	
Murree Formation	Oligocene to lower Miocene
--------------Unconformity--------------	
Kuldana Formation	Middle Eocene
Chor Gali Formation	Lower Eocene
Margala Hill Limestone	Lower Eocene
Patala Formation	Upper Paleocene
Lockhart Limestone	Lower Paleocene
Hangu Formation	Lower Paleocene
--------------Unconformity--------------	
Abbottabad Formation	Cambrian
Hazara Formation	Precambrian

PREVIOUS WORK

The project area has remained a site of deep interest for the geologists working on stratigraphy and tectonics since a long time. A brief summary of the previous work is given below:

Lydekker (1876, 1883) and Middlemiss (1896) carried out their work in Kashmir and Hazara. They established the broad outline of the geology in this region and named some of the rock units.

Wadia (1931) explained the syntaxis of the northwest Himalaya on the basis of geosynclinal group of deposits laid down on the bed of Tethys against the northern shores of Gondwana land.

Qureshi and Imam (1960) did the geological mapping of the area for iron and manganese ore deposits.

Calkins, Offield, Abdullah and Ali (1975) mapped Balakot area at 1:125,000 and discussed its geology. They delt the stratigraphy and structure of a sequence of rocks that range in age from Precambrian to Miocene. Structurally the area lies on the western flank of the Hazara Kashmir Syntaxis and contains iron, manganese, high alumina, clays, gypsum, dolomite and graphite. This work was done jointly by the Geological survey of Pakistan and U.S. Geological Survey.

The main interest of field of Thakur and Gupta (1983) was the regional stratigraphy, paleontology and structure of Kashmir and Ladakh Himalayas.

The Swiss geologists Bossart, Dorthe, Dietrich, Greco, Ottiger and Ramsay (1984) in collaboration with Institute of Geology Azad Jammu& Kashmir University described the lithological, stratigraphic and structural features of Hazara Kashmir Syntaxis.

Ottiger (1986) did his work on the geology of Hazara-Kashmir Syntaxis. He reviewed the lithological Formations and rhythmic sedimentation in Lower Murree Formation in detail.

Ghazanfar, Chuadry and Latif (1987) established three different sets of stratigraphic sequences which occur close together in the region of Hazara-Kashmir Syntaxis. These have been termed as the Kashmir sequence, the Muzaffarabad sequence and the Hazara sequence. The Balakot area contains elements of all three but mainly the Muzaffarabad sequence.

Ghazanfar, Chaudry, Zaka and Baig (1987) mapped nearly 65 square Kilometers of the area in vicinity of Balakot and described major structures and stratigraphy of the area. A new stratigraphic interpretation of the metamorphics was presented. The small but interesting Bamphora structure was explained. Bossart, Dietrich, Greco, Ottigar and Ramsay (1988) gave the interpretation of the tectonic and structure of the Hazara Kashmir Syntaxis, southern Himalayas of Pakistan.

Bossart and Ottiger (1989) studied the rocks of Murree and described it as a descending foreland basin of Late Paleocene to Middle Eocene age.

Greco Antonio (1990) described the stratigraphical and metamorphic features of the rocks of the Hazara Kashmir Syntaxis. He subdivided the area into Sub, Lesser and Higher Himalayan tectonic elements. A mode for the tectonic evolution of the area based on the coherent and continuous development of the observed small and large scale structural and metamorphic features were suggested by him.

Table-2:
Stratigraphic Correlation from Cambrian to Miocene Rocks of Hazara-Kashmir Syntaxis, Northwest Himalayas, Pakistan.

Western limb of Hazara Kashmir Syntaxis Hazara	Eastern limb of Hazara Kashmir Syntaxis			AGE
	Balakot	Kotli	Yadgar	
Murree Formation	Murree Formation	Murree Formation	Murree Formation	Miocene
Fetehjang member -- disconformsity— Kuldana Formation	Kuldana Formation	Kuldana Formation	Kuldana Formation	Early to Middle Eocene
Chor Gali Formation	Chor Gali Formation	Chor Gali Formation	Chor Gali Formation	Early Eocene
Margala Hill Limestone	Margala Hill Limestone	Margala Hill Limestone	Margala Hill Limestone	Early Eocene
Patala Formation		Patala Formation	Patala Formation	Late Paleocene
Lockhart Limestone			Lockhart Limestone	Late Paleocene
Hangu Formation	Hangu Formation	Hangu Formation	Hangu Formation	Early Paleocene
---------unconformity---------	unconformity	unconformity	unconformity	
Kawagarh Formation				Late Cretaceous
Lumshiwal Formation				Early Cretaceous
Chichali Formation				Early Cretaceous
Samana Suk Formation				Jurassic
Datta Formation ----------unconformity---------				Jurassic
Guldanian Formation --------disconformity--------				Cambrian
Hazira Formation				Cambrian
Abbottabad Formation	Abbottabad Formation	Abbottabad Formation	Abbottabad Formation	

Photo – 1: Line A – B marks the thrusted contact between the Abbottabad Formation above and The Murree Formation below at Neela Dandi, Muzaffarabad.

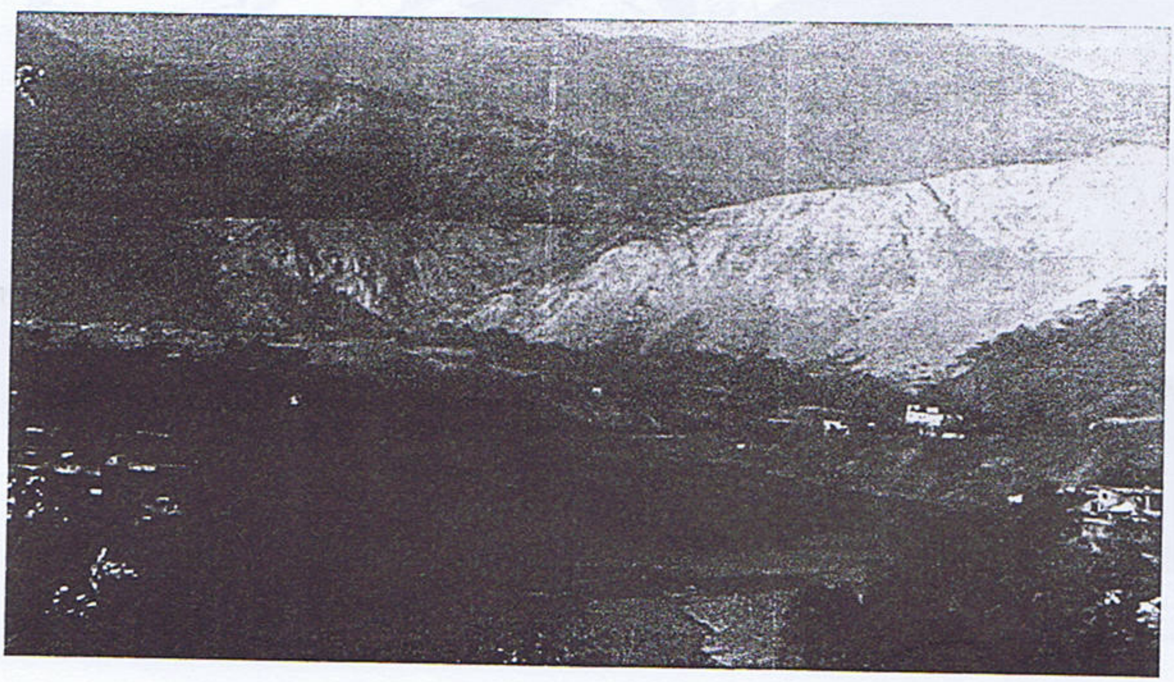

Photo – 2: Neelum River crosses the Abbottabad and the Murree Formations and the BBT at Chehla Bandi near University Campus Muzaffarabad.

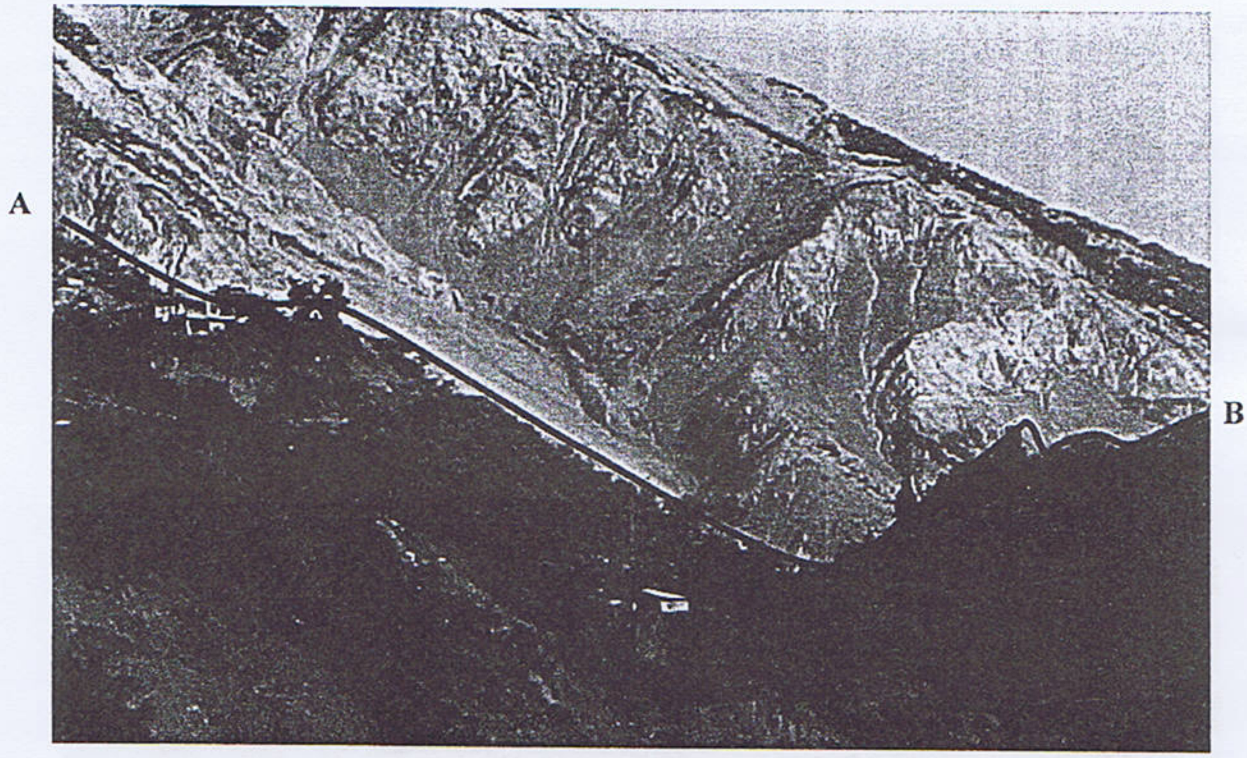

Photo – 3: Line A – B marks the BBT at Upper Ranjata, Muzaffarabad.

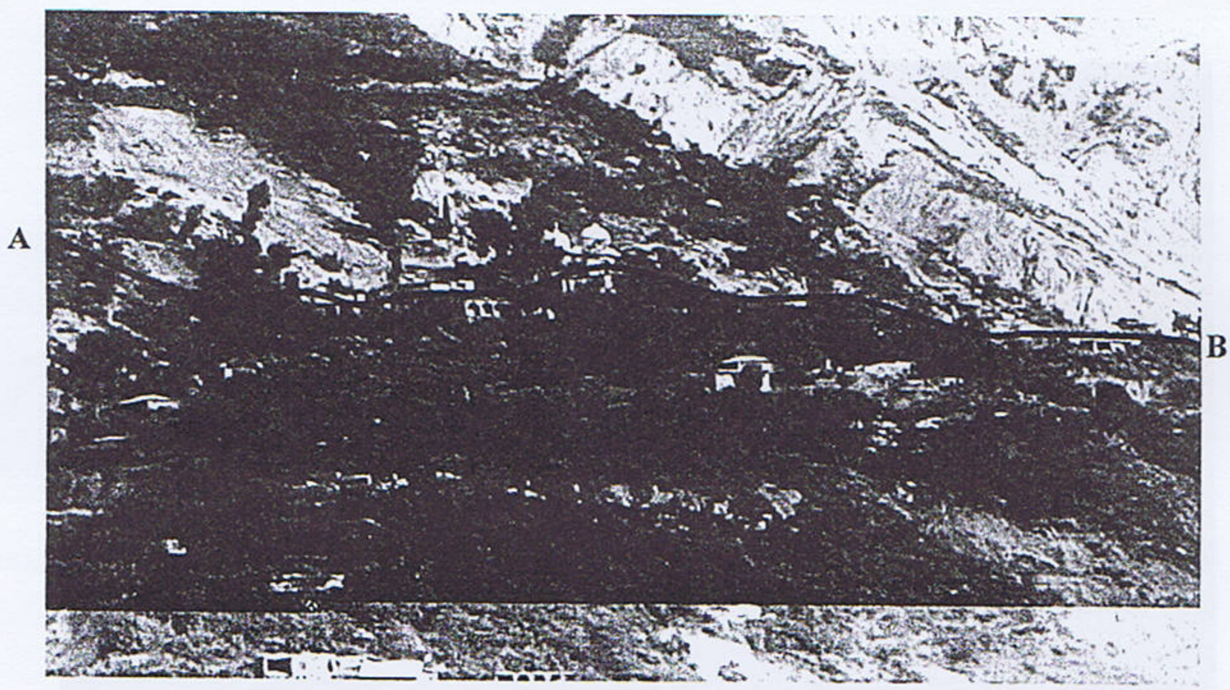

Photo – 4: Line A – B marks the BBT at Chattakian, Muzaffarabad.

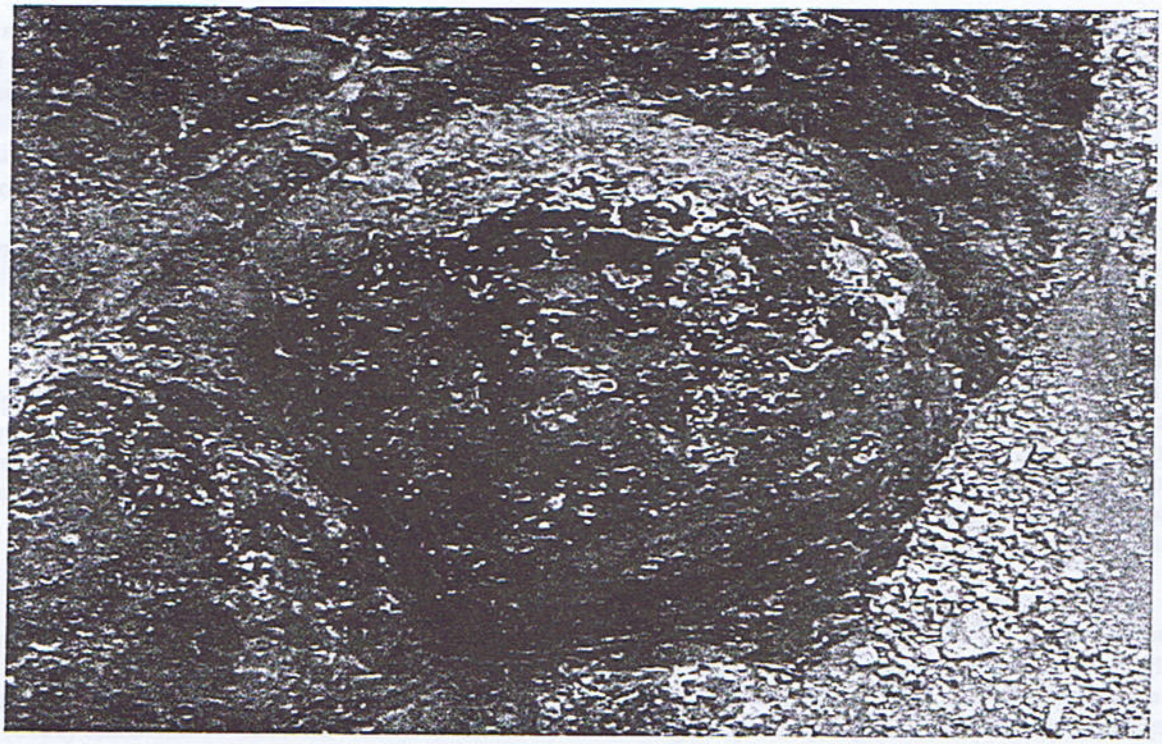

Photo – 5: Stromatolites upto 1meter within the Abbottabad Formation.

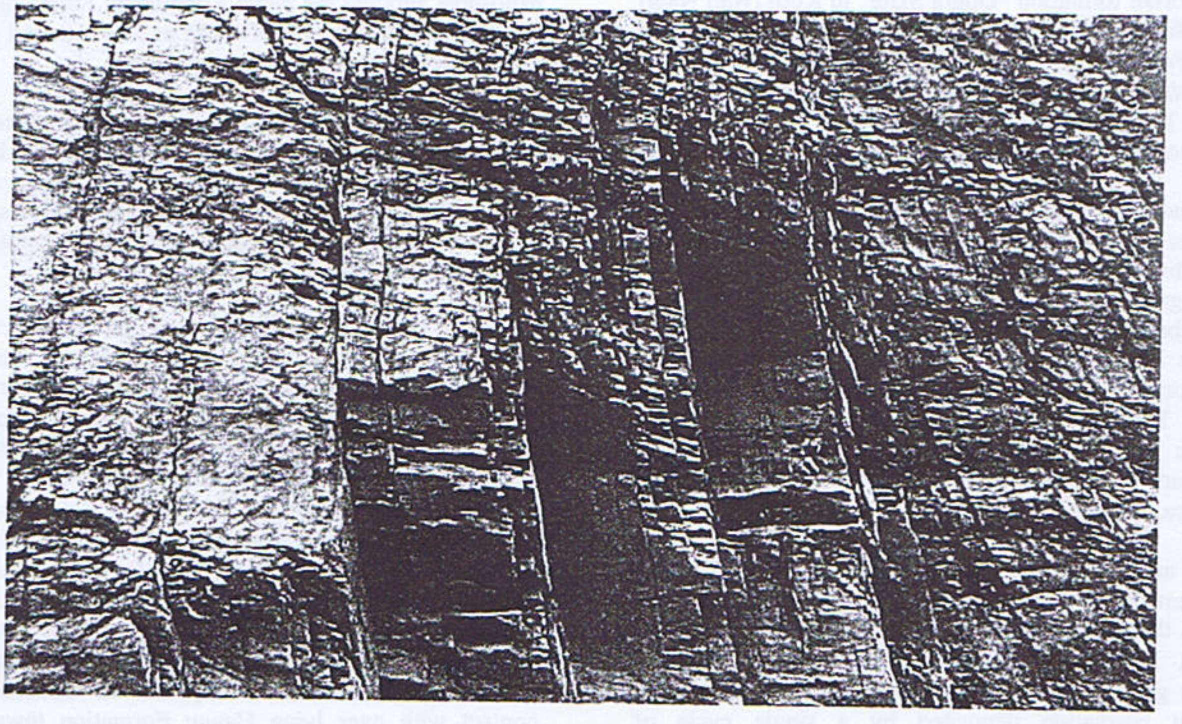

Photo – 6: Bedded Muzaffarabad Formation at Yadgar, Muzaffarabad.

Medlicott (1876) did the preliminary work on Jammu Hills as the Sub-Himalayan Series.

Lydekker (1883) described the geology of Kashmir and Chamba territories and the British district of Kaghan for Geoloigcal Survey of India.

Wadia (1928) first time described the Geology of the Poonch state (Kashmir) and adjacent portions of the Punjab on 1:4 inches scale. His studies were mainly focused on stratigraphic and mineralogical aspects. He established broad outline of the geology of this region. He reported a nearly identical Ossiferous Pseduconglomerates with chelonian and mammalian bones from the basal purple shales at Nikial. The paleontologists of the University of Michigan and the Museum National de Historre Naturelle of France visited Wadia's sections in 1981, but they were unable to rediscover his fossil bed.

Ashraf and Chaudhry (1980) have carried out a comprehensive work on the geology of Azad Kashmir especially in Poonch and Kotli area. They also described the clayey bauxite and clay deposits of Kotli in detail. They separated the Siwalik Group by comparing the overall compositions of these rocks in Poonch area.

Ashraf, Chaudhary and Qureshi (1983) discovered the Precambrian formation "Dogra Slate" in Kotli (Nail Nala) for the first time. The lithostratigraphic units range in age from Precambrian to Recent consisting mainly of sedimentary rocks with minor intrusions of basic sills and dykes. They described two prominent unconformities. Their work in the area has led many geologists.

Baig and Lawrence (1987) did an extensive geological work on the different phases of orogeney and dated the Precambrian to Early Paleozoic rocks in the Himalaya. They gave the evidence of tectonism from Late Precambrian to Early Cambrian rocks in Hazara, Kotli and the Nepal Himalaya by the presence of an angular unconformity. They also correlated the Hazaran orogeney in the Himalaya which occurred before the Permo-Triassic breakup of Gondwana with the Pan-African, Baikalian, Cadomian, Katangan and Assyntic orogenies of Africa, Asia and Europe.

Wells and Gingerich (1987) interpreted the paleo-environments of Paleogene strata in the area. In their studies they correlated these strata with Muzaffarabad, Hazara, Kohat, Kala Chitta, Kalakot and the Jammu regions giving the names of the units from A to J as Subathu Formation deposited by a single cycle of transgression and regression during the Early Eocene.

Recent work has been contributed by Rustam (2003) on the study of shallow geological structure in the core of Hazara Kashmir Syntaxis based on residual gravity data in the area. All this geological work in the area is mainly on the structure, tectonics and stratigraphy. In the light of the previous work mentioned above, it is evident that the present research is the first comprehensive contribution in the new direction related to the stratigraphic analysis of the stratified rocks of Neotethys Ocean in Azad Kashmir and Hazara area of the Himalayas of Pakistan related to the BBT.

STRATIGRAPHIC SETTING

The rock units exposed along the Balakot-Bagh Thrust (BBT) formerly known as Kashmir Boundary Thrust (KBT)/ Murree fault (MF)/ Muzaffarabad fault (MF)/Himalayan Frontal Thrust (HFT) are Abbottabad formation, Murree Formation and Siwalik group.

ABBOTTABAD FORMATION

Waagen and Wynne in 1872 studied the sequence of dolomite and quartzite rocks overlying the Hazara Formation in the Sirban Hill near Abbottabad town and named it "Below the Trias". Middlemiss (1896) renamed it "Infra-Trias". Marks and Ali (1962) suggested the name Abbottabad Formation. Calkins, Offield and Ali (1969) who mapped southern Hazara and studied all its exposures adopted the name Abbottabad Formation. Latif (1970a) named this unit of rocks as "Abbottabad Group" and divided it into constituent formations.

The type section of the formation is designated near Abbottabad town. The exposures are found between Muzaffarabad and Balakot and in the upper area of Hazara Kashmir Syntaxis. The formation consists mainly of cherty dolomite, chert bands and pure dolomite bands with many lithologic facies from place to place.

At some places, basal conglomerate is overlain by quartozose sandstone followed upward by alternating dolomite and limestone which is mainly fractured with white, grey, creamish, off white and blue in colour. The large sized stromatolites upto one meter radius are present at based bedding plains especially in Yadgar area of Muzaffarabad (Photo-5). The Main Boundary thrust (MBT) after swinging around the syntaxial bend becomes Balakot-Bagh Thrust (Murree Thrust) near Muzaffarabad separating Hazara Formation and Abbottabad Formation (Sirban Formation of Latif, 1974). The formation is 100-900m thick in the Hazara Kashmir Syntaxis. From Balakot to Muzaffarabad city, it has unconformable contact with over lying Hangu Formation towards the northeastern Neelum valley and Thrusted contact towards the south-western side with Murree Formation. The formation has revealed the presence of small conical tubes

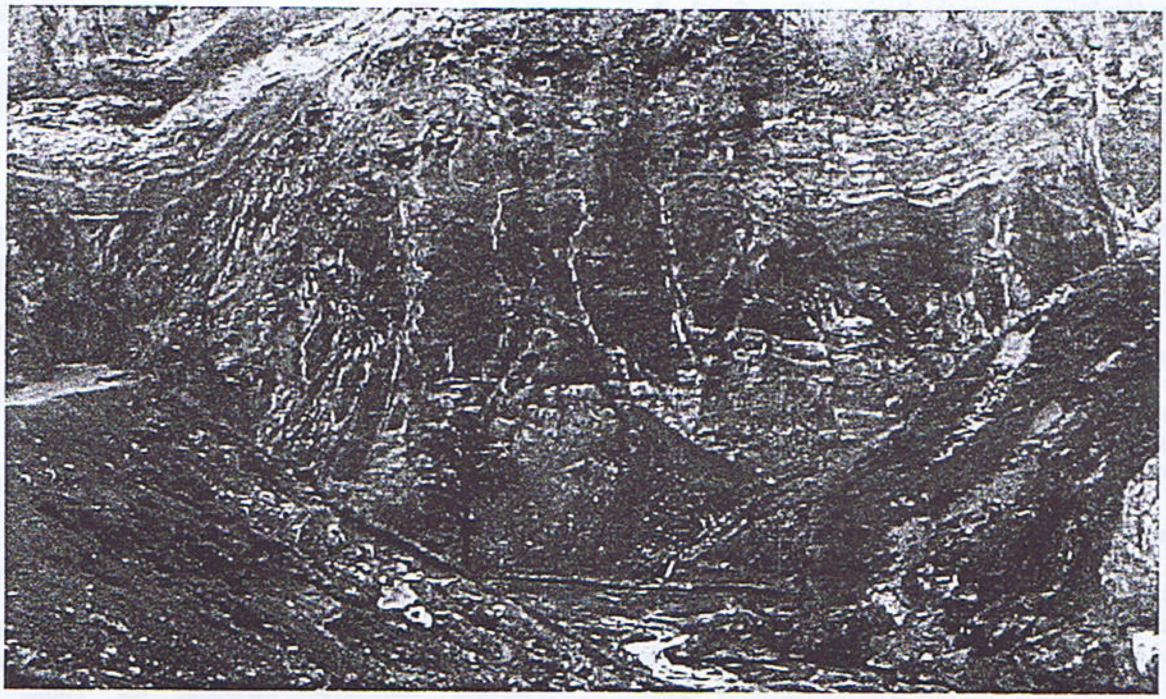

Photo – 7: Neelum River crossing the BBT and the Paleogene sequence at Yadgar Muzaffarabad.

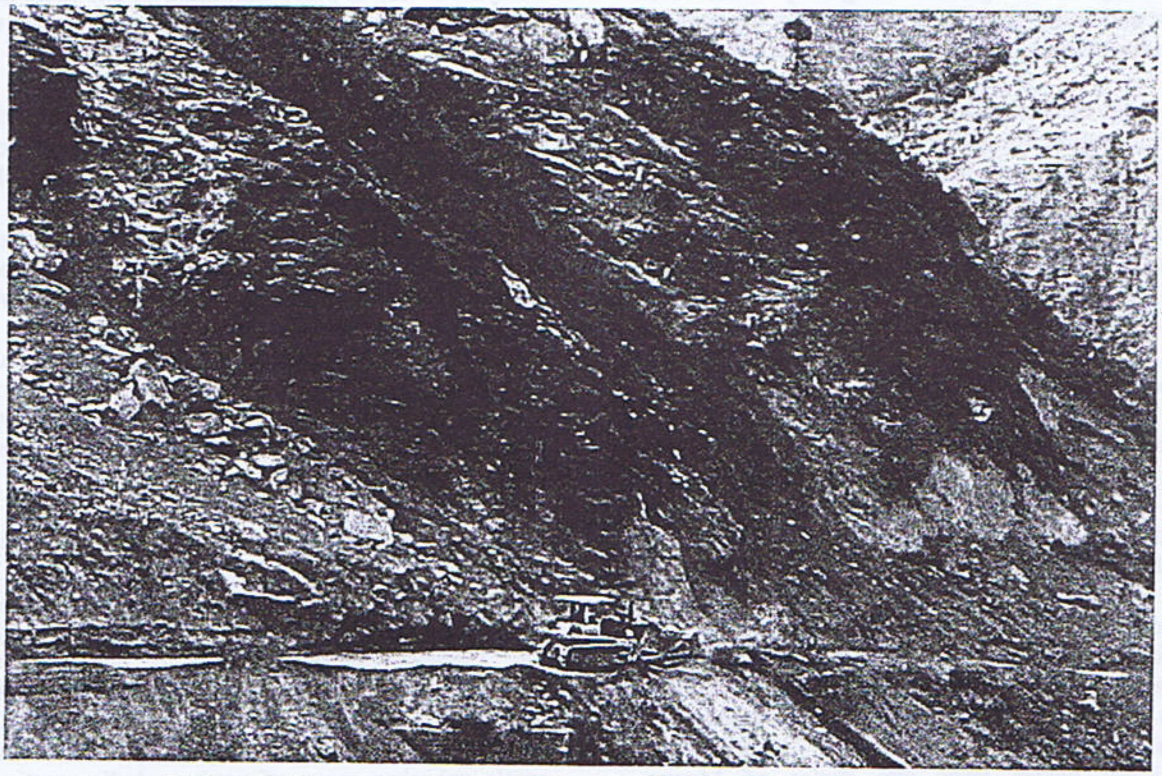

Photo – 8: Paleogene sequence in the core of BBT at Yadgar Muzaffarabad.

known as *Hyolithes* sp. on the basis of these fossils the Cambrian age is given to the formation.

The sheared material (Aggregate) of Abbottabad Formation were used in building and other construction purposes which caused heavy damage in the area. This invaluable material is still being used by the people for constructions (Photo - 6).

MURREE FORMATION

The "Mari Group" of Wynne (1874), "Murree Beds" of Lydekker (1876) and "Murree Series" of Pilgrim (1910) have been formally named Murree Formation by the Stratigraphic Committee of Pakistan from the Murree Hills in Murree District.

The formation is composed of red thinly laminated siltstone, shale, clay, with subordinate intraformational conglomerate. The sandstone is fine to medium grained, pale green to grey, maroon coloured, calcareous and greywacke in nature. The beds of sandstone, clay or shale alternate with each other. This pattern shows a cyclic deposition. In sandstone veins of calcite and quartz are common. At few places beds of calcareous sandy conglomerates are calcareous, flattened and squeezed in various shapes. Some of which are tapered to point on one end. Evidently these pebbles originally were soft calcareous and balls formed at the site of depositions rather than the detritus material brought from elsewhere.

The large areas of Jhelum Valley and Neelum Valley are covered with Murree Formation (Figs 1&2). In the Jhelum Valley it is thickly exposed and its upper faulted contact with Punjal Volcanics throughout the area extending in SE direction to the occupied Kashmir, in NW direction to the Neelum valley with in the Hazara Kashmir Syntaxis (Fig. 2). It is unconformably underlain by the Kuldana Formation of Middle Eocene time (Photo - 7).

This contact is marked by Ashraf et al. (1993) as brecciated base near Panjgran, Neelum valley. Bossart et. al. (1983) and Greco (1989) misidentified Kuldana Formation and called it as lower part of Murree Formation giving Paleocene and Eocene age, which is misinterpretation possibly due to reworked complete forminiferal fauna found by them in this formation. The lithology and fauna of Kuldana Formation is distinctly different from it everywhere so as in this area. Therefore, their inclusion of Kuldana formation erroneously in this formation is due to two reasons. First may be due to similar colour of both the formations and secondly due to reworking of unbroken foraminiferal fauna from soft natured Kuldanas to stratigraphically higher level into shales of Murree Formation. Ashraf et. al, (1973) marked the Main Boundary Thrust between Carboniferous to Triassic Panjal Formation and Miocene Murree Formation along the eastern limb of Hazara Kashmir Syntaxis. (Figs.1 & 2)

DISCUSSION

The Himalayan mountain belts have developed as a result of collisions between various continental and micro continental plates of Gondwana and Euresia (Stocklin, 1977, Tahirkheli et. al, 1979, Farah et. al, 1984). Early separated plates of Gondwana (Cimmeria) separated during the Permo-Triassic times and collided with Euresia in the Mid-Mesozoic in association with the closing of the Paleotethys sea (Sengor, 1984).

Between the Late Cretaceous and Mid-Eocene, the Indo-Pakistani Plate collided with Cimmeride Blocks and the Neotethys ocean was closed initiating the formation of current system of Himalayan folded Belts. The complete closer of the Neotethys ocean occurred in the Middle Eocene, followed by initiation of the main phase of thrusting and folding in the northwest Himalayas. The Kashmir Himalayas including the Panjal Block, Karakuram Range, Harmosh Range as well as the Nangaparbat Dome are all essentially closely related units. Powell & Conaghan (1973) put them all in the Himalayas. During the lower Cretaceous period the Tethys was well in place with India on one shore and Asia on the other. At least part of the Pir Panjal Range was not submerged. It formed part of the Indian mass.

Transgression of the sea took place in Paleocene and during Paleocene to Middle Eocene sea conditions persisted. However, sedimentation took place under unstable shelf basin conditions. The collision resulted in cyclic up and down movements resulting in the deposition of a sequence of limestones and shales. During part of Paleocene fairly shallow water restricted sea conditions developed where by coal and ironstones were formed followed again by the local deepening and deposition of limestones, shales and sandstones of Lockhart Limestone, Patala Formation, Margala Hill Limestone, Chor Gali Formation, Kuldana Formation and Murrree Formation. The Indian plate started under thrusting the Asian plate in Early Miocene.

Structurally the area is characterized by severe tectonic effects. It is highly folded, faulted and jointed. This is because the area lies close to one of the major syntaxial bend of the Himalayas know as Hazara Kashmir Syntaxis. The Hazara Kashmir Syntaxis is one of the most important structural feature of the region and displays prominent scar on the geological map (Fig. 2). The southern range of the Himalaya extend northward in a gentle unbroken curve of northern India, continue into Kashmir and Hazara District of Pakistan, where they from the eastern limb of the Syntaxis. Essentially continuous, the major faults and most of the geological units turn abruptly westward at Paras to form the apex of the Syntaxis and then southward to form the western limb. The two main boundary faults wrap around the Syntaxis are considered equivalent to Waadia's Punjal and Murree Faults. Stratigraphically the syntaxis contain the youngest rocks in the core and successively older rocks wrap around the periphery.

CONCLUSION

1) The Earthquake of 8th Oct. 2005 was struck along the Balakot-Bagh Thrust formerly known as Murree Fault/ Muzaffarabad Fault/ Main Boundary Thrust, Himalayan Frontal Thrust becomes steeper near Balakot NWFP in the north and at Muzaffarabad it turns in the north south trend & dips very steeply westward to the Bagh District of Azad Kashmir.

2) Stratigraphically the Balakot-Bagh Thrust is running between the late Cambrian Abbottabad Formation & Miocene Murree Formation from Balakot to Muzaffarabad city. Afterward it occurred within the Miocene Murree Formation upto Bagh towards South east direction.

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MICROFACIES ANALYSIS AND DIAGENETIC SETTINGS OF THE SAMANA SUK FORMATION, CHICHALI NALA SECTION, SURGHAR RANGE, TRANS INDUS RANGES, PAKISTAN

BY

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Abstract: *The Middle Jurassic Samana Suk Formation, exposed in the Chichali Nala Section, Surghar Range, Trans Indus Ranges, Pakistan, was investigated to study its microfacies, and diagenetic settings after collecting 105 rock samples from a total thickness of 43.27m. A total of 89 thin sections were studied from this section. The identified microfacies are oolitic grainstones, peloidal grainstones, grainstones with intraclasts and grainstones with grapestones, skeletal wackestones/packstones and carbonate mudstones. A variety of cement morphologies has been identified from early to late diagenetic phases. Micrite and spar have been developed in different diagenetic settings. Diagenetic features like stylolites, calcite veins and open fractures have been observed in this section. Dolomitization has been developed at various levels as cement as well as replacement. Dolomitization has also been observed along stylolites. At horizon, where the dolomite is pervasive one, all the three types of crystals mosaic, such as idiomorphic, hypidiomorphic and xenotopic, have developed. The calcitization of dolomite or dedolomitizatioin has also been noted. The shallowing upward successions, microfacies analysis and the diagenetic settings all contribute towards the shallow shelf depositional environment.*

INTRODUCTION

The Middle Jurassic Samana Suk Formation is a distinctive stratigraphic unit ranging in thickness from 5m (Nammal Gorge, Western Salt Range) up to 366m (Sheikh Buddin Hills, Marwat Range) recognizable over a wide area of northern Pakistan (Shah, 1977). It is the most important assemblage of carbonates in the Mesozoic succession of the Trans Indus Ranges, Salt Range, Kohat Tribal Range, Samana Range, Kala Chitta Range and Hazara area. The Samana Suk Formation is predominantly a limestone/dolomitic limestone. In the Chichali Nala Section the lower stratigraphic contact is transitional and conformable with the Shinawari Formation and is marked by the last sandstone bed of Shinawari Formation (Akhtar, 1983 and Mertmann and Ahmad, 1994) while the upper contact is disconformable with the Chichali Formation and is marked by the lateritic encrustation on dolomitic limestone (Sheikh, 1991, 1992). The laboratory techniques, comprising analysis of thin sections using light microscope, chemical staining with Alizarin Red S and Potassium Ferricyanide and digital photomicrography have been applied to describe its sedimentological features.

This formation is co-related with the Mazar Drick Formation and Chiltan Formation of the Sulaiman Fold and Thrust Belt and Murree Brewery Gorge near Quetta, Pakistan (Sheikh, et al., 2005). It is equivalent of the Chiltan Formation in the marginal areas of Kala Chitta Range, Hazara Sedimentary Basin and Trans Indus Ranges and to the west in the Kirthar Range (Sheikh et al., 2002).

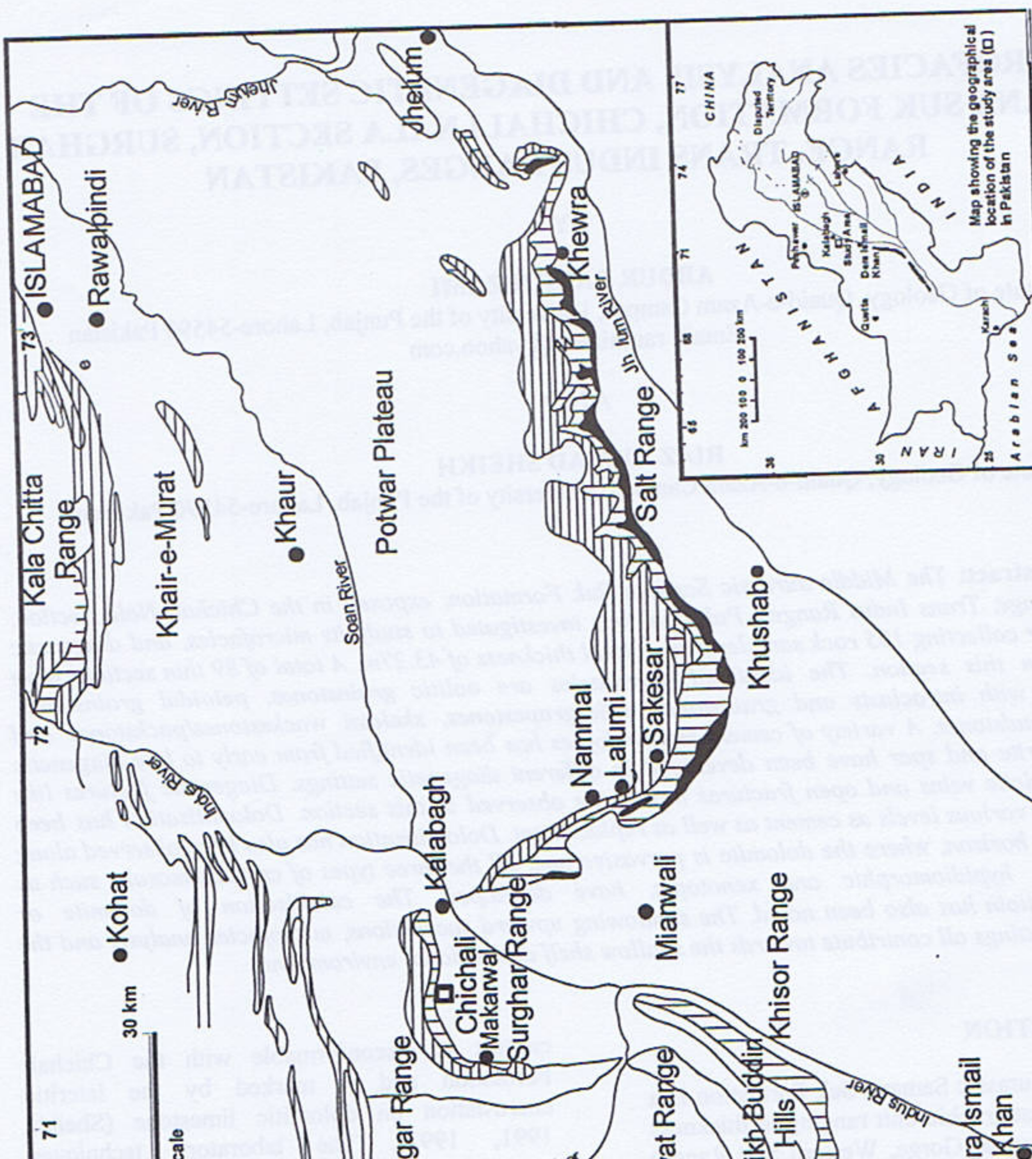

Fig. 1: Map showing the location of Chichali Nala Section (in the Trans Indus Ranges (Modified after Gee, 1989)

PLATE 1

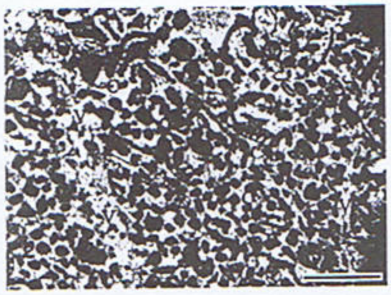

Fig. 1

Fig. 2

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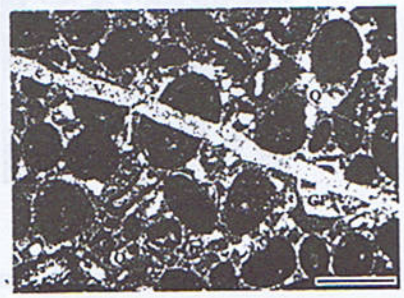

Fig. 4

Fig. 1 Photomicrograph showing pelloidal grainstone with intergranular cement **(C)**. A calcite vein **(V)** is cross cutting the peloids and cement, therefore, postdates cementation of the grainstone. A few foraminifers' shells **(FM)** are also present. Samana Suk Formation, Chichali Nala Section, Surghar Range, (XN, Scale bar=250 micrometer) Sample No. CHN-67

Fig. 2 Photomicrograph showing skeletal grainstone composed of sponge **(S)** shells and fragments with a few intraclasts **(Black arrow)** and red algae **(R)**. Samana Suk Formation, Chichali Nala Section, Surghar Range (PPL, stained, Scale bar=250 micrometer) Sample No. CHN-60A

Fig. 3 Photomicrograph displays skeletal grainstone with intraclasts **(Black arrow)**. The younger dog tooth cement **(DT)** and older intergranular equent calcite cement **(C)** are present. The skeletal grains have lost internal structure due to dissolution-precipitation phenomenon and now possess micritic envelopes **(E)**, which serve to preserve the outline and morphology of the grains. A small fracture filled by ferroan calcite **(FC)** is, also, present. Samana Suk Formation, Chichali Nala Section, Surghar Range (PPL, stained, Scale bar=250 micrometer) Sample No. CHN-60A

Fig. 4 Photomicrograph showing ooidal grainstone with a calcite filled fracture **(V)** cross cutting the cement and grains. Crinoid **(CR)**, pelloids **(P)** and quartz grains **(Q)** are present along with ooids **(O)**. The ooids possess concentric laminar structure. The dislocation of ooids by occluded fracture is self descriptive. Samana Suk Formation, Chichali Nala Section, Surghar Range (PPL, stained, Scale bar=250 micrometer) Sample No. CHN-61

PLATE 2

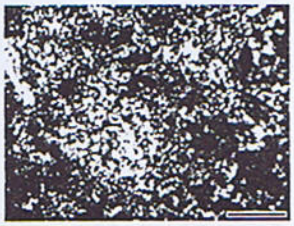

Fig. 1

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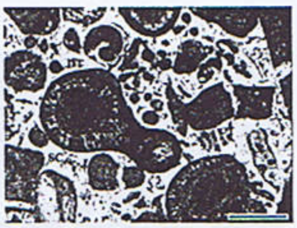

Fig. 3

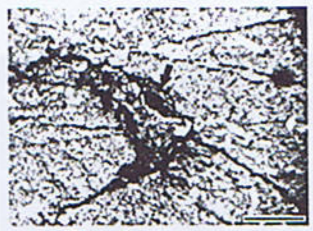

Fig. 4

Fig. 1 Photomicrograph showing a ferroan dolomite forming a hypidiomorphic mosaic of crystals. The light blue staining colour indicates the incorporation of a small amount of Fe in dolomite. Samana Suk Formation, Chichali Nala Section, Surghar Range (PPL, stained, Scale bar=250 micrometer) Sample No. CHN 40

Fig. 2 Photomicrograph showing ooidal grainstone with pelloids **(P)** and grapesstones **(G)** cemented by intergranular calcite cement **(C)** with drusy mosaic of crytals. The ooids have concentric laminae. The grainstone shows signatures of mechanical and chemical compaction. The cortices of the ooids are spalled off **(OFF)** and filled by calcite. The grain to grain contacts are mostly sutured **(SC)**. Samana Suk Formation, Chichali Nala Section, Surghar Range (PPL, Scale bar=250 micrometer) Sample No.CHN-68

Fig. 3 Photomicrograph displays an ooidal grainstone with pelloids and grapestones **(G)**. A gastropod shell **(GP)** is, also, present. The signatures of mechanical compaction are shown by the broken grains and those of chemical compaction by sutured grain contacts **(SC)**. The ooids are concentric with superimposed radial micro structure. The younger circumgranular dog tooth cement **(DT)** and older intergranular equent calcite cement **(IC)** are present. Samana Suk Formation, Chichali Nala Section, Surghar Range, (XN, Scale bar=250 micrometer) Sample No. CHN-69

Fig. 4 Photomicrograph showing a low amplitude stylolite with ferroan dolomitization **(Black arrow)** along it as styloccumulate in a mudstone. Samana Suk Formation, Chichali Nala Section, Surghar Range (PPL, stained, Scale bar=250 micrometer) Sample No. CHN 21

PLATE 3

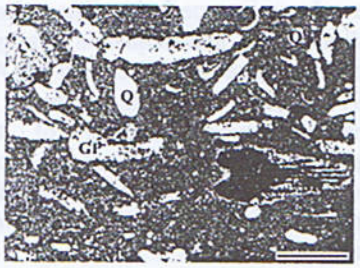

Fig. 1

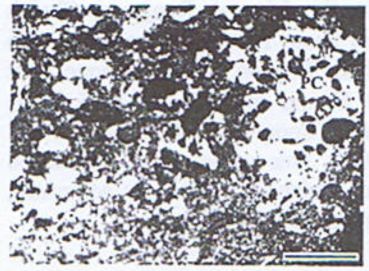

Fig. 2

Fig. 3

Fig. 4

Fig. 1 Photomicrograph displays a skeletal wackestone comprising of pelecypod (P), gastropod (GP), echinoid (E) and other skeletal grains (originally aragonitic and now calcitized). Occasional quartz (Q) grains are, also, present. Samana Suk Formation, Chichali Nala Section, Surghar Range, (XN, Scale bar=250 micrometer) Sample No. CHN-49

Fig. 2 Photomicrograph showing a poikilotopic cement (PC) in a pelloidal grainstone. Samana Suk Formation, Chichali Nala Section, Surghar Range, (PPL, Scale bar=250 micrometer) Sample No. CHN 94

Fig. 3 Photomicrograph showing a matrix selective dolomitization (dolomite cement) forming xenotopic mosaic of dolomite crystals. Samana Suk Formation, Chichali Nala Section, Surghar Range, (XN, Scale bar=250 micrometer) Sample No. CHN 34

Fig. 4 Photomicrograph showing multiphase cementation from the younger circumgranular dog tooth cement (DC) through the intergranular equent calcite cement (IC) to the late stage ferroan dolomite cement **(Black arrow)**. Samana Suk Formation, Chichali Nala Section, Surghar Range, (PPL, stained, Scale bar=250 micrometer) Sample No. CHN 60

In Trans Indus Ranges the Samana Suk Formation is exposed in the Surghar Range at a number of locations and in the Marwat Range at Sheikh Buddin Hills near Pezu. The approximate location of the Chichali Nala Section, Surghar Range, is at latitude 350030 N and longitude 712425 E on Survey of Pakistan Topographic Sheet No. 38 O/8 of a scale 1:50,000. This section can be accessed from the town of Kalabagh in District Mianwali, Punjab (Fig. 1, after Gee, 1989).

PREVIOUS WORK

The Samana Suk Formation, exposed in the Salt Range, was originally named as Samana Suk Limestone by Davies (1930). In the Kala Chitta Range it was named as Kioto Limestone by Cotter (1933) and Gee (1947) and in the Trans Indus Ranges as Baroach Limestone by Gee (1947).

The Stratigraphic Committee of Pakistan(Fatmi 1973) formalized its name as Samana Suk Formation. Fatmi, et al. (1990) indicated that the upper part of Jurassic succession is represented by the Samana Suk Formation and lower part of Chichali Formation and it is a shallow water marine carbonate rock. Mensink, et al. (1988), Fatmi, et al. (1990) and Mertmann and Ahmad (1994) described that the rocks of the Jurassic succession are exposed at a number of localities in the Trans Indus Ranges. Hallam and Maynard (1987) investigated the both, iron ore of the Chichali Formation and Samana Suk Formation, exposed in this section and produced valuable material on the Jurassic sediments regarding stratigraphy and sea level changes during the Jurassic period.

The facies development during Jurassic of Trans Indus Ranges was studied by Mensink, et al. (1988). They found five subsequent phases of facies development from the sand sedimentation of Datta Formation to shale deposition of Chichali Formation as a result of their investigations. This work covers the Jurassic succession present in the Trans Indus Ranges as a whole. Mensink, et al. (1988), Fatmi, et al. (1990) and Mertmann and Ahmad (1994) carried out studies on microfacies and depositional environments of the Samana Suk Formation of this area. With the similar objectives Mertmann and Ahmed (1994) worked on the facies and depositional environments of Shinawari and Samana Suk formations from the Surghar and Salt Ranges and presented an overview of the facies and depositional environments of the whole stratigraphic succession deposited during the Jurassic period. The Jurassic shelf sedimentation and sequence stratigraphy of the Surghar Range was discussed by Ahmed, et al. (1997) and indicated that facies and biostratigraphical analysis of the Jurassic deposits of Surghar Range show that the platform development was affected by both the variations in sea level and the influence of a nearby hinterland.

The present authors carried out an extensive research work on the different diagenetic aspects and various microfacies of the Samana Suk Formation from the Surghar Range exposed at Chichali Nala Section. Studies were carried out using a petrographic microscope along with the application of staining techniques. 105 rock samples of this formation were collected from a total thickness of 43.27 m at Chichali Nala Section, Surghar Range, while 89 thin sections were studied. Fig. 2 shows depositional synthesis log of Samana Suk Formation of the studied section.

METHODOLOGY

The following parameters have been taken into consideration for this research work:

- Field work
- Mapping work
- Section measurement
- Laboratory techniques

a) Analysis of thin sections using petrographic microscope
b) Chemical staining with Alizarin Red S and Potassium Ferricyanide
c) Digital photomicrography

MICROFACIES

The microfacies analysis of the Samana Suk Formation was carried out keeping in view the classification scheme suggested by Dunham (1962) for the microfacies of carbonate rocks.

The microfacies, found in the Samana Suk Formation, were skeletal grainstone oolitic grainstones, peloidal grainstones, grainstones with intraclasts and grainstones with grapestones, skeletal wackestones/packstones and carbonate mudstones.

PLATE 4

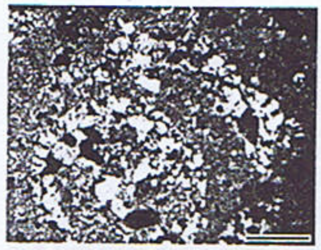

Fig. 1

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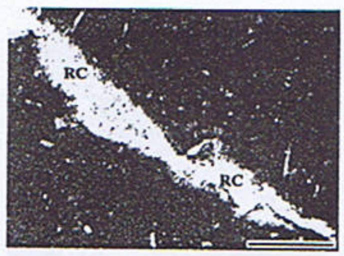

Fig. 3

Fig. 4

Fig. 1 Photomicrograph showing fabric/grain selective dolomitization. Samana Suk Formation, Chichali Nala Section, Surghar Range (XN, Scale bar=250 micrometer) Sample No. CHN-34

Fig. 2 Photomicrograph displaying an early stage stylolite **(ST)** with high amplitude in a mudstone. Samana Suk Formation, Chichali Nala Section, Surghar Range (PPL, Scale bar=200 micrometer) Sample No. CHN-22

Fig. 3 Photomicrograph showing radiaxial cement **(RC)** in a mudstone. Samana Suk Formation, Chichali Nala Section, Surghar Range (PPL Scale bar=200 micrometer) Sample No. CHN-21

Fig. 4 Photomicrograph showing syntaxial rim cement **(SR)** developed on echinoderm **(EC)** grain exhibiting characteristic single crystal structure extinction. Cleavage of calcite cement is continuous (i.e. in optical continuity) with the echinoid grain. A few micritic envelopes **(E)** are present also. (XN, Scale bar=250 micrometer) Sample No. CHN-64

PLATE 5

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 1 Photomicrograph displays a grainstone composed of pelloids and ooids **(O)**. The ooids have concentric and radial concentric laminae. It, also, shows dolomitization **(D)** in some of ooids. Samana Suk Formation, Chichali Nala Section, Surghar Range, (PPL, Scale bar=250 micrometer) Sample No. CHN 66

Fig. 2 Photomicrograph showing a dolomitized horizon with partial calcitization/dedolomitization. The neomorphosed calcite is a non-ferroan calcite **(NFC)** with red/pink colour. The dolomite displays an idiomorphic mosaic of crystals. Samana Suk Formation, Chichali Nala Section, Surghar Range (PPL, stained, Scale bar=250 micrometer) Sample No. CHN 51

Fig. 3 Photomicrograph shows a highly fractured mudstone. A medium amplitude stylolite **(ST)** is cross cutting these fractures **(F)**, hence, postdating these fractures. Samana Suk Formation, Chichali Nala Section, Surghar Range (XN, stained, Scale bar=250 micrometer) Sample No. CHN 71

Fig. 4 Photomicrograph displaying a mudstone with a cavity filling calcite cement **(DM),** exhibiting characteristic drusy mosaic of calcite crystals. Samana Suk Formation, Chichali Nala Section, Surghar Range, (XN, Scale bar=250 micrometer) Sample No. CHN 22

PLATE 6

Fig. 1

Fig. 2

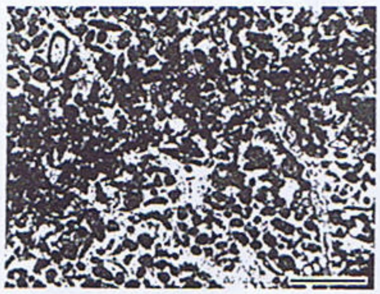

Fig. 3

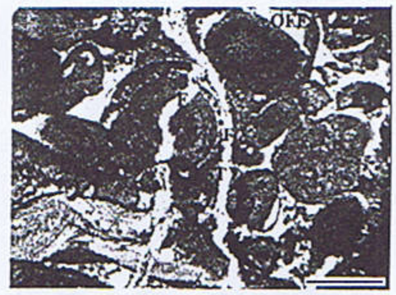

Fig. 4

Fig. 1 Photomicrograph is showing a wackestone with skeletal fragments of gastropod **(GP)** and pelecypod **(P)**. A medium amplitude stylolite **(ST)** is, also present with styloccumulate **(Black arrow)**. Samana Suk Formation, Chichali Nala Section, Surghar Range, (XN, Scale bar=250 micrometer) Sample No. CHN 31

Fig. 2 Photomicrograph displays a highly fractured (now filled with calcite) mudstone. The fractures belong to multi phase fracturing. Samana Suk Formation, Chichali Nala Section, Surghar Range, (PPL, Scale bar=250 micrometer) Sample No. CHN 55

Fig. 3 Photomicrograph displays a stylolite **(ST)** passing through a fractured pelloidal grainstone. These fractures pre-date the stylolite as it is cutting these fractures. Samana Suk Formation, Chichali Nala Section, Surghar Range, (PPL, Scale bar=250 micrometer) Sample No. CHN 67

Fig. 4 Photomicrograph displays a grainstone with a medium amplitude stylolite **(ST)** and fractures **(F)**, now occluded by sparite. The stylolite is older than one of fractures (cross cutting it) and is younger than the other one (being cross cut by it). Samana Suk Formation, Chichali Nala Section, Surghar Range, (XN, Scale bar=250 micrometer) Sample No. CHN 68

PLATE 7

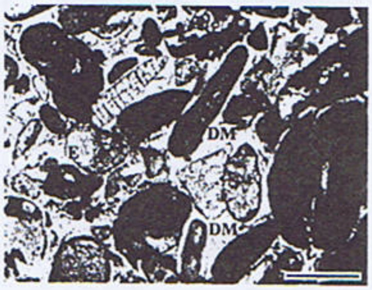

Fig. 1

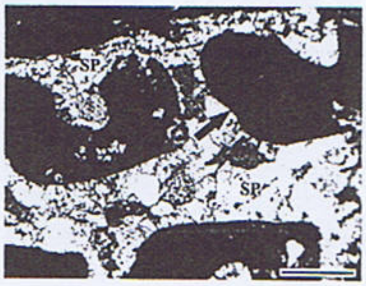

Fig. 2

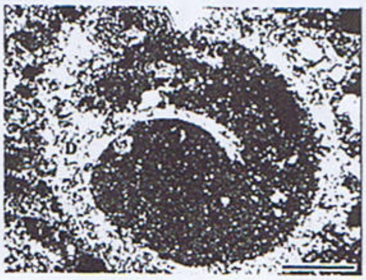

Fig. 3

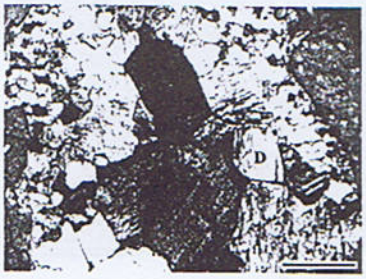

Fig. 4

Fig. 1 Photomicrograph showing an intraclastic grainstone with circumgranular dog tooth cement **(DT)** and intergranular drusy mosaic calcite cement **(DM)**. The micritic envelopes **(E)** are, also, present. Samana Suk Formation, Chichali Nala Section, Surghar Range, (PPL, Scale bar=250 micrometer) Sample No. CHN 60

Fig. 2 Photomicrograph showing a packstone with calcitized gastropod shells, which were originally aragonitic. The aragonite, being metastable, converted to sparry calcite **(SP)**. Acicular circumgranular cement **(Black arrow)** has nucleated these shells. Samana Suk Formation, Chichali Nala Section, Surghar Range, (XN, Scale bar=250 micrometer) Sample No. CHN 11

Fig. 3 Photomicrograph displaying pervasive dolomitization in a packstone. The part of gastropod shell, originally of aragonitic composition, was calcitized fisrt and then dolomitized **(D)**, showing two episodes of diagenetic conversion. Samana Suk Formation, Chichali Nala Section, Surghar Range, (PPL, Scale bar=250 micrometer) Sample No. CHN 37

Fig. 4 Photomicrograph displaying cavity filling dolomitic cement **(D)** with hypidiomorphic mosaic of dolomite crystals. Samana Suk Formation, Chichali Nala Section, Surghar Range, (XN, Scale bar=250 micrometer) Sample No. CHN 25

Grainstones

The petrographic analysis revealed the following sub-microfacies of grainstones as an outcome of present investigation:

Skeletal grainstone

This type of grainstone consists of skeletal shells and fragments of organisms sometimes along with intraclasts, pelloids and sometimes with oncoids and/or ooids (Plate 2, Fig. 1 and Plate 4, Fig. 1).

Pelloidal grainstone

The pelloidal grainstones are found at a number of levels in this section (Plate 1, Fig. 1). This microfacies is composed of faecal pellets and pelloidal grains which are micritized. These grainstones are also found in associations with other carbonate grains (Plates 1, Fig. 4 and Plate 2, Fig. 2).

Ooidal grainstone

Ooids present in these grainstones have, generally, concentric laminar microfabrics (Plate 1, Fig. 4). However, ooids with superimposed radial microstructure are also found in these grainstones (Plate 2, Fig. 3). Various skeletal grains, pelloids and quartz grains act as nucleus in the ooids (Plate 1, Fig. 4). Ooidal grainstones with pelloid as nucleus are also present (Plate 3, Fig. 2).

Grainstones in association with intraclasts

The intraclastic grainstone microfacies has not been found. However, grainstones in association with intraclasts are present in Plate 1, Fig. 2 and Plate 1, Fig. 3.

Grainstones in association with grapestone

Grapestones are actually aggregate grains and formed by the agglutination of other types of carbonate material. These are found commonly in grainstones. However, no grainstone comprised entirely of grapestones has been observed. The grapestones, found in association with other types of grains, are shown in the Plate 2, Fig. 3. It is noted that the frequency of their appearance in the grainstones is very low.

Packstone

The packstone microfacies, commonly, show various types of skeletal grains as their components. The frequency of occurrence of various skeletal shells/grains/biodebris shows range of component skeletal grains as shown in Plate 5, Fig. 2.

Wackestone

According to Dunham's classification (1962) the carbonate microfacies with more than 10% skeletal grains is categorized as wackestone. Like other facies the wackestones are found at various levels in the Samana Suk Formation (Fig. 2). Faunal diversity is also observed in wackestones found. Wackestones with different faunal assemblage are present (Plates 3, Fig. 1 and Platte 6, Fig. 1).

Mudstone

Mudstones are present at different horizons of the Samana Suk Formation, exposed in this section. The observed mudstones at places are highly fractured, which are filled with calcite. Mudstones with skeletal grains (Plates 4, Fig. 2; Plate 4, Fig. 3 and Plate 5, Fig. 3) and without any skeletal grain have been found (Plate 5, Fig. 3).

Diagenesis

The petrographic analysis supplemented with chemical staining techniques, was conducted to decipher the diagenetic settings of the Samana Suk Formation from the studied section. Formation is dolomitized and de-dolomitized in places, which is one of its most significant diagenetic character. Spar precipated in the micro fabric of different component grain and in fractures, and presence of stylolites, at different levels are also important characters. Chemical compaction and dissolution have caused the sutured boundaries and stylolites. Under the effect of this compaction the embayments of one grain into the other are present. Brittle deformation has been caused by over burden and a number of fractures are developed. Following diagenetic features have been found.

Fractures and stylolites

Various phases of fracturing, sometimes along with stylolitization, filled with calcite, were observed in this formation (Plate 5, Fig. 3; Plate 6, Fig. 2; Plate 6, Fig. 3 and Plate 6, Fig. 4). The low amplitude stylolites developed in the carbonate mudstone facies disrupted the calcite veins (Plate 5, Fig. 3 and Plate 6, Fig. 3 and 4).

In connection with the late void and micro fracture filling spars some spars related to the deep burial environments are precipitated between the spalled off cortices of the ooids (Plates 2, Fig. 2 and Plate 6, Fig. 4). Fractures are commonly found at various levels in the measured section. Mudstones particularly bear fractures, which at places are highly fractured (Plate 5, Fig. 3 and Plate 6, Fig. 2) with several phases of fracturing sometimes. Fractures are also found in other microfacies (Plate 1, Fig. 1 and Plate 6, Fig. 3, 4 and Plate 3, Fig. 2). Almost all these fractures are filled with spor.

The stylolization has been observed at various levels of the formation (Fig. 2), which range from low amplitude (Plate 4, Fig. 2) to high amplitude (Plate 7, Fig. 2) and are found mostly in the mudstones. However, the stylolites are also present in other microfacies (Plates 6, Fig. 1; Plate 6, Fig. 3 and 4). Some of the stylolites are found across the filled fractures and thus postdate the fracturing of that microfacies (Plate 5, Fig. 3; Plate 6, Fig. 3 and 4. While some pre-date these spar filled fractures (Plate 6, Fig. 4). The precipitation of dolomite along stylolites as stylocummolate in Plate 2, Fig. 4.

Micritic envelopes

These envelopes develop on grains with original aragonitic mineral composition. Aragonite being metastable among carbonate minerals is dissolved in the first phase of diagenesis of carbonate sediments and replaced by calcite (Plate 4, Fig. 4; Plate 7, Fig. 2 and 3. Micritic envelopes serve to preserve the outline and morphology of the grains.These envelopes, present in the Samana Suk Formation of Chichali Nala Section, are similar to those described by Kendal and Skipwith (1969) from the recent carbonate sediments and resemble with those illustrated from the Jurassic and Carboniferous Limestones by Bathurst (1964). The micritic envelopes are found on skeletal and non-skeletal grains in different grainstones and packstones at a number of levels of this formation from the Chichali Nala Section (Plate 1, Fig. 3 and Plate 7, Fig. 1).

Cements

Cementation of the carbonate sediments is an important diagenetic process, which endows strength and stability to the concerned microfacies. Early diagenetic cement precipitates as fibrous aragonite. While dog tooth cement (circum granular cement), dolomite cement, drusy mosaic calcite cement, poikilotopic cement and rediaxial cement precipitate as later diagenetic cements. Various stages of cement formation and stratigraphy are shown in Plate 1, Fig. 3 and Plate 3, Fig. 4. Following cement types have been found at different levels and in different microfacies of the Samana Suk Formation from the Surghar Range:

A. Circumgranular cement

The following two types of this cement have been found:

a) Dog tooth cement

The dog tooth cement is circumgranular equant cement which precipitates as later diagenetic cement. Its examples are given in Plate 7, Fig. 2 and 3.

b) Acicular circumgranular cement

The acicular circumgranular cement is rare and found just in the lower part of the Samana Suk Formation. The acicular circumgranular cement found in this formation is shown in Plate 7, Fig. 2. According to Tucker (1988) the acicular cement belongs to marine origin.

B. Intergranular cement

The intergranular cement which is mostly equant in texture, is found at a number of horizons of Samana Suk Formation (Plate 3, Fig. 4). According to Sheikh (1992) it is the next phase of carbonate diagenesis. The Intergranular spary calcite cement with drusy mosaic of meteoric phreatic environment has also been observed in Plate 7, Fig. 1). This cement resembles with the sparry calcite cement, which is actually cavity filling cement with respect to characteristic drusy mosaic.

C. Syntaxial rim cement

The syntaxial rim cement grows over the host grain in optical continuity. It is common in many carbonate rocks. It usually develops on echinoderm shells in optical continuity and recognized by simultaneous extinction. It was been observed at a number of levels in Samana Suk Formation on various crinoid and echinoid shells (Plate 3, Fig. 1 and Plate 4, Fig. 4. According to Lohmann and Mayres (1977), Mayres and Lohmann (1978) and Kaufman, et al. (1988) this cement is mostly considered to be of meteoric origin.

D. Radiaxial acicular cement

The radiaxial acicular cement has been found in a mudstone of Samana Suk Formation (Plate 4, Fig. 3). This cement is mineralogically low magnesium calcite (LMC), which has replaced the originally high magnesium calcite (Tucker, 1988).

E. Drusy calcite cement

It is a cavity filling cement, which might be sparry calcite or dolomite. Its crystals are of small size at margins of cavity and gets larger towards the centre of cavity. It has been found in Plate 5, Fig. 4 (Calcite) and in Plate 7, Fig. 4 (Dolomite).

F. Poikilotopic cement

This cement develops after the development of pervasive dolomitization and intergranular cements. In this type of cement coarse crystals enclose fine grains, which look like speks. It develops in phreatic environment commonly in burial regime. It is shown in Plate 3, Fig. 2.

Dolomitization

The dolomitization of limestones during the course of diagenetic processes is a common feature of the Samana Suk Formation. It is developed at various levels in this formation in Chichali Nala Section as cement and as replacement. Dolomitization has also been observed along stylolites (Plate 2, Fig. 4). At horizons where the dolomite is pervasive all the three types of crystal mosaics, such as xenotopic, hypidiotopic and idiotopic, have been developed (Plate 2, Fig. 1 and Plate 7, Fig. 3).

Dolomitization has been developed at various levels in this formation. Following three types of dolomitization have been observed:

a) Texture preserving dolomitization

The texture preserving non-mimic dolomitization is restricted to the matrix and has been found in the Samana Suk Formation of the studied section. This type of dolomitization attacks the matrix and destroys it (Plate 3, Fig. 3).

b) Pervasive dolomitization

It is formed as a result of extensive process of dolomitization in limestones. In this type the dolomitization is not texture selective and attacks fabric of the rock and the whole of the rock gets dolomitized (Plate 7, Fig. 3).

c) Microdolomitization

In this type of diagenetic process crystals of dolomite develop in a very small size and sometimes larger magnification is required to observe these crystals Plate 5, Fig. 2).

Dedolomitization

It is a reverse process in which during diagenesis the dolomite is calcitized. It is a common phenomenon in carbonate rocks. The dedolomitization has been observed in Samana Suk Formation from the under investigation section (Plate 5, Fig. 2).

Diagenetic events

The sequence of diagenetic events in the Samana Suk Formation is determined as follows:

a) Micritic envelopes

It is the first diagenetic phase, which takes place in the marine diagenesis of limestones. Micritic envelopes develop around fauna which have original aragonitic mineralogical composition. These envelopes serve to define and preserve the outline and morphology of the carbonate grains over which these envelops develop.

b) Dissolution of aragonite

In the second phase the aragonite dissolves in the faunal grains having aragonitic mineralogy and is precipitated as sparite. Sometimes the internal structure of the skeletal grains is totally destroyed and no relict structure observed at all. However, the outline and morphology of these grains is preserved.

c) Matrix selective dolomite

It is the next phase of the diagenetic history of carbonate rocks, only dolomitization of matrix takes place and component grains (allochems) are not dolomitized.

d) Fracturing and physical compaction

Physical compaction of the carbonate sediments is the next diagenetic event. Under this diagenetic process the inter-grain space reduces, which results in the overall reduction of porosity of the rock. In case of poorly cemented sediments the component grains may break due to physical compaction process. This and other factors produce fractures and ultimately enhance the porosity and permeability of the rock.

e) Chemical compaction

In this phase as a result of increasing overburden first the grain to grain contacts take place and then simple grain contacts developed into sutured grain contacts. Later on dissolution of grains starts at these contacts. Sometimes the embayment of one grain into the other is, also, observed.

f) Stylolitization

It is the last diagenetic event. The stylolites are actually manifestation of a diagenetic phenomenon, named as pressure-dissolution or chemical compaction.

CONCLUSIONS

As a result of these investigations the following conclusions have been drawn:

1) The Samana Suk Formation belongs to Jurassic carbonate rocks in Pakistan with its wide distribution and was deposited on the northern shelf of Tethys as carbonate platform depositional product. It represents carbonate rocks with some assemblage of siliciclastics (shale/marl) and it is believed that the deposition took place under the inner, middle and in the outer shelf environments.

2) Shallowing upward successions are the characteristic of this formation. Every succession starts from argillaceous contents (shale/marl).

3) Hard ground surfaces have been developed at various levels in this formation. These hard ground surfaces represent regressive events.

4) Indications of physical and chemical compaction have been observed at various levels of this Formation. Sutured grain contacts and phenomenon of stylolitization is present at different horizons in this formation. The signs of tight packing have been noticed as well.

5) Replacement dolomite is the precipitation product of solutions, produced as a result of chemical compaction. Mg liberated from the pelloids due to compaction at an early stage and caused precipitation of dolomite as styloaccumulate along stylolites.

6) At some later stage Fe incorporated into calcite and dolomite and resulted in the formation of ferroan dolomite and ferroancalcite.

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MICROFACIES ANALYSIS AND THE ENVIRONMENTAL PATTERN OF THE CHICHALI FORMATION, KALA CHITTA RANGE, PAKISTAN.

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Abstract: *The Chichali Formation, a sequence of glauconitic sandstone and shale has been investigated from nine sedimentological sections from the Kala Chitta Range. Broadly speaking, four mirofacies have been identified The entire study has highlighted the depositional style of the Chichali Formation indicating that it has a variable environment of deposition from shallow marine to anoxic environment. The shallow marine environments are manifested by the presence of robust belemnites and ammonites in the glauconite bearing sequence, whereas, the presence of black shales are reminiscent of anoxic environment. The presence of age diagnostic fauna combined with palynological data establishes the Upper Jurassic to Lower Cretaceous age.*

INTRODUCTION

The name "Chichali Formation" has been introduced by Danilchik and Shah (1967) for the "Belemnite beds" of Gee (1945) from the Chichali Pass in the Trans Indus Salt Range and formalized by the Stratigraphic Committee of Pakistan (Fatmi,1973). Its thickness varies from 60 m to 70 m from type area. The name has been extended in the Kala Chitta Range (Fig. 1) for the Spiti Shales of Cotter (1933). It is widely distributed in northern Pakistan including the Hazara and Samana ranges. However, very little work has been carried out on this formation in the Kala Chitta Range. The present research is the first contribution based upon nine sections of the Chichali Formation which are systematically measured for detailed sedimentological work, though Fatmi (1972) made a substantial contribution about age assignment and reported *Belemnopsis gerardi, Hibolithes, Gryphaea* sp., *Rhynchonellid* and *Terebratulid, Perisphinctes, Neocosmoceras, Aulacosphinctes, Himalayites.* According to the faunal contents Fatmi (1972), concluded Late Oxfordian to Neocomian age which was further substantiated by the palynological studies due to the presence of *Laevitriletes* sp., *Impardecispora cf parvelentus, Indotriletes korbaensis, Alisporites grandis, Podocarpites* sp., *Minutosaccus crenulatus* and *Alisporites bilateralis.*

LITHOSTRATIGRAPHY

The lithological distribution and thickness variations of the Chichali Formation in the Kala Chitta Range are given in Fig.2 The formation is generally divisible into two parts in the Kala Chitta Range; a glauconitic quartzose sandstone in the lower part and sandy glauconitic shale in the upper part. However, in the western Kala Chitta Range at Bata Section (Fig.2), The dark pyritic silty shale is present in the upper part which is not present in the central and eastern areas (Surg, Jhalar, Neka, sections). Lithologically, the Chichali Formation shows remarkable similarity of facies and thickness in the central and eastern Kala Chitta Range. In the vicinity of Jhalar area (Fig. 2) it comprises a total thickness of 12.5 m with 0.5 to I meter thick glauconitic, rubbly calcareous sandstone at the base having abundant Belemnites. Most common are *Belemnopsis gerardi, Hibolithes* sp., poorly preserved Perisphinctid ammonites, brachiopods, bivalves and gastropods, overlain by 5.5 m thick dark green glauconitic soft sandstone with phosphatic and calcareous nodules, succeeded by over 6 m thick greenish, sandy glauconitic shale having *Hibolithes* sp., *Gryphea* sp.

In Surg section, the formation is 6 m thick comprising yellowish orange glauconitic sandstone in the lower part overlain by olive splintery and sandy shale. At Chapra, the Chichali Formation is only 9 m thick and is composed of greyish orange glauconitic sandstone spotted with light brown specks, overlain by pale brown laminated sandy shale and grey to yellow siltstone.

At Togowala, east of Sakhi Zindapir the formation is only 8 m thick having glauconitic fossiliferous sandstone at the base followed by unfossiliferous sandy shale. Further east, it is 10 m thick at Neka Village, 6 m at Langer and 13.5 m south of Jabbi without any remarkable change in lithology. South of Jessian, in the Kawagarh Hills the Chichali Formation is 10m thick.

A conspicuous change in lithology and thickness has been observed in the western Kala Chitta Range. It is 30 m thick at Bata near the Indus River and 60 m thick at Sujhanda. At these localities, dark pyretic silty shales are present at the top.

The formation has disconformable contact with the underlying Samana Suk Formation, whereas, its upper contact with the Lumshiwal Formation is gradational and conformable.

PETROGRAPHIC ANALYSIS

The sandstone horizons in the Chichali Formation are restricted to lower part that also has very limited thickness. The thin section study of the selected sandstone samples from various sections of the Chichali Formation in the Kala Chitta Range shows that the sandstones comprise silt and sand sized quartz and glauconite grains and pellets, with varying amount of clay and iron oxide matrix. Carbonate and quartz cements are common. Quartz is the main rock forming mineral and varies in most of cases from 20% to 60% of the rock. The next important mineral is glauconite which in some cases is more than quartz and is present both in pellets form as well as in the cement. Some well-cemented samples show floating grains, indicating that the cementation is prior to the compaction. In some cases, flint is present as cement indicating siliceous diagenesis. Replacement of quartz by glauconite and corroded grain margins are commonly observed. Some poorly cemented samples have shown tightly compacted grains which form both planer and sutured contacts. In samples close to the lower contact of the formation with Samana Suk Formation, disconformity surfaces having ferruginous clay matrix and reworked clasts are observed. Fine clay film around quartz and glauconite grains is also present. Near the top of the Chichali Formation close to its contact with the Lumshiwal Formation the ratio of calcareous material increases and the formation grades into the Lumshiwal Formation by a gradual change from glauconitic siltstone/sandstone to glauconitic sandy limestones and increasing fragmented bioclasts.

MICROFACIES

The sandstone of the Chichali Formation represents no marked facies variations, which is an indication of continuation of similar depositional conditions. The microfacies variations as observed during the petrographic study are classified as under.

Clay and iron oxide cemented glauconite bearing sandstone:

The quartz grains are angular to subangular moderately well sorted. In between quartz and glauconite grains clay is present and constitutes groundmass that is also oxidized imparting re colouration. Muscovite, tourmaline is the tiny accessory minerals. Due to the presence of clay the grain contacts are planer and long, but sutured grain contacts are also not uncommon. The glauconite is also affected by iron oxide. Apart from clay and glauconite, the carbonaceous matter is also acting as cement. Reworked and fragmented clasts are commonly seen. The reworked clasts with oxidized groundmass are commonly observed close to the lower disconformable contact of the Chichali Formation with the Samana Suk Formation.

Calcite and flint cemented glauconitic sandstone

These are fine to medium grained carbonate and flint cemented sandstone. The rock is moderately well sorted and the quartz and glauconite grains mostly float in the cement. However, some grains are in point or planer contact with each other. Diagenetic replacements of silica by calcite are observed. Patches of small flint material in calcite are also seen. The rock is compositionally and texturally submature to mature.

Clay and silica cemented quartzose sandstone

The quartz grains are angular to subangular with subordinate glauconite and flint. Clay film around quartz grain is present. The contacts are planer and long. The accessory minerals include microcline, muscovite, tourmaline and epidote.

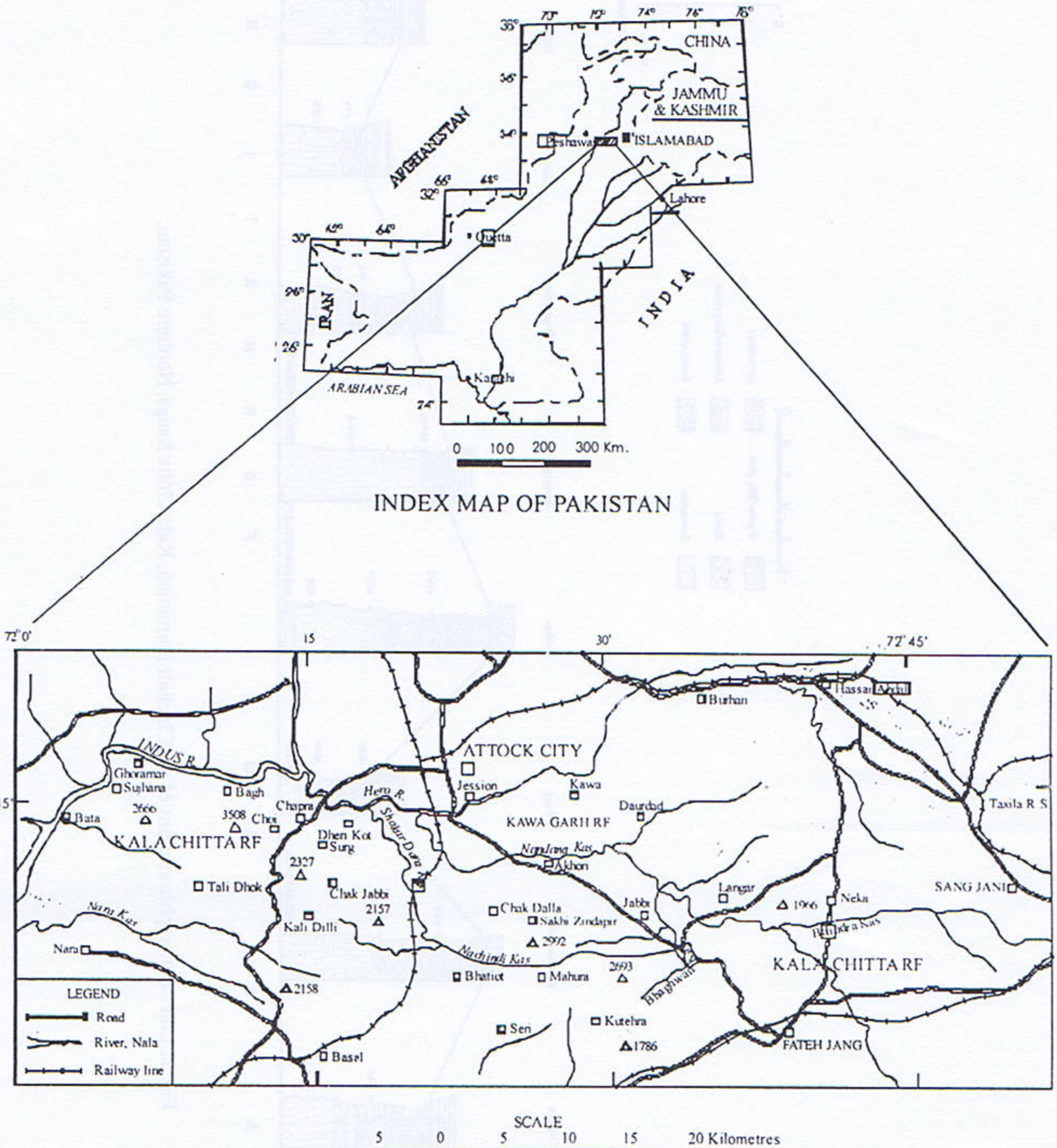


Fig. 1: Location map of the Kala Chitta Range

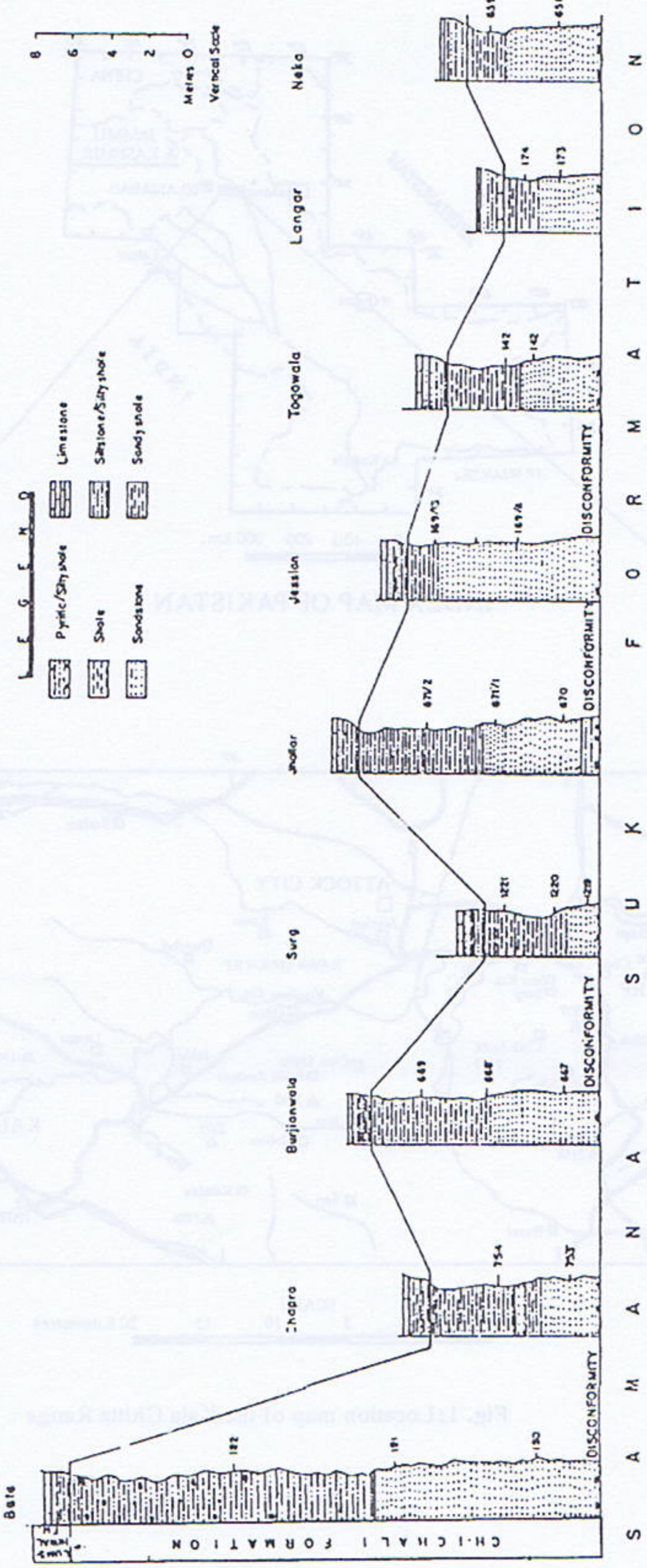


Fig. 2: Lithostratigraphic sections of the Chichali Formation, Kala Chitta Range, Northern Pakistan.

Plate - 1

a

Unidenified VAM propagules. Chichali Formation, Neka section, Kala Chitta Range. Scale bar 30 m

b

Alisporites bilateralis. Chichali Formation, Bata section, Kala Chitta Range. Scale bar 30μ m

c

Impardecispora cf. Parvelentus, Chichali Formation, Chapra section, Kala Chitta Range. Scle bar 30μ m

d

Laevitriletes sp. Chichali Formation, Burjianwala Laman section, Kala Chitta Range. Scale bar 30μ m

e

Glomus sp., Chichali Formation, Surg section, Kala Chitta Range. Scale bar 30μ m

f

Minutosaccus crenulatus. Chichali Formation, Burjianwala Laman section. Kala Chitta Range. Scale bar 30μ m

g

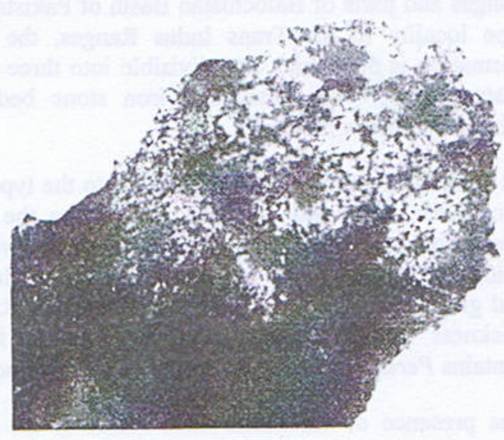
Alisporites grandis, Chichali Formation Bata section. Kala Chitta Range. Scale bar 30μ m

h

Alisporites grandis, Chichali formation, Burjianwala Laman section, Kala Chitta Range. Scale bar 30μ m

i

Indotriletes korbaensis. Chichali Formation, Chapara section, Kala Chitta Range. Scale bar 30μ m



j

Podocarpites sp., Chichali Formation, Chapra section, Kala Chitta Range. Scale bar 30μ m

Clay and glauconite cemented glauconitic sandstone

The rock is mostly fine grained and moderately well sorted. Glauconite is present both as cement and as pallet. Quartz grains are subangular to subrounded. In some cases the clay, glauconite and carbonate cements are present in close association. The grain contacts are planer and long, however, sutured grain contacts are also present.

DIAGENESIS

The glauconite cementation is early diagenetic and mostly the galuconite occurs both as pellet and as irregular interstitial cement. The boundaries between grains are mostly marked by impurities like clay and iron oxide. The presence of flint indicates its formation by the dissolutioning of quartz and free silica, and also the dissolutioning of the skeletal parts of siliceous organisms, most probably the diatoms etc. The formation of flint also appears to be early diagenetic. The presence of micro stylolite and sutured grains having stylotizied contacts are interpreted to be formed during deep burial by pressure solutioning.

Considering the early cementation in some units and closely packed nature with paucity of matrix in others, the original porosity in the sandstone appears to be lesser. However, by fracturing and dissolutioning the porosity increased that in some cases was occluded by carbonate and/or glauconite cements.

DISCUSSION

The Upper Jurassic-Lower Cretaceous transgression is widespread in the IndoPakistan Subcontinent and well developed marine sequences are represented by the classic sections in the Spiti and Kachchh areas of India and in Hazara, Kohat, western Salt Range, Trans Indus Ranges and parts of Balochistan Basin of Pakistan. At the type locality in the Trans Indus Ranges, the Chichali Formation is 60m thick and divisible into three members (Fatmi, 1972) with prominent iron stone beds in the middle and upper members.

At Kohat, the lithology is very similar to the type locality except for attenuated thickness. In Hazara the Chichali Formation represents two distinct lithofacies variations, being black shale facies exposed north of the Haro River and glauconitic sandstone facies south ofHaro River. The thickness variation is from 61m to 41m. The formation contains *Perisphinctes* sp. and small size *Belemnopsis* sp.

The presence of the black shale facies is the result of anoxic environment being devoid of the faunal contents. However, there is a variation in the depositional style, for example, The frequency of Belemnites which are more common in thin beds of a few centimeters thickness at the base and at the upper part of the lower unit are unlikely to reflect the original population fluctuations. The great majority of belemnites lies parallel to the beddin but quite a number are seen to lie obliquely or even vertically, presumably as a result of bioturbation. The paucity and abundance of these belemnites at certain levels within the lower sandy beds have all the resemblance to the winnowed deposits produced as lags after intermittent storms had stirred the sea bed (Hallam and Maynard, 1987).

The presence of much higher sand contents of the Upper Jurassic and Lower Cretaceous rocks (Chichali Formation) as compared with the Middle Jurassic (predominantly carbonate ofthe Samana Suk Formation) suggests a significant increase in run off that is more likely to be associated with a tectonic rise of Indian Shield than with a climatic change from a more arid to more humid. The clastic influxes and regressive tendencies are considered to be directly dependant on the tectonic events that have been taking place in the Pakistan-Indian region during Late Jurassic-Early Cretaceous times.

The depositional environments are envisaged as sand deposit with low energy and low sedimentation rate. The clay filled the pore spaces between the quartz and glauconite grains in the presence of acidic waters of probable meteoric origin. The presence of flint shows siliceous diagenesis and the replacement requires diagenetic pore waters, super saturated with respect to crystalline silica and under saturated with respect to calcite where pH is low (Selley, 1985) in a zone where meteoric ground waters mix with sea waters. The calcite spar is present as irregular veins which cut the rock and are late diagenetic.

The clay fills the pore spaces between the grains and this cementation occurred at shallow depths in the presence of acidic waters. This is followed by the quartz cementation resulting into cement and over growth of quartz on glauconite grains. The solubility of silica increases with pH, so the silica cement occurs where the acid fluids have moved through the pores (Selley, 1985).

The occurrence of the glauconite mineral has been variously interpreted. It is generally agreed that glauconite forms in mildly alkaline environment and according to Greensmith (1981) the principal deposits in the modern ocean occur in the warm waters (15-20 °C) with low sedimentation rate. The good sorting and subrounded grain indicate mild current action below water-sediment interface. The early diagenetic glauconite cement and pellets were formed during deposition and very shallow burial. The clay filled the pore spaces within the grains.

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Geol. Bull. Punjab Univ. Vol. 42, 2007, pp 61-68

PLANKTONIC FORAMINIFERA FROM UPPER CRETACEOUS KAWAGARH FORMATION, JABRI AREA, LORA-MAQSOOD ROAD, HAZARA, NORTHERN PAKISTAN

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Abstract: *Kawagarh Formation in Jabri area is well exposed with a thickness of 123 meters. Forty samples were collected from bottom to top at equal intervals for micropaleontological studies from two different localities along the Lora-Maqsood road. Thin sections were prepared from hard samples of limestone while loose material was also collected from the marly part of the Formation for the study of complete specimens. Five species of genus* ***Globotruncana*** *were observed along with* ***Planoglobulina sp., Heterohelix reussi, Textularia baudouiniana.*** *The presence of* ***Globotruncana arca*** *in the upper part of the Formation indicate that the deposition of the upper part of the Kawagarh Formation may extended into lower Mastrichtian in this area (range of* ***G. arca*** *is from* ***Globotruncana cancavata*** *zone to* ***Globotruncana gansseri*** *zone). On the basis of the observed fauna the age of the Kawagarh Formation ranges from Middle Coniacian to Lower Mastrichtian in this area.*

INTRODUCTION

Jabri (long. 73 10 15", lat. 33, 55) is an easily accessible locality from capital Islamabad via Ghora Gali, located on Lora-Maqsood road where Kawagarh Formation is widely exposed along the road on the north bank of Haro river and when moving further towards north along the road, it is also repeated after Paleogene succession due to fault (Fig. 1).

Day (in unpublished report of Attock Oil Company) introduced the name "Kawagarh Marls" for the Upper Cretaceous rocks exposed in the Kawagarh Hills, north of Kala Chitta Ranges. Stratigraphic Committee of Pakistan had approved the name "Kawagarh Formation" and extended to its facies changes in Kohat ("Sublithographic Limestone" of Davies, 1930 and "Darsamand Limestone" of Fatmi & Khan, 1966) and Hazara area ("Chinali Limestone" of Mir Latif, 1970).

The Kawagarh Formation at Jabri is 123 meters (430 feet) thick, trending NE-SW, comprises mainly of very fine grained limestone with marly beds at the base and in the lower-middle part of the formation. The limestone contains dolomitic patches and is light brown, chocolate , whitish grey, light grey to pinkish grey on fresh surface. It weathers to off-white, light rusty grey, pale yellowish and light grey. The limestone breaks with concoidal to subconcoidal fracture.

The thickness of the beds varies from 6 cm to 70 cm. Basal portion of Kawagarh Formation comprises mainly of earthy grey to light grey, off-whitish grey, creamish off-white to very light grey marl with nodular layers of limestone. It weathers to rusty grey, off-whitish grey to dirty grey. The marl is highly fossiliferous, splintery, thinly laminated and at places, contains intercalations of nodular (2 cm x 6 cm) limestone bands (4 cm to 7 cm thick). The limestone contains glauconite which imparts a green tinge to this part. The formation contains (1 to 2.5 cm thick) calcite veins which are frequent in the unit.

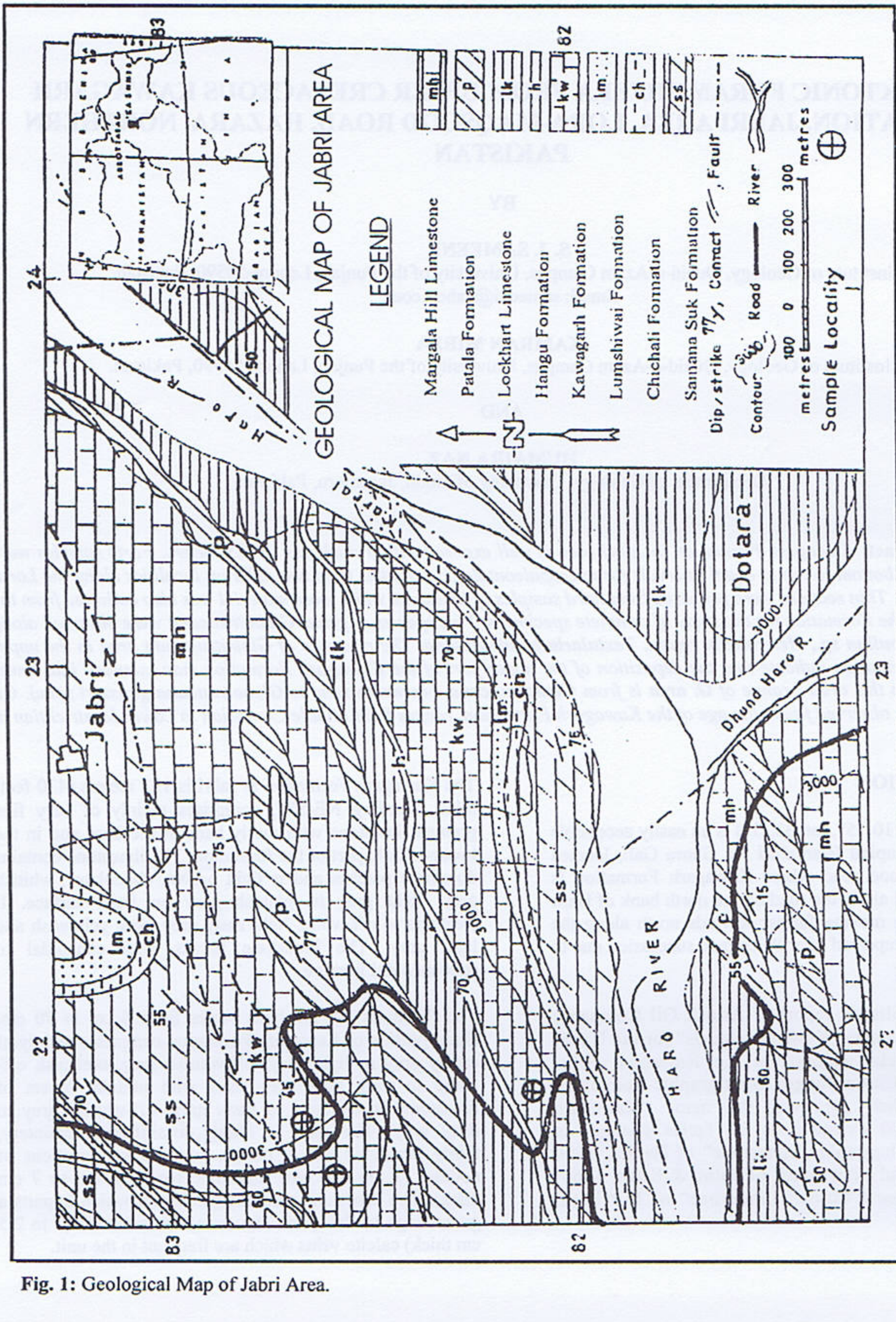

Fig. 1: Geological Map of Jabri Area.

Plate 1

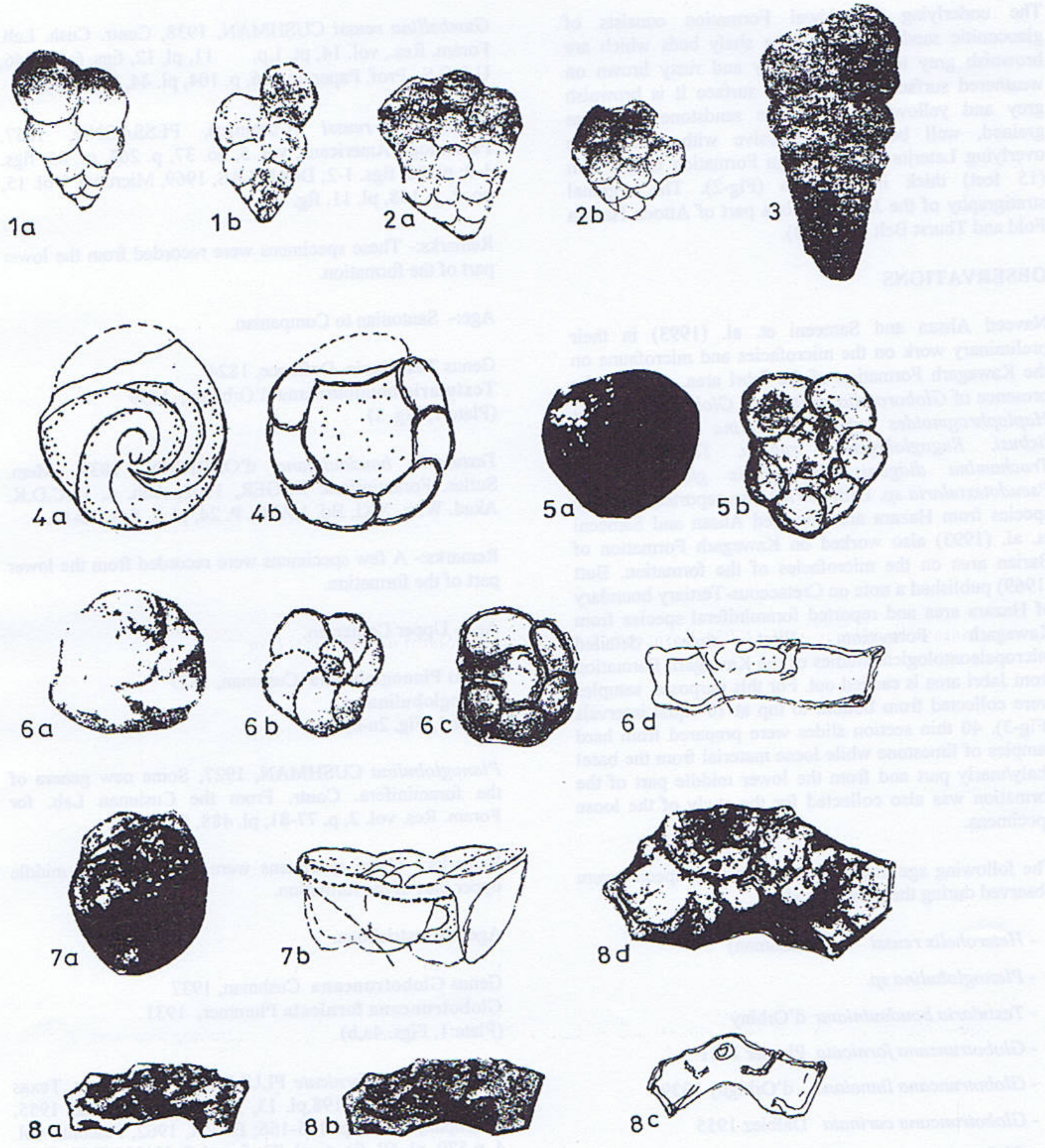

PLATE-1:

Fig-1a,b: *Heterohelix reussi* (Cushman); **Fig-2a,b:** *Planoglobulina sp.;*
Fig- 3: *Textularia boudouiniana* d'Orbigny ; **Fig-4a,b:***Globotruncana fornicate* Plumer 1931
Fig-5a,b: *Globotruncana ventricosa* White 1928; **Fig-6a-d:***Globotruncana linneiana* d'Orbigny 1939
Fig-7a,b:*Globotruncana carinata* Dalbeiz 1955; **Fig-8a-c:***Globotruncana arca* (Cushman) 1926
Fig-8d: *Globotruncana arca* (Cushman) 1926 Text Fig.

The underlying Lumshiwal Formation consists of glauconitic sandstone and some shaly beds which are brownish grey to yellowish grey and rusty brown on weathered surface and on fresh surface it is brownish grey and yellowish green. The sandstone is coarse grained, well bedded to massive with joints. The overlying Laterite of the Hungu Formation is just 3 m (15 feet) thick in the area (Fig-2). The regional stratigraphy of the Jabri area is a part of Attock Hazara Fold and Thurst Belt (AHFTB).

OBSERVATIONS

Naveed Ahsan and Sameeni et. al. (1993) in their preliminary work on the microfacies and microfauna on the Kawagarh Formation of the Jabri area, reported the presence of *Globorotalia multisepta, Globotruncana sp., Haplophrogmoides eggeri, Lenticulina sp., Planularia liebusi, Rugoglobigerina rugosa, Textularia sp., Trochamina diagonis, Heterohelix globulosa* and *Pseudotextularia sp.* Latif (1970) also reported the same species from Hazara area. Naveed Ahsan and Sameeni et. al. (1993) also worked on Kawagarh Formation of Barian area on the microfacies of the formation. Butt (1969) published a note on Cretaceous-Tertiary boundary of Hazara area and reported foraminiferal species from Kawagarh Formation. First time detailed micropaleontological studies of the Kawagarh Formation from Jabri area is carried out. For this purposes samples were collected from bottom to top at 10 equal intervals (Fig-3). 40 thin section slides were prepared from hard samples of limestone while loose material from the basal shaly/marly part and from the lower middle part of the formation was also collected for the study of the loose specimens.

The following age diagnostic foraminiferal species were observed during the present study.

- *Heterohelix reussi* (Cushman)
- *Planoglobulina sp.*
- *Textularia boudouiniana* d'Orbiny
- *Globotruncana fornicata* Plumer 1931
- *Globotruncana linneiana* d'Orbigny 1939
- *Globotruncana carinata* Dalbiez 1955
- *Globotruncana arca* (Cushman) 1926

SYSTEMATIC PALEONTOLOGY:-

Genus **Heterohelix** Ehrenberg, 1853
Heterohelix reussi (Cushman)
(Plate:1 Fig: 1,2)

Gumbellina reussi CUSHMAN, 1938, Contr. Cush. Lab. Foram. Res., vol. 14, pt. 1,p. 11, pl. 12, figs. 6-9; 1946, U.S.G.S., Prof. Paper no.206, p. 104, pl. 44, figs. 18-19.

Heterohelix reussi (Cushman), PESSAGNO, 1067, Paleontogr. Americana, vol. 5, no. 37, p. 263, pl. 85, figs. 1-9; pl. 86, figs. 1-2; DOUGLAS, 1969, Micropal. Vol. 15, no. 2, p. 158, pl. 11, fig. 15.

Remarks:- These specimens were recorded from the lower part of the formation.

Age:- Santonian to Companian.

Genus **Textularia** Defrance, 1824
Textularia boudouiniana d'Orbigny, 1839
(Plate 1, Fig. 3)

Textularia boudouiniana d'ORBIGNY, 1839, Mem. Surles. Foraminifera; EGGER, 1902, Abh. d. 11/C.D.K. Akad. Wiss. XXI, Bd. 1,Alith. P. 24, pl. 2, figs. 10-11.

Remarks:- A few specimens were recorded from the lower part of the formation.

Age:- Upper Coniacian.

Genus **Planoglobulina** Cushman, 1927
Planoglobulina sp.
(Plate 1, Fig. 2a-b)

Planoglobulina CUSHMAN, 1927, Some new genera of the foraminifera. Contr. From the Cushman Lab. for Foram. Res. vol. 2, p. 77-81, pl. 488, figs. 1-10.

Remarks:- These specimens were recorded from middle upper part of the formation.

Age:- Maastrichtian.

Genus **Globotruncana** Cushman, 1937
Globotruncana fornicata Plummer, 1931
(Plate:1, Figs. 4a,b)

Globotruncana fornicate PLUMMER, 1931, Univ. Texas bull., no. 3101, p. 198,pl. 13, figs. 4-6; DALBIEZ, 1955, Micropal., vol. 1, p. 165-166; BARR, 1962, Paleont., vol. 4, p.570, pl. 69, fig. 6; pl. 72, figs. 1-2; VAN HINT, 1965, Proc. Kon. Nederl. Akad. Wetensch., Ser. B., vil. 68, no. 1, p. 21, pl. 1, fig. 1,; pl. 2, fig. 1-2; TAKAYANAGI, 1965, Tohoko Univ. Sci. Rep., 2nd Ser. (Geol.), vol. 36, no. 2, p. 214, pl. 24, fig. 4.

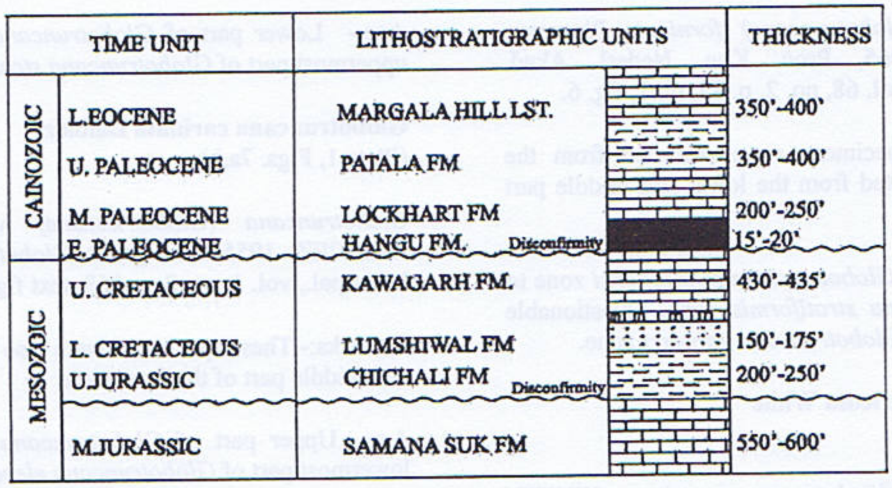

Fig. 2: Stratigraphic Sequence of the Jabri Area.

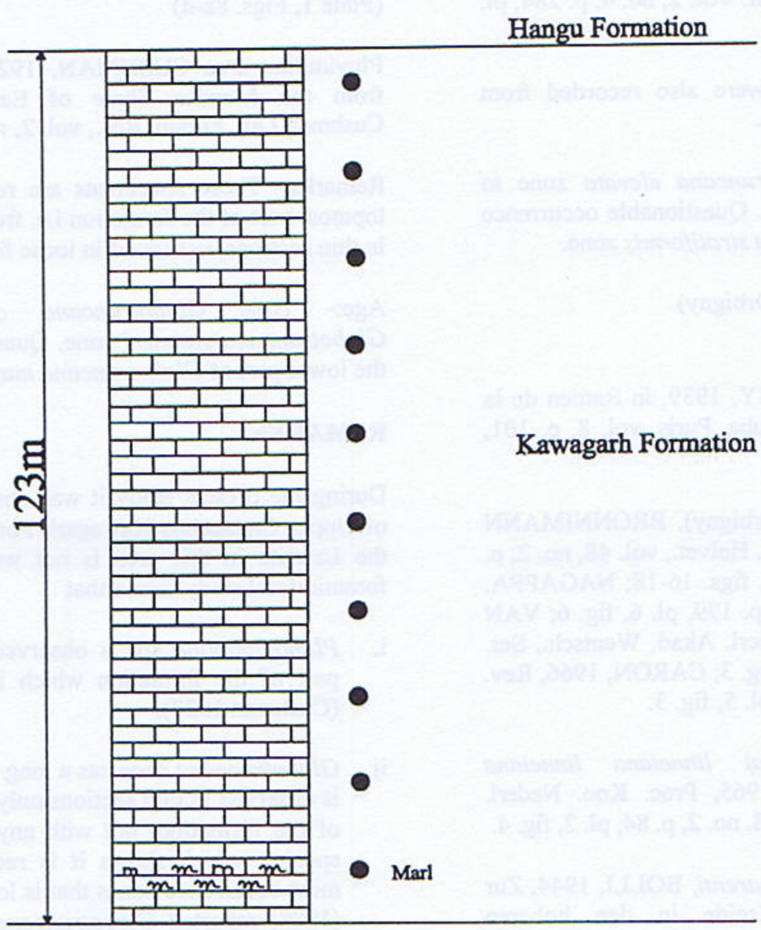

Fig: 3: Stratigraphic column of Kawagarh Formation at Jabri area.

● Level of sample collection.

Golobotruncana (Globotruncana) fornicate Plummer, VAN WHITE, 1965, Proc. Kon. Nederl. Akad. Wetensch., Ser. B., vol. 68, no. 2, p. 83, pl. 1, fig. 6.

Remarks:- These specimens were recorded from the loose material collected from the lower and middle part of the formation.

Age:- Upper part of *Globotruncana schneegansi* zone to top of *Globotruncana stratiformis* zone. Questionable occurrence in lower *Globotruncana ganserri* zone.

Globotruncana ventricosa White
(Plate 1, Figs. 5a,b)

Globotruncana canaliculata var. *ventricosa* WHITE, 1928, Some Index Foraminifera of Tampico embayment area of Mexico. Jour. of Paleont. Vol. 2, no. 4, p. 284, pl. 38, figs. 5 a-c.

Remarks:- These specimens were also recorded from lower and part of the formation.

Age:- Lower part of *Globotruncana elevata* zone to *Globotruncana calcarata* zone. Questionable occurrence in lower part of *Globotruncana stratiformis* zone.

Globotruncana linneiana (d'Orbigny)
(Plate 1, Figs. 6a-d)

Rosalina linneiana d'ORBIGNY, 1939, in Ramen de la Sagra, Hist. Phsy. Pol. Nat. Cuba, Paris, vol. 8, p. 101, pl. 5, figs. 10-12.

Globotruncana linneiana (d'Orbigny), BRONNIMANN & BROWN, 1955, Eclog. Geol. Helvet., vol. 48, no. 2, p. 540, pl. 20, figs. 13-17; pl. 21, figs. 16-18; NAGAPPA, 1959, Micropal., vol. 5, no. 2, p. 179, pl. 6, fig. 6; VAN HINTE, 1965, Proc. Kon. Nederl. Akad. Wentsch., Ser. B., vol. 68, no. 1, p. 23, pl. 1, fig. 3; CARON, 1966, Rev. Micropal., vol. 9, no. 2, p. 83, pl. 5, fig. 3.

Globotrucana (Globotruncana) linneiana linneiana (d'Orbigny), VAN WHITE, 1965, Proc. Kon. Nederl. Akad. Wetensch., Ser. B., vol. 68, no. 2, p. 84, pl. 2, fig. 4.

Globotruncana lapparenti lapparenti, BOLLI, 1944, Zur Stratigraphie der Oberen Kreide in den hoheren helvetischen Decken. Ecologicae Gelologicae Helvetiac, vol. 37, no. 2, p. 230, text fig. 1, nos. 15,16, pl. 9, fig. 1.

Remarks:- These frequently existing specimens were recorded from lower and middle part of the formation both in the form of loose specimens as well as in thin sections.

Age:- Lower part of *Globotruncana concavata* zone to uppermost part of G*lobotruncana stratiformis* zone.

Globotruncana carinata Dalbiez
(Plate 1, Figs. 7a,b)

Globotruncana (Globotruncana) ventricosa carinata DALBIEZ, 1955, The genus *Globotruncana* in Tunisia. Micropal., vol. 1, no. 2, p. 168, text fig. 8.

Remarks:- These specimens were also recorded from lower and middle part of the formation.

Age:- Upper part of *Globotruncana concavata* zone to lowermost part of *Globotruncana elevata* zone.

Globotruncana arca (Cushman)
(Plate 1, Figs. 8a-d)

Pluvinulina arca CUSHMAN, 1926, Some Foraminifera from the Mendez Shale of Eastern Mexico. Contr. Cushman Lab. Foram. Res., vol. 2, no. 3, pl. 3, figs. 1a-c.

Remarks:- These specimens are recorded only from the topmost part of the formation i.e. from hard limestone only in thin sections, not found in loose form.

Age:- Base *Globotruncana calcarata* zone top *Globotruncana gansseri* zone. Questionable occurrence in the lower part of *Globotruncana mayaroensis* zone.

REMARKS:-

During the present study it was observed that the erosion of Upper Cretaceous Kawagarh Formation is minimum as the Laterite in this area is not well developed. Further foraminiferal study shows that

i. *Planoglobolina* sp. is observed in the middle upper part of the formation which is of Mastrichtian age (Cushman 1927).

ii. *Globotruncana arca* has a long stratigraphic range and is observed in thin sections only in the upper most part of the formation, not with any other *Globotruncana* species, which shows it is recorded from its upper most occurrence zones that is lower Mastrichtian. Butt (1988) reported *Globotruncana* arca from Kawagarh Formation of the Kala Chitta area but don't mentioned from which level of the formation it was recorded.

On the basis of the above mentioned observation the age of the Kawagarh Formation may extended into Lower Mastrichtian (Fig-4) in this area.

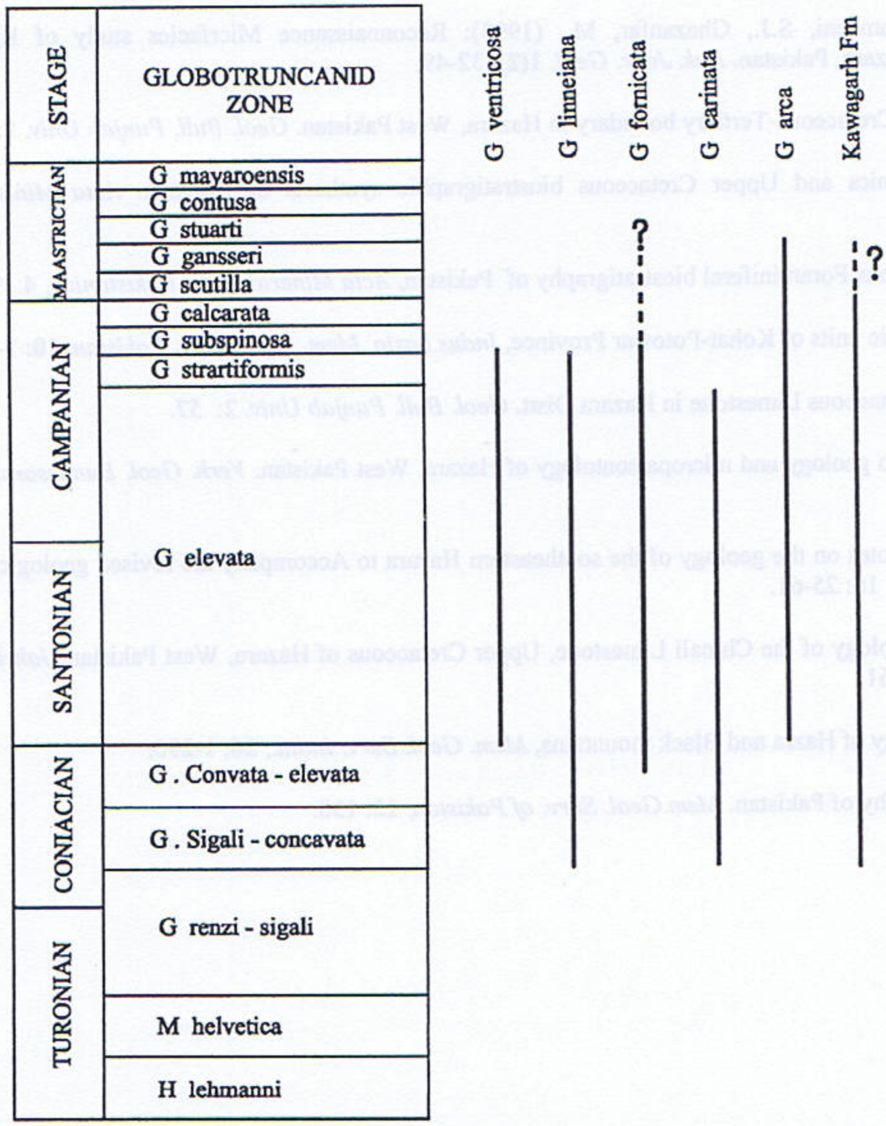

Fig. 4: Late Cretaceous Planktonic formaminiferal zonation after Hinte (1976), Gorsel (1978) and based on numerous workers stratigraphic range of recorded species.
G=Gobotruncana

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GENESIS OF NICKELIFEROUS ORE MINERALS OF THE DARGAI COMPLEX, PAKISTAN

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Abstract: *Disseminated nickeliferous ore minerals in Dargai complex in order of abundance are heazlewoodite, awaruite and pentlandite. These minerals are associated with serpentinized dunite, peridotite and chromitite. The chemical composition of these ore minerals are comparable with Table Mountain and blow Me Down ophiolites. The composition of co-existing heazlewoodite-awruite corresponds to Ni-Fe-S experimental assemblages. It is postulated here that submarine metamorphism was mainly responsible for the formation of serpentinites and associated ore minerals. These processes (i.e. alteration process, tectonic emplacement of Dargai complex and Neogene metamerphism) have played significant role in remobilization of elements such as Ni, Cu, Fe and S.*

INTRODUCTION

Disseminated Fe-Cu-Ni-S mineral assemblages occur sporadically in the Dargai complex. Occurrences of similar Fe-Cu-Ni sulfides associated with ophiolitic rocks have been reported by Ashley (1975), Eckstrand (1975). Panayiotou (1979), Bertolina et al. (1980), Ahmed and Bevan (1981), Ahmed and Hall (1982), Papunen and Idman (1982), Lorand (1987) and Arif (1994).

Nickeliferous opaque minerals were reported by Ahmed and Hall (1982) from this complex. According to them, the opaque minerals are mainly associated with altered chromites. However, the present study show that the opaque minerals are mainly associated with serpentinized dunites and wherlites and not encountered in the gabbroic unit. Usually they are found along fractures within at the margins of relic olivine grains. They occur as bleb, inclusion and in disseminated forms.

The common mineral assemblages are in order of abundance heazlewoodite, awaruite and pentlandite, with the heazlewoodite being the most common. The proportion of nickeliferous opaque mineral does not exceed 2 wt% of the rock composition. The origin of such assemblages in mantle derived rocks is not well understood. In this paper an attempt is made to understand the origin of such assemblages in the light of present data and from the known patrologic relationships.

Petrographic Features

The grain size of nickeliferous opaque minerals varies from 4 *11m* to 20 *11m.* Ni-sulfide minerals are also observed as inclusions in some Cr-spinels. The average size of the inclusions varies from 5 to 25 *11m.* Heazlewoodite is the most common mineral in these inclusions and is accompanied by awaruite. Disseminated nickeliferous opaque minerals also occur as intergranular grains in harzburgites. The composition of such minerals varies from Ni-rich to Fer-rich (Lorand, 1987). The nickel-rich assemblages are heazlewoodite (Ni)Sz), pentlandite (Fe, Ni)9SS and awaruite (Ni)Fe). The Fe-rich ore mineral magnetite was also encountered in a few serpentinized rocks from ,the Dargai complex.

Genesis of Disseminated Nicleliferous Ores

Several theories have been proposed for the formation of nickeliferous ore deposits associated with ultramafic and ophiolitic rocks (Panayiotou, 1979; Economou and Naldrett, 1984 and Lorand, 1987). Field studies of the Dargai complex revealed no massive sulfide horizon, which suggests that the parent magma was not accompanied by any sulfide liquid. Sulfide inclusions in chromite were probably formed by hydrothermal fluids like those responsible for serpentinization of the host rock. Therefore, the sulfide inclusions are of non-magmatic origin.

The polished section study showed that nickeliferous opaque minerals in the Dargai complex are Heazlewoodite, Awaruite and Pentlandite. The presence of Pentalandite over considerable range of f02 or f52, indicate its wide stability range. Wager et al. (1957) proposed that low sulphur contents of basic magma was the reason that sulfides are not formed in the magmatic stages; instead nickel goes in to ferromagnesian minerals, such as olivine. The ferromagnesian minerals break down and release nickel during their alteration processes.

In the Dargai complex, nickeliferous opaque minerals are found on tractures. This is an indication that remobilization and concentration of sulfide occurred during the serpentinization of the host rocks. Addition of sulphur from the pyrite rich country rocks, during tectonic deformation and metamorphism of the Dargai complex cannot be ruled out.

During submarine metamorphism and possibly during early stages of serpentinization, hydrothermal convection of seawater introduces seawater sulfate into the oceanic crust. Along the path of convective circulation through hot crustal rocks, reactions of sulfate with Fe2+ bearing silicates reduces S04-2 to H2S. A two stage process is proposed here, most S04-2 is converted to H2S while mafic rock is altered to greenstone:

(i)

$$\underbrace{3Mg_2SiO_4 + 6Fe_2SiO_4}_{\text{in olivine}} + \underbrace{2(NaCaAl_3SisO_{16})}_{\text{plagioclase }(An_{50})} + \underbrace{4Mg^{2+}_{(aq)} + Si_4^{-2}{}_{(aq)} + 2HCO_{3(aq)}}_{\text{in seawater}} + 10H_2O \longrightarrow$$

$$\underbrace{2Mg_5Al_2Si_3O_{10}(OH)_8}_{\text{chlorite}} + \underbrace{2NaAlSi_3O_8}_{\text{albite}} + \underbrace{2CaCO_3}_{\text{calcite}} + \underbrace{4Fe_3O_4}_{\text{magnetite}} + \underbrace{7SiO_2}_{\text{quartz}} + 4H^+_{(aq)} + H_2S_{(aq)}$$

Nickel content in the mantle rocks is thirty times more than in the crustal rocks. Nickel has dual property, i.e. lithophile and chalcophile. At high temperature Ni substitutes for Mg in olivine and pyroxene (lithophile) whereas at low temperature it is both lithophile and chalcophile. By hydrothermal convection current the dissolved H2S may be carried by seawater metamorphic fluid trom mafic to ultramafic portions of the sequence containing Ni bearing olivine. The Ni grabs the sulphur trom solution while the rest of the dunite/harzburgite is being altered to serpentinite.

(ii)

$$8H_2S + \underbrace{10Fe_2SiO_4 + 4Ni2SiO4 + 14Mg2SiO4}_{\text{in olivine}} + \underbrace{4Mg2Si2O6}_{\text{OPX}} + 10H2O \longrightarrow$$

$$\underbrace{Ni_5Fe_4S_8}_{\text{Pentlandite}} + \underbrace{Ni_3Fe}_{\text{awaruite}} + \underbrace{5Fe_3O_4}_{\text{magnetite}} + \underbrace{6Mg_3Si_2O_5(OH)_4}_{\text{serpentine}} + \underbrace{6Mg_3Si_4O_{10}(OH)_2}_{\text{talc}}$$

The mineral assemblages formed in the Dargai complex correspond to above mentioned equations.

Analytical Procedure

Chemical analyses of the minerals were performed on an automated MAC 500 electron microprobe. All microprobe analysis were carried out at an acceleration potential of 15Kv and with a beam current of 0.01 to 0.02μA. A beam size of 3 μm was used to avoid overlaps during the analysis of ore minerals. For all samples the counting period for each elements was 30 seconds or 30,000 counts. The standards used were obtained from U.S Geological Survey.

Mineral Chemistry and Phase Relationships

The Ni/Fe ratio of pentlandite from the Dargai complex ranges from 90 to 1.12 which is comparable with the compositional range published by Misra and Fleet (1973). The concentration of Co is low, it ranges from .61 to 1.54 wt%. Pentlandite occurs along fractures in serpentinized dunites (Table 1).

In heazlewoodite (Ni_3S_2), the amount of Fe varies from zero to .58 wt%, Ni varies from 70.79 to 75.74 wt% and S varies from 23.60 to 28.03. These analyses compare well with the disseminated heazlewoodite analysis trom Table Mountain ophiolite, Newfoundland (Table 2). Heazlewoodite is generally associated with awaruite in harzburgite. The analyses of co-existing heazlewoodite and awaruite are given in Table 3. The heazlewoodite composition from the Dargai complex compares well in composition with the nickeliferous sulfide assemblages from Blow-Me Down Mountain ophiolite massif, Newfoundland (Lorand, 1987).

The compositional variation of awaruite is 75.63 to 83.14 wt% Ni, 15.16 to 23.75 wt% Fe,.11 to .94 wt% Co and .15 to 1.93 wt% Cu (Table 4). This amount extends considerably beyond the previously reported concentration of 0.27 wt% Cu in samples from the Dargai complex (Ahmed and Hall, 1982). The individual analyses (Table 4) show a slight correlation. The amount of Cu increases with increase in Ni content. By comparing the composition of awaruite alone and co-existing awaruite-heazlewoodite, the awaruite associated with heazlewoodite has higher Fe and lower Ni content. Similar to heazlewoodite, awaruite occurs in intergranular spaces and also along fractures in serpentinized dunite and harzburgites.

Secondary magnetite forms overgrowth rims around chromite grains during the process of serpentinization. This reaction creates reducing environment in serpentinizing solutions. Representative analyses of secondary magnetite produced in serpentinized rocks of the Dargai complex are given in Table 5. These analyses compare well with the analysis from Deer, Howie and Zussman (1978). The Dargai complex contains pentlandite, heazlewoodite, awaruite and secondary magnetite.

The stability of heazlewoodite, pentlandite and awaruite are below *806°C,* 610°C and 503°C, respectively (Kullerud and Yund, 1962, Kullerud, 1964). It has been also observed that with increasing confining pressure the breakdown temperature of pentlandite decreases and it is stable below *400°C* at 30Kb. Thus the Dargai complex nickeliferous ore minerals have formed in environments similar to low temperature experimental assemblages (Craig et al., 1968).

Discussion and Conclusion

In order to evaluate the origin of disseminated sulfides and awaruite in the Dargai Ultramafic complex, three processes played significant roles in remobilizing Ni, Cu, Fe, Co and S. These processes are arranged in probable chronological order as:

1. Alteration processes

2. Tectonic emplacement ofthe complex

3. Neogene regional metamorphism

Reflected and transmitted light studies of the rocks from the Dargai complex show that tresh dunite and harzburgite samples are devoid of nickeliferous opaque minerals. In the Dargai complex mostly nickeliferous ore minerals are associated with serpentinized rocks. During serpentinization, olivine and pyroxene break down and released elements such as Ni, Fe and Co. These elements later were available to form sulfide ores with sulphur derived probably from convecting seawater S04-2 anion.

Post-magmatic phases in the Dargai complex include serpentine, talc, chlorite, secondary magnetite and carbonates. These phases represent relatively oxidizing and reducing environments as described earlier. In these environments not only silicates are formed but also nickeliferous ore minerals. Under highly reducing conditions in serpentinization, heazlewoodite breaks down into awaruite. The study of disseminated sulfides from the Dargai complex show that pentlandite is less commonly associated with awaruite. It probably indicates that pentlandite has been transformed into awaruite. The distribution of awaruite and heazlewoodite along fractures is an indication that nickeliferous ores were forced into fractures during dynamic metamorphism.

Field relations show that the Dargai complex was emplaced in supracrustal rocks. Some of the supracrustal rocks from the southern contact contain are rich in pyrite. The northern contact is with micaceous schists and phyllite. Ultramafic rocks when emplaced in pyrite rich country rocks, will provide heat to break down pyrite in the country rocks producing pyrrhotite and sulphur (Kullerud and Yoder 1959). It was also observed in this study that nickeliferous ore minerals are more near the southern contact, but are lacking in the mafic rocks which occur near the northern contact. This may indicate some of the sulphur was absorbed from the southern country rocks at the time of tectonic emplacement of the Dargai complex. More sampling of supracrustal rocks are required to find out the source of sulphur. In this regard sulphur isotope study may be useful in delineating the exact source of sulphur in disseminated sulphides.

It is more likely that Neogene regional metamorphism has produced ore minerals alongwith serpentine in the Dargai complex. The mobility of sulphur was probably promoted during this metamorphic event. Presence of disseminated nickeliferous ore minerals in this complex reflect this hypothesis very well.

Acknowledgement: The valuable contribution made by late professor Gunnar Kullerud and Robert Ray Loucks is gratefully acknowledged.

Table-1

Representative microprobe analyses of pentlandite from the Dargai complex.

Analyses	DC.119-1	DCll19-2	DC.119-3	DC.119-4
Wt%				
S	31.14	31.07	30.91	31.00
Fe	32.69	31.17	34.86	30.50
Ni	34.06	33.82	33.43	36.20
Co	1.36	1.28	0.61	1.54
Cu	0.27	0.67	0.96	0.74
Total	99.52	98.01	100.77	99.98
At%				
S	44.95	45.36	44.15	44.57
Fe	27.17	26.21	28.67	25.28
Ni	26.85	26.96	26.06	28.42
Co	1.06	0.98	0.45	1.19
Cu	0.18	0.46	0.64	0.50
Ni/Fe	0.98	1.02	0.90	1.12

Table-2

Average compositions of representative microprobe analyses of heazlewoodite from the Dargai complex.

Sample No.	Q-2A	DC-25	DC-83	DC-II 7	DC-183	*T-163
Wt%						
S	25.97	25.14	24.40	23.90	24.98	26.56
Range	(23.92-28.03)	(24.98-25.30)	(24.11-24.79)	(23.60-24.21)	(24.13-24.98)	
Fe	0.00	0.04	0.38	0.35	0.05	2.11
Range	(.00-.00)	(.03-.06)	(.23-.58)	(.32-.32)	(.05-.10)	(1.7-2.81)
Ni	72.47	73.62	73.62	73.39	73.85	70.31
Range	(70.79-74.15)	(73.23-73.62)	(73.12-73.93)	(73.02-73.76)	(73.85-75.74)	(69.7-70.6)
Co	0.08	0.04	0.08	0.01	-	0.]4
Range	(.06-.11)	(.04)	(.06-.35)	(.00-.02)	-	(0.]-0.2)
Cu	0.00	0.02	0.00	0.00	-	0.05
Range	(.00)	(.02-.03)	(.00-.97)	(.00)	-	
Total	98.52	98.86	98.48	97.65	98.88	99.]7
At%						
S	39.60	38.46	37.63	37.68	38.24	40.08
Fe	-		0.29	0.30	-	1.84
Ni	60.34	61.53	62.01	62.46	61.75	57.96
Co	0.04	-	0.04	-	-	0.]2
Cu						

* Analysis is from Table Mountain ophiolite, Newfound]and (after Lorand, 1978).

Table-3
Representative microprobe analyses of co-existing heazlewoodite and awaruite from the Dargai complex.

Sample No.	DC-4 Hz	DC-4 Aw	DC-83 Hz	DC-83 Aw	*8-63 Hz	* 8-63 Aw
Wt%						
S	25.04	0.0]	24.79	0.02	26.23	0.05
Fe	0.08	20.61	0.23	21.24	0.52	25.]9
Ni	73.09	78.5]	73.82	77.57	72.95	74.63
Co	0.04	0.11	0.1]	0.35		
Cu	-	1.54	-	0.97	-	0.35
Total	98.25	100.78	98.94	100.15	99.76	100.30
At%						
S	38.52	-	38.00	-	39.54	
Fe	0.04	21.36	0.19	22.12	0.43	26.10
Ni	61.42	77.19	61.79	76.71	60.03	73.55
Co	-	0.05	0.04	0.29		
Cu	-	1.38	-	0.87	-	0.35

* Analyses are from Blow Me-Down Mountain ophiolite, Newfoundland (after Lorand, 1978).
Hz = Heazlewoodite
Aw = Awaruite

Table-4
Representative microprobe analyses of awaruite trom the Dargai complex.

Sample No.	DC-4	DC-34	DC-83	LR-2	DC-29
Wt%					
S	-	0.14	0.03		
Range	(.00-.01)	(.00-.11)	(.02-.04)	(.00-02)	
Fe	18.51	20.37	20.05	17.60	23.00
Range	(16.43-20.61)	(18.48-20.98)	(15.16-23.75)	(17.36-18.36)	(15.64-23.00)
Ni	80.83	78.96	78.40	79.99	75.42
Range	(83.14-78.51)	(78.15-81.18)	(75.63-82.00)	(79.75-81.61)	(75.42-82.94)
Co	0.29	0.46	0.58	0.33	0.88
Range	(.11-.46)	(.41-.57)	(.35-.94)	(.25-.34)	(.48-.88)
Cu	1.26	0.28	1.01	1.82	0.55
Range	(.98-1.54)	(.00-1.23)	(.15-1.93)	(1.59-1.82)	(.55-1.78)
Total	100.88	100.21	100.07	99.74	99.84
At%					
S	-	0.23			
Fe	19.16	21.20	20.94	18.84	24.02
Ni	79.50	77.92	77.66	79.18	74.69
Co	0.23	0.40	0.52	0.29	0.81
Cu	1.09	0.23	0.87	1.66	0.46

Table-5
Representative microprobe analyses of secondary magnetite from the Dargai complex.

Sample No.	Q-1	DC-4	DC-25	DC-29	DC-112	*Z-4
Na_2O	0.00	0.00	0.37	0.00	0.02	
MgO	1.91	0.45	1.27	1.64	0.57	tr
Al_2O_3	0.01	0.02	0.00	0.06	0.08	0.21
SiO_2	0.14	0.12	0.29	1.41	0.17	0.27
K_2O	0.00	0.00	0.00	0.00	0.00	
CaO	0.02	0.00	0.02	0.00	0.04	tr
TiO_2						
Cr_2O_3	0.30	2.16	0.02	1.82	3.75	
MnO	0.13	0.05	0.19	0.01	0.08	
Fe_2O_3	67.85	67.07	71.02	65.68	65.02	68.85
FeO	27.08	30.55	27.71	30.96	30.23	30.78
NiO	0.56	0.00	0.00	0.00	0.00	
Total	98.08	100.46	101.27	101.66	99.96	100.11

* Analysis is after Deer, Howie and Zussman (1978).

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ULTRAMAFIC CUMULATES AND GNEISSES SUBJACENT TO THE MAIN MANTLE THRUST AT DOMEL, UPPER KAGHAN VALLEY, PAKISTAN.

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Abstract: *The sequence of Indian plate rocks subjacent to the Main Mantle Thrust (MMT) described herein is exposed in Domel, Sohch and Lidi village areas of the upper Kaghan Valley. In this part of the "High Himalayan Crystallines", ultramafic cumulate rocks occur (i) as dunite and pyroxenites near Lidi village; and (ii) as clinopyroxenites at Domel, lying to the immediate southeast of MMT. These are succeeded down-section by the medium to high grade Barrovian type para-metamorphites. The kyanite-grade para-gneisses at Domel give way towards SE to the garnet-biotite gneisses, with interbeds of marble and amphibolites. This NW direction of progressive increase in grade of Barrovian type metamorphism adds up another linear direction of grade increase to the previously described general NE increase of metamorphic grade in the Kaghan Valley transect by Rehman et al. (2007). Felsic orthogneisses occur at Sohch and at places bear more mafic enclaves and very coarse porphyroblasts of feldspar. They carry higher SiO_2, Na_2O and K_2O than the less felsic paragneisses including the "Naran Gneisses" that occur along the main valley of Kunhar river. In this part of Kaghan Valley, the NE-SW road-side section exposes amphibolite facies paragneisses with gross-banded amphibolites, pure to impure marble interbeds and calc-silicate gneisses.*

INTRODUCTION

Ultramafic plutonic rock bodies denote geological features and processes extending to deeper Earth as they originate in the mantle. They are frequent along geotectonic boundaries linked to sub- crustal processes. One such boundary in northern Pakistan, is the Main Mantle Thrust (MMT), which demarcates a suture zone and has attracted a great deal of attention in the past because of its important role in the geotectonic evolution of this region. At many locations along the MMT, ultramafic rock bodies are known and have been described (e. g., Ahmed, 1977; Ahmed and Ahmad, 1974; Ahmed and Chaudhry, 1976, Jan et al., 1993; Klootwijk et al., 1985; Yamamoto and Nakamura, 1996). However, they exhibit variations in detail and their tectonic evolution is still poorly understood. The present work is related to such occurrences in the upper Kaghan Valley.

Previous literature pointed to the occurrence of ultramafic rocks sporadically in the region alongside the Kunhar river, in proximity of places like Sohch town (GPS: 34° 56′ N; 73° 42′ E) and Lidi village (GPS: 34° 58′ N; 73° 40′ E). At Sohch, no ultramafic body was located during the present study. The reconnaissance mapping of upper Kaghan Valley (Chaudhry and Ghazanfar, 1987, 1990) shows the Main Mantle Thrust (MMT) passing near to this area. Certain ultramafic bodies, especially clinopyroxenites, occur close to the MMT map-trace that defines a suture zone developed between the continental Indian plate and the Kohistan Island Arc complex. This report also documents the mineralogical and chemical characteristics of clinopyroxenites present at Domel, comparing them with typical mantle or crustal pyroxenites, and discusses their processes of formation.

The Kaghan Valley is an important region for understanding the metamorphism and tectonism of the Himalayas due to its exposures of Himalayan metamorphic belt with rocks spanning the low grade to ultrahigh-pressure (UHP) metamorphism. Thus significant contributions to the geology of Kaghan Valley region have been made in the past inter alia by Ahmed and Chaudhry (1976), Ghazanfar and Chaudhry (1986), Chaudhry and Ghazanfar (1987), Greco et al. (1989), Treloar et al. (1989), Greco and Spencer (1993), Tonarini et al. (1993), Spencer et al. (1995), Burg et al. (1996), O'Brien et al. (2001) and Rehman et al. (2007). These researches have pointed out many aspects that require more attention. The present work focuses on petrography, and whole-rock and mineral

Table 1
Location and description of rock samples selected for this study

Sample #	Rock name & description	GPS
D1	Olivine-bearing clinopyroxenite of Domel.	N 34°59.323'; E 73° 43.689'.
D2	Pegmatoidal pyroxenite (very coarse crystals)	Do.
D3	Coarse clinopyroxenite.(Finer than sample D2)	Do.
D4	Green ultramafic rock (Finer than D2, D3).	Do.
D5	Clinopyroxenite	Do.
D6	Clinopyroxenite,	Do.
D7	Kyanite- garnet gneiss.	Do.
D8	Gneiss.	Do.
D9	Gneiss.	Do.
D10	Garnetiferous gneiss.	N 34°58.055'; E 73°43.372'.
D11	Marble bed in gneiss.	Do.
D12	Amphibolite interbedded with gneiss.	Do.
D13	Serpeninite; sample from stone dump at Sohch	N 34°56.535';E 73° 42.513'.
D14	Granite gneiss banded with less felsic gneiss.	N 34°56.123';E 73° 40.157'.
D15	Garnet-biotite, less felsic, gneiss	Do.
D16	Garnet amphibolite	N 34° 56.188'; E 73°40.124'.
D17	Garnet amphibolite hosted by banded gneiss.	N 34° 57.307';E 73° 40.154'.
D18	Calc-silicate gneiss.	N 34° 56.410';E 73° 40.176'.
D19	Mylonitic granitic gneiss.	N 34° 56.510';E 73° 40.134'.
D20	Biotite gneiss.	N 34° 56.624';E 73° 40.175'.
D21	Dunite, partly serpentinized.	N 34°56.634';E 73° 40.155'.
D22	Clinopyroxenite	Do.
D23	Calc-silicate paragneiss ("Naran gneiss")	N 34°55.814' ; E73° 39.890'.
D24	Biotite-calcite paragneiss ("Naran gneiss").	N 34° 55.864'; E73° 40.078'.
D25	Granitic orthogneiss	N 34° 56.484'; E73° 42.614'.
D26	Calcareous dyke in gneiss.	Do.
D27	Mylonitic garnetiferous felsic gneiss	N 34° 56.494'; E73°42.341'.
D28	Granite gneiss (rich in felspar porphyroblasts)	N 34°56.500'; E73° 42.638'.
D29	Biotite-richer enclave in granitic gneiss	Do.
D30	Calc-silicate gneiss.	N 34° 54.960';E73° 47.489'.
D31	Garnetiferous amphibolite	Do.
D32	Para-amphibolite	Do.
D33	Impure marble	N 34°54.804';E73°48.532'.
D34	Impure marble	Do.
D35	Impure marble (fuchsite-bearing).	Do.
D36	Banded calc-silicate marble	Do.
D37	Banded marble	Do.

chemistry, and tectonic evolution of a small, but geotectonically significant segment of this region.

This study reports the ultramafic rocks of Domel and Lidi villages. It also documents the mineralogical and chemical characteristics of clinopyroxenites present at Domel, comparing them with typical mantle or crustal pyroxenites, and discusses their processes of formation.

The metamorphic rock sequence present in the Sohch-

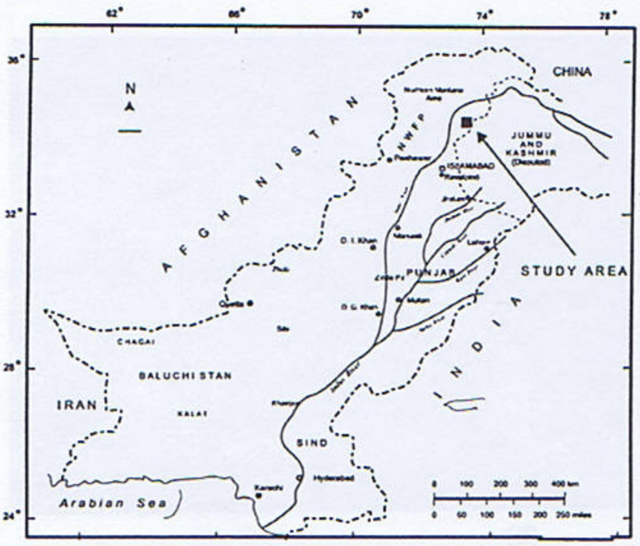

Fig. 1a

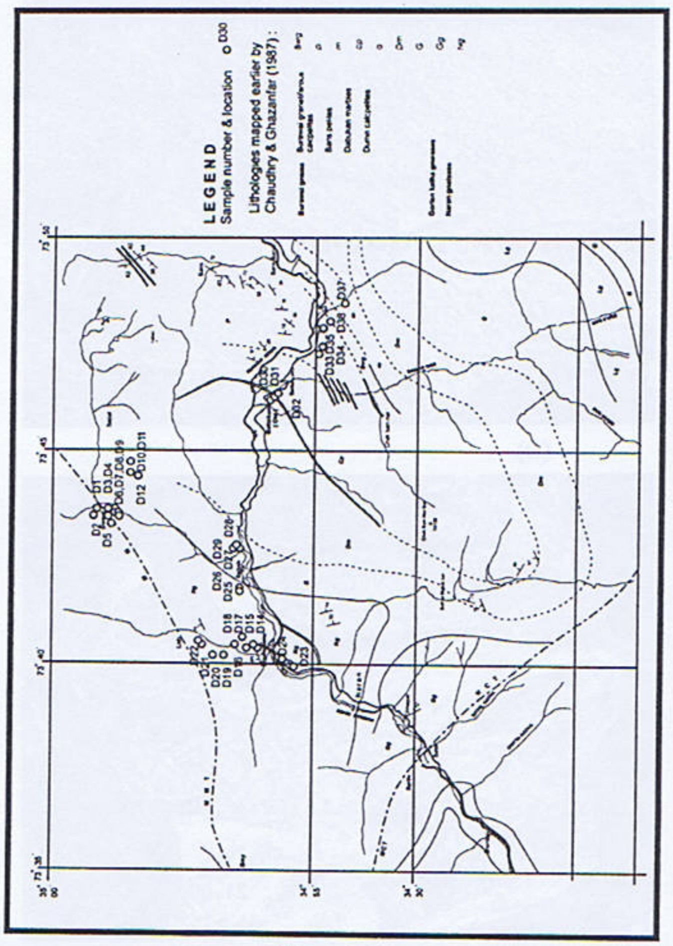

Fig. 1 b

Domel section has been considered to belong to the Indian plate, and form part of the larger units called "Kaghan nappe" (Kazmi and Jan, 1997) and the "Higher Himalayan Crystalline Nappe" (Greco and Spencer 1993). The stratigraphy and age of rocks of this region is not well constrained; and the distribution of Lower Proterozoic rocks is uncertain. Metamorphism in this region probably ended by late Eocene (DiPietro and Pogue, 2004).

In the present study, sections are examined along two tributary gorges of the Upper Kaghan Valley, namely the Domel- Sohch part of the "Sapat katha" gorge and its parallel Dhamdama- Lidi part of the gorge called "Kinari da katha". The gneisses of this section exhibit higher grade metamorphic rocks than previously envisaged, such as the gneisses of kyanite grade and mylonitic rocks.

In a recent work on the main Kunhar river valley (Kaghan Valley) transect (Rehman et al. 2007) have shown that pelitic and psammitic gneisses outcrop north of Naran. This study has also covered a part of this section to characterize the gross-banded amphibolites and interbeds of marble that occur within the less-felsic paragneisses.

GEOLOGY OF THE SOHCH REGION

The lithological variants of the Sohch area were named by Qadir (1979), who reported the occurrence of garnet mica schist, graphitic schist, marble, amphibolites, granite gneiss, pegmatites, aplites, dunite, serpentinite, pyroxenite and talc-carbonate rocks. Ahmad (1981) reported the Sohch serpentinite to contain Ni concentration of 0.28 to 0.32 %, which is mainly contained in the heazlewoodite and pentlandite.

Lithologies exposed in this region are observed from the rock types developed along three major sections: (i) the Domel-Sohch section, (ii) the Dhamdhma –Lidi section along the gorge formed by "Kinari da Katha" valley; and (iii) the Sohch-Burawai section of the main Kaghan Valley (Fig. 1).

Domel - Sohch section:

The traverse from Sohch to Domel displays gneissic rocks of medium to high metamorphic grade interbedded with amphibolites and fewer marble beds (Fig. 2). Kyanite-garnet gneiss (Fig. 2D; Table 2, sample D-7) represents the gneiss of highest regional metamorphic grade found in this study at Domel. Ductile deformation is manifested at many places in the area.

Typical ophiolite rocks described previously from this locality (e.g., Ahmad, 1981) are not present. Ultramafic rocks have been located at two places. An ultramafic body occurs in the upper reaches of Lidi stream, which joins the right bank of Kunhar river at Dhamdama village. Samples of dunite and clinopyroxenite were collected from this occurrence.

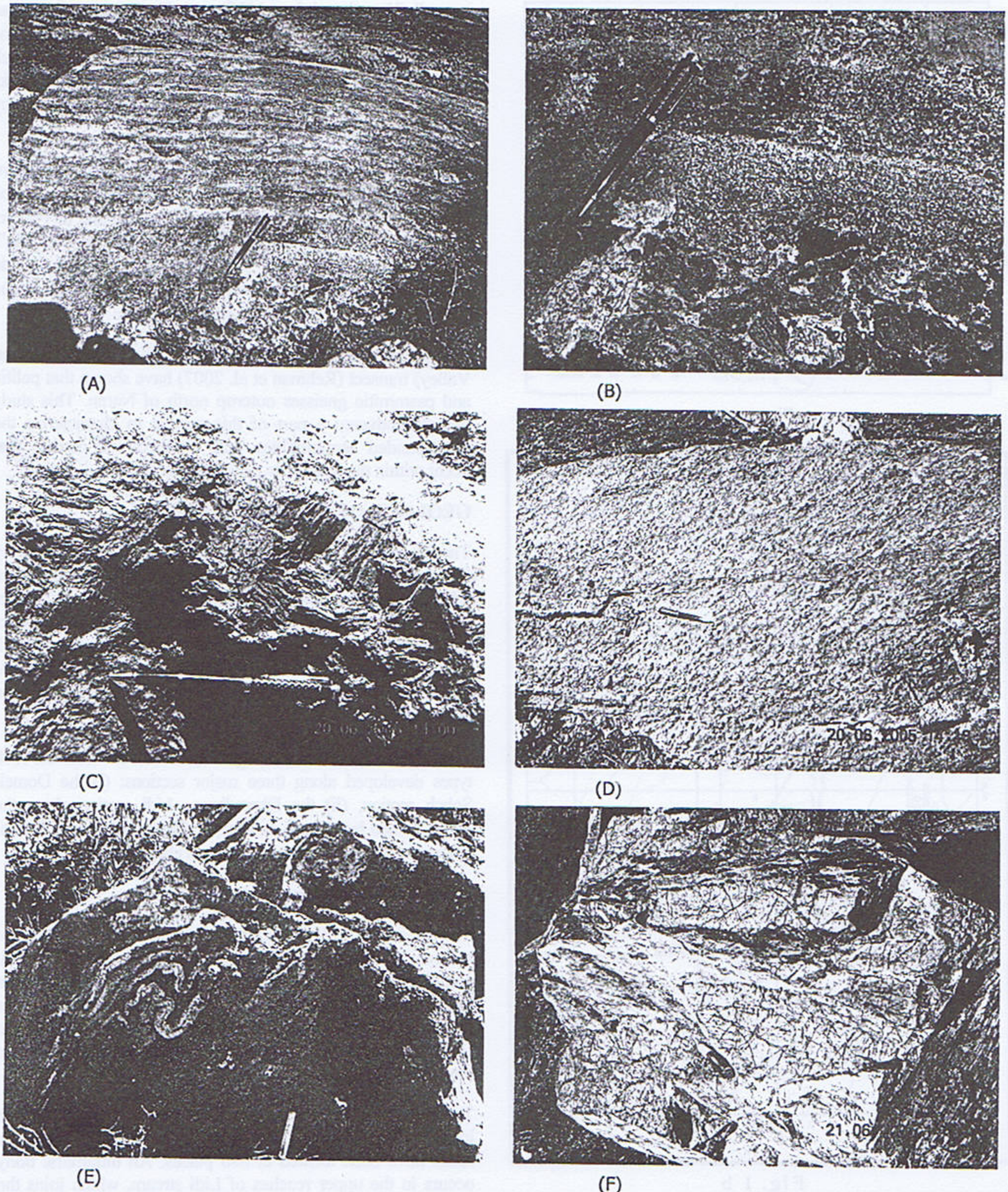

Fig.2: Rock relations of Sohch area, upper Kaghan Valley, Pakistan. (A) Well-developed layered structure of the pyroxene-dominant cumulate rocks at Domel. GPS: N 34° 56.546' ; E 73° 42.480'. (B) A closer view of the exposure shown in (A) highlighting coarse crystals of the clinopyroxenite layer. (C) Pegmatoidal coarse crystals of clinopyroxenite outcrop at Domel. (D) Outcrop of kyanite-garnet gneiss at Domel with more resistant crystals of garnet. (E) Ptygmatic folding in less felsic para- gneiss exposed in the valley towards Lidi at GPS: N 34° 56.624'; E 73° 40.175'. (F) Dunite surface near Lidi shows darker serpentinous veinlets, joints filled with soapstone.

Another ultramafic rock outcrop has been located at Domel. A clinopyroxenite body outcrops much southwards of previously known location of the MMT. The ophiolitic nature of this clinopyroxenite body can't be ascertained as it lacks other features of ophiolites. However, layered structure at some places indicates its cumulus nature (Fig. 2A, B). The pyroxenite is pegamtitic at places as it has developed large crystals (>1 cm length; Fig. 2C). This work is also more elaborate study than earlier work of Chaudhry and Ghazanfar (1987), who reported only two units, i.e., "Naran gneisses" and "granites gneiss / granite" from the area. The present study has recognized widespread garnetiferous gneisses and other rocks as well. The nature of these garnetiferous rocks will be determined after lab work on the samples. Traverse from Sohch to Domel revealed presence of garnet-biotite gneisses, but gross banding is also noticed at places.

Granitic gneiss makes most of the rock exposures in the vicinity of Sohch. At Sohch, the gneissic display typical granites compositions, and at places, remnant macro-phenocrysts of alkali feldspar of protolith granite are present. Relatively mafic enclaves of granite have been stretched by ductile deformation. Thus, the rocks seem to have suffered ductile deformation before the later, more brittle deformation. Mylonitic gneisses occur west of Sohch.

Dhamdhma –Lidi section:

It displays rocks similar to those in the Sohch –Domel section; because of their extensions along strike, dominated by the quartzo-feldspathic gneisses. These gneisses also display gross banding and a few massive sills concordant to layering in gneisses. The lower part of Kinari gorge also displays mylonitic rocks and ductile deformation. Garnet amphibolites may form more massive-looking band that alternate with more micaceous gneiss.

Sohch- Burawai section:

This is a part of the main Kaghan Valley section. Rocks along this section are mapped by Rehman et al. (2007) as "pelitic and psammitic gneisses". At Sohch, a less- felsic gneiss is exposed, previously named as "Naran gneiss" (Chaudhry and Ghazanfar, 1987). Folds in this gneiss are accentuated by gross banding. Northwards (e.g., at GPS 34° 54.960′ N; 73° 47.489′ E), gross-banded para-amphibolite occurs as concordant layers and comprises some more massive bands, and some small-scale bands, and carry frequent quartz veins. Coarsely crystalline marble beds are quarried at places (e.g., at GPS 34° 54.804′ N; 73° 48.532′ E). Marble colours vary from white to slightly greenish or brownish due to silicate impurities like epidote and fuchsite. Near Sohch, less felsic paragneiss named "Naran gneiss" occurs widespread.

METHODS OF STUDY

Laboratory studies reported herein pertain to a selection of 37 rock samples listed in Table 2. These samples were made into polished thin sections and thin sections udied under a polarizing microscope. Whole-rock chemical analyses were carried out using the atomic absorption spectrometry facilities at the Pakistan Atomic Energy Minerals Centre, Lahore. Quantitative analyses of various mineral phases were performed using the electron microprobe analyzer unit set up at the Centre of Excellence in Geology, Peshawar University, Pakistan, using standard operating conditions and procedures of matrix correction.

PETROGRAPHY

Ultramafic rocks are mainly cumulates of clinopyroxene, followed in abundance by those bearing some olivine and/ or a little orthopyroxene.

Clinopyroxenites of Domel area form coarse to very coarse-grained granular rocks composed mainly of augite but carrying lesser hypersthene and olivine. They exhibit minor degree of serpentinization in the form of veinlets of serpentine, and olivine pseudomorphs. The serpentine veinlets often carry central magnetite granules. Some of the samples exhibit clinopyroxenes with exsolution lamellae of orthopyroxenes, which may be regular and straight, or bleb-like oriented inclusions elongated parallel to prismatic cleavage of host crystals. Some grains show such lamellae only in more clearer parts of grains where cleavages are widely spaced or lacking; the exsolution lamellae being absent from darker parts with closely-spaced cleavages (Fig. 4). Exsolved platelets of Fe-Ti oxides are also present in some clinopyroxene grains. Some samples exhibit exsolution textures that vanish towards crystal rims. Pyroxenites also contain minor amounts of olivine, derived-serpentine and spinel grains. Cataclastic effects are also noticed in microscopic views. Minor minerals of pyroxenites are olivine and amphibole. Some amphibole grains show battelemented ends. Sphene granules are observed in some parts. Kinari gorge clinopyroxenites may contain minor olivine (sample D-21) or orthopyroxene (sample D-22).

Dunite of Kinari valley contains coarse olivine, which is partly serpentinized.

Gneisses occur towards SE from Domel, and frequently contain garnet.

Kyanite-garnet gneiss (e.g., sample D-7) contains biotite, quartz, plagioclase, potash feldspar, and accessory sphene.

Garnet-biotite augen gneiss (e.g., sample D10) contains abundant foliation-aligned earlier biotite; and lesser post-kinematic biotite, which is developed in niches such as the pressure shadows of garnet porphyroblasts. Albite-twinned plagioclase and quartz are present in major amounts.

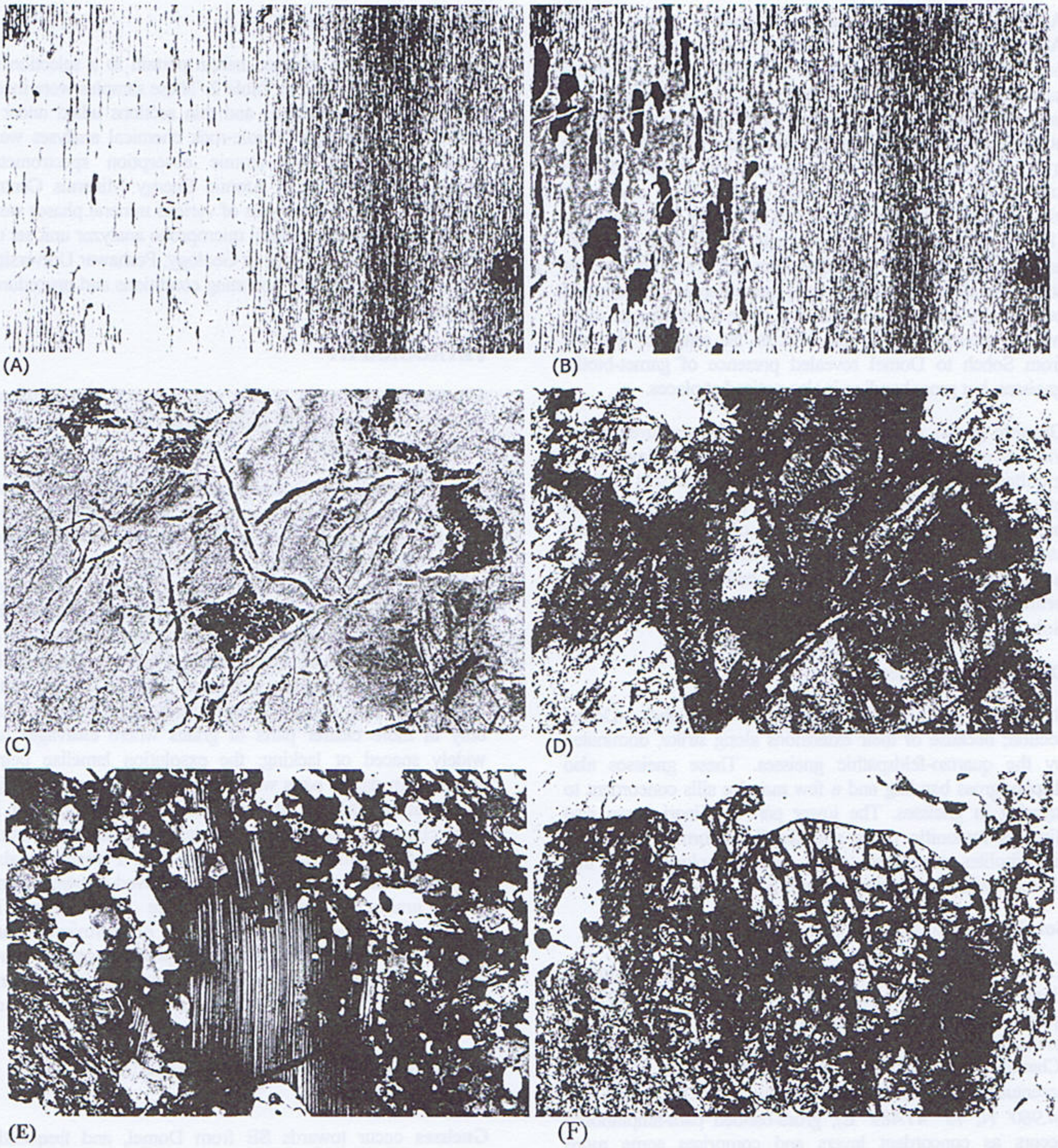

Fig. 3: Photomicrographs from rock samples included in this study. (A) Plane-polarized light (PPL) and (B) crossed polarized light (XPL) views of sample # D-5 of clinopyroxenite of Domel (GPS: N 34° 59.323' ; E 73° 43.689'). The view shows individual augite grains possessing two types of areas. Darker, closely-cleaved part lack orthopyroxene exsolution, whereas clearer, less-closely cleaved part shows bleby exsolution, more obvious in the XPL view. (C) PPL and (D) XPL views of sample # D-1of olivine-clinopyroxenite from Domel, showing olivine pseudomorphed by serpentine with byproduct magnetite central to veinlets. Fibrous chrysotile is more obvious in the XPL view. (E) XPL view of sample D-10 of garnet-biotite paragneiss from GPS 34° 58.055' N ; 73° 43.372' E, that shows plagioclase augen with bent twin lamellae. (F) PPL view of sample D-10 of garnet-biotite paragneiss with garnet porphyroblast replacement partitioned on one side. Size of each view is 2.6 × 1.8 mm.

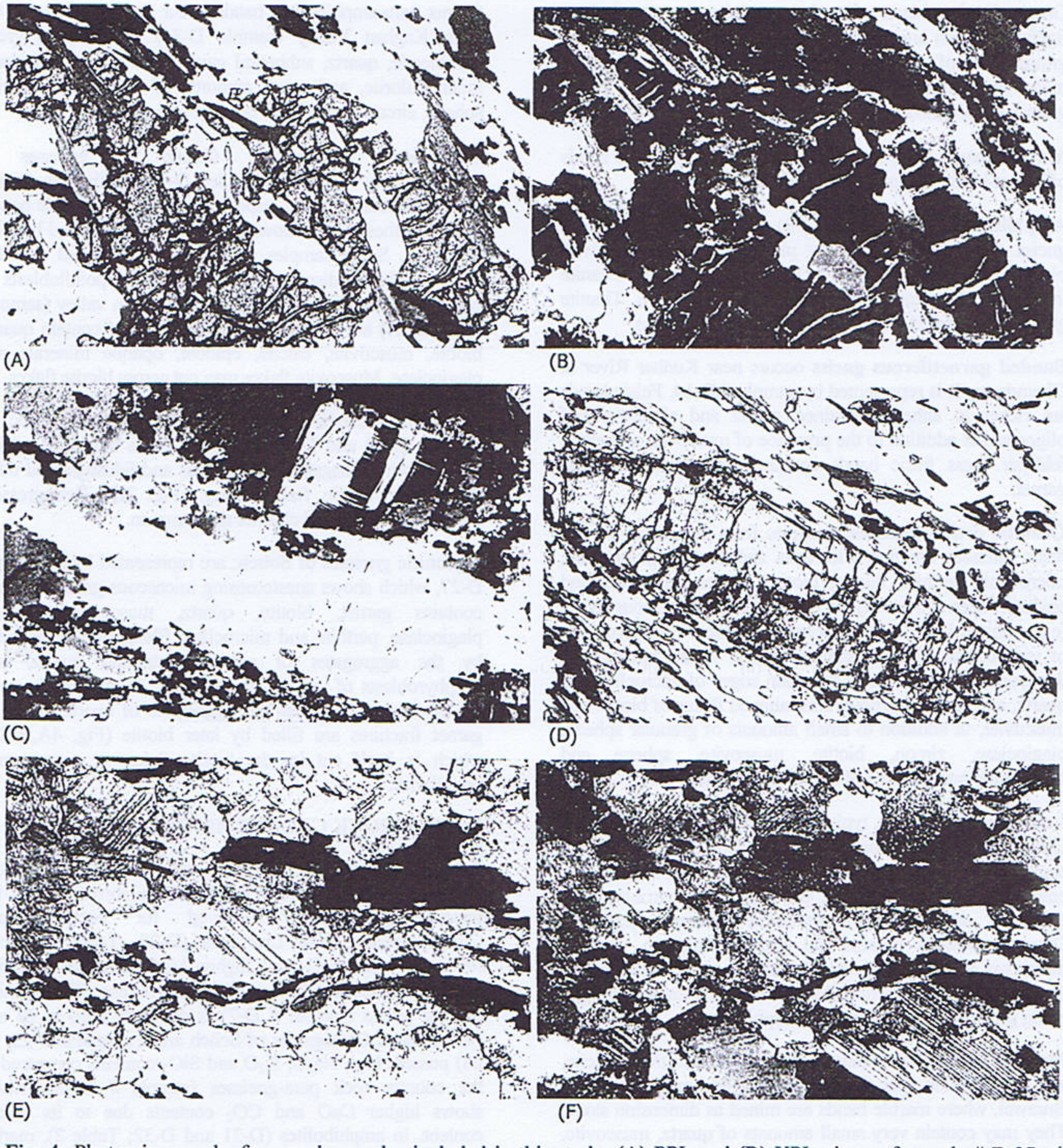

Fig. 4: Photomicrographs from rock samples included in this study. (A) PPL and (B) XPL views of sample # D-27 of ductilely-deformed gneiss from west of Sohch (GPS: N 34° 56.494' ; E 73° 42.341') showing high relief garnet grains with transverse fractures filled by biotite flakes which are truncated by later generation biotite grown outside garnet. (C) XPL view of sample D-27 (GPS: N 34° 56.494'; E 73° 42.341') of mylonitic gneiss showing elongated quartz, and a streak of minute neoblasts of quartz, and one coarse feldspar with wedge-like twin lamellae. (D) PPL view of sample D-33 (GPS: N 34° 54.804' ; E73° 48.532') of calc-silicate gneiss showing elongated coarse epidote. (E) PPL and (F) XPL views of sample # D-35 (GPS: N 34° 54.804'; E 73° 48.532') of calc-silicate marble showing coarse calcite and foliation-parallel biotite.

Garnet porphyroblasts often form nodular augen and show fractures, which are parallel within-grain but not in adjacent grains. Parts of some garnet porphyroblasts are replaced by muscovite and chlorite. Unreplaced parts of these garnet grainse show euhedrism.

Marble bands (e.g., sample D11) may dominate the bands of garnet-biotite augen gneiss at certain locations.

Amphibolites (e.g., sample D12) occurs interbedded with gneiss. They contain strongly pleochroic hornblende with bluish green colour. Quartz inclusions are present. Titanite inclusions often carry an opaque mineral as core. Titanite grains are fractured into small saccharoidal subgrains.

Banded garnetiferous gneiss occurs near Kunhar River at Dhamdama. It is represented by sample # D-14. Felsic bands are richer in anhedral strained quartz and albite-twinned oligoclase in addition to the presence of muscovite and alkali feldspar. Less felsic bands contain more hornblende and garnet.

Granitic ortho- gneisses: Samples from Sohch (D-25) are felsic gneisses are non-calcareous and contain plagioclase, microcline, perthite, quartz, biotite, muscovite, garnet and epidote traces. They may be cur across by calcareous dykes (e.g., sample D-26). The gneisses also show porphyroblasts of very coarse feldspar (sample D-28). **Mafic enclaves** in this gneiss are gneissose and contain augen of microcline and quartz, and broken garnet grains, aligned flakes of biotite and muscovite, in addition to small amounts of granular sphene, plagioclase, zircon, biotite, muscovite, sphene and myrmekitic intergrowths of quartz and feldspar.

Less felsic paragneiss, typically forms the "Naran gneiss" of Chaudhry and Ghazanfar (1987). One sample (D-15) contains garnet, biotite, quartz, plagioclase, muscovite, epidote and zircon. Most of the garnet porphyroblasts are elongated and contain biotite-filled transverse fractures. Quartz inclusions parallel the garnet elongation, but are discordant to gneissosity. Biotite forms coarse to fine grains that show wavy extinction. Many biotite flakes are straight, being grown by retrograde metamorphism.

Marble: Calcite-rich bands contain more than 90% calcite, and are common near the paragneisses and amphibolites of Burawai, where marble bands are mined as dimension stone. They may contain very small amounts of quartz, muscovite, epidote, zircon and opaque ore grains.

Garnet amphibolites are represented by sample D-16. Para-amphibolites contain strongly pleochroic green hornblende and almandine-rich garnet, which shows fractures transverse to elongation of grains. Hornblende sometimes shows symplectitic intergrowths with quartz. Some hornblende – rich bands (sample D-17) shows nearly euhedral garnet grains with fewer inclusions.

Garnet para-amphibolites bands occur in metapelites of the main Kaghan Valley (sample D-31) and contain green hornblende, quartz, subhedral garnet with quartz inclusions, green chlorite, and small amounts of plagioclase, calcite, sphene, zircon and rod-like ilmenite and magnetite.

Calc-silicate paragneiss: Calcite in gneisses is approximately 10 % (sample D-18), although higher amounts occur in bands, especially those near marble bands. Biotite in these rocks shows undulose extinction and buckled cleavages. Some samples (D-19) show fine-sized euhedral garnet neoblasts dispersed in the rock, and poikiloblasts of plagioclase. Samples from the main Kaghan valley (samples D-23, D-24) are petrographically similar and contain quartz, biotite, muscovite, calcite, epidote, opaque minerals and plagioclase. Muscovite flakes may cut across biotite flakes.

Mylonitic gneisses of Kinari gorge: are represented by samples D-19 and D-20, are felsic rocks that lack calcite. Quartz forms elongated segregations and feldspars and other typically mylonitic features (e.g., Fig. 2E). Retrogressive biotite, muscovite and chlorite are common.

Mylonitic gneisses of Sohch: are represented by the sample D-27, which shows anastomosing micaceous gneissosity and contains garnet, biotite, quartz, muscovite, twinned plagioclase, perthite and microcline. Elongation is exhibited by the aggregates of anhedral strained quartz, and porphyroblasts of garnet and perthite. Transverse fractures are developed in garnet and aggregates of quartz. Some of garnet fractures are filled by later biotite (Fig. 4A,B,C), which is itself cut by the biotite flakes at garnet grain boundaries.

WHOLE-ROCK GEOCHEMISTRY

Table 2 reports the 12 whole-rock analyses of various metamorphic lithologies. Chemical data correspond to the mineral assemblages observed for each sample. Clinopyroxenite from Lidi area (D-22, Table 2) shows relatively lesser SiO_2 and higher MgO contents reflecting presence of minor amount of orthopyroxene. The kyanite-bearing gneiss (sample # D-7) is distinctly high in Al and Fe^{3+} content. Orthogneiss of Sohch area (sample # D-25, D-28) possess high Na_2O, K_2O and SiO_2 contents compared to the country rock para-gneisses (sample # D-23), which shows higher CaO and CO_2 contents due to its calcite content. In amphibolites (D-31 and D-32; Table 2), marble bands lower their SiO_2 contents. The marble is calcitic rather than dolomitic, as shown by the lower MgO of sample D-32. The enclaves of orthogneiss (sample # D-29) has higher Fe content than the host orthogneiss.

MINERAL CHEMISTRY

Analyses of various mineral phases present in these rocks are given in Tables 3 through 5. Pyroxene multi-component systems provide an example of very well-studied mineral group (Lindsley, 1983; Rajesh, 2006), and often portrayed as compositions within the pyroxene quadrilateral. Tables 3 and 4 present the pyroxene compositions. They contain rather low CaO and Al_2O_3 contents. For orthopyroxene, CaO content is below 0.3 %; and Al_2O_3 between 2.33 and 4 %. In clinopyroxenes, CaO variation is large, and ranges from 13.1 to 25.1 %. The orthopyroxenes contain very little Cr_2O_3. The clinopyroxenes lack NiO altogether, which is present in orthopyroxene upto 0.17 % (Table 3). Al_2O_3 for most clinopyroxenes analyses unlike that of secondary clinopyroxenes, except a few analyses.

Garnet analyses are reported in Table 4. All analyses show the predominance of almandine end-member molecule. The compositions are comparable to those of the garnets from the pelitic metamorphic rocks of the main Kaghan Valley transect reported by (Rehman et al., 2007) except slightly lower CaO and Al_2O_3 for the Domel-Sohch gneisses.

DISCUSSION

The rocks in this study underlie the MMT, which locally follows a NE - SW trend at Domel, and serves as a contact between the NW-side outcrops rocks of the Kohistan island arc and SE-side rocks of the Indian plate.

Domel - Sohch transect comprises rocks of the High Himalayan Crystalline nappes that lie just to the SE of MMT. These nappes contain rocks divisible into basement gneisses (granitic- and para-gneisses), with overlying Paleozoic to early Mesozoic sequence of amphibolites, marble, dolomite, quartzite and mica schist (Greco et al., 1989; Spencer, 1993; O' Brien et al., 2001). Mafic sheets < 1m thick occur in these rocks and are considered by O' Brien et al. (2001) to have probably formed initially as eclogites, but later retrograded to amphibolite and greenschist facies. These High Himalayan Crystalline nappes are also known to contain eclogites (Lombardo et al., 2000). O' Brien et al. (2001) reported coesite-bearing massive eclogite from the core of large boudins in basement gneisses at Loihaloi Nala (stream) north of Gittidas. Such rocks carry petrogenetic significance as indicators of ultra-high pressure metamorphism (Zhang et al., 1995).

On the regional map of DiPietro and Pogue (2004) the rocks of Domel-Sohch transect are shown as "Lower Proterozoic Metamorphic Rocks" interspersed with "Tethyan metamorphic Rocks", that occur east of the Jhelum- Balakot transverse fault.

In the Central Himalayas, Main Central Thrust (MCT) is widely recognized as a major intracontinental thrust fault boundary between the High Himalayan crystalline rocks and the Lesser Himalayan rocks with none or low-grade metamorphism (Gansser, 1993). It exhibits synmetamorphic ductile deformation and a "schuppenzone". DiPietro and Pogue (2004) argued that in Naran region, the late to post-metamorphic Panjal Thrust represents MCT. Presence of higher regional metamorphic grade in Dome - Sohch rocks indicate this area lies away from the MCT.

Clinopyroxenites:

Occurrences of clinopyroxenites have been reported in the following settings and genetic fashions: (i) As layers, veins or dykes in supra-subduction zone peridotites formed by metasomatism of mantle-wedge peridotite protoliths by melts or fluids derived from the subducted plate (Berly et al., 2006). (ii) In the recycled elongated slices of subducted oceanic lithosphere through the convecting mantle (Allègre and Turcotte, 1986; Kornprobst et al., 1990).

(iii) As dominant rocks of crustal island arc related cumulate pyroxenites (DeBari and Coleman, 1989; Schiano et al., 2000).

(iv) Massif pyroxenites formed by high-pressure mineral segregation from primitive basaltic magmas (DeBari and Coleman, 1989).

At Domel, clinopyroxenites occur close to the MMT.

Pyroxene exsolution:

The shapes of exsolution lamellae provide evidence for changing cooling rates, and of interactions between rocks and fluid phases, reflecting differences in thermal histories (Rajesh, 2006). Exsolution intergrowths of pyroxenes in clinopyroxenites, occur in different stages. The thicker irregular and discontinuous pyroxene lamellae resulted probably from initial heterogeneous nucleation. During slow cooling, exsolution continued as fine platelets of orthopyroxene and as homogeneous nucleation of regularly spaced more uniform orthopyroxene lamellae. Exsolution textures also indicate that after initial metamorphic recrystallization, the pyroxenes re-equilibrated to lower temperatures.

Presence of rims without exsolution lamellae that surround the clinopyroxenes showing exsolution texture indicate continuity of crystal growth after culmination of exsolution.

Nature of ultramafic rocks:

The occurrence of dunites or olivine-pyroxene cumulates associated with pyroxenites very close to the MMT gives no clear evidence as to the provenance of these ultramafic rocks. Composition of primary spinel could have been used as a petrogenetic indicator, as in many studies of similar rocks elsewhere (Ahmed, 1984); but the samples didn't contain a primary spinel phase. The spinel grain analyzed in this study are either a "ferritchromit" or magnetite. Lack of orthpyroxene-richer rocks of mantle affinity at Domel also indicates their non-ophiolitic character and relatively lower depth of origin.

Pyroxenites are known from many arc environments where they suggest to have formed as medium- to high- pressure ultramafic-mafic cumulates in middle to lower crustal magma chambers of sub-arc Mohorovicic discontinuity. These include the Alaskan complexes (Irving, 1974, DeBari and Coleman, 1989), ultramafic rocks from Canada (Findlay, 1969), California (Quick, 1981), intra-oceanic arcs of southern New Zealand (Spandler et al., 2003), Kohistan island arc of Pakistan (Jan and Howie, 1981; Kausar, 1998) and the Beni Bousera massif of Morocco (Pearson et al., 1993). Such crustal pyroxenites differ from mantle-derived pyroxenites in their narrower ranges of CaO variation, Al_2O_3 variation, and lesser variety of rock types (Berly et al., 2006). In their primary pyroxenes, Al_2O_3 is lower and CaO is higher than the generally known ranges of mantle pyroxenes. In terms of these criteria, the Domel pyroxenites resemble those of the arc crustal origin, and are dissimilar to the mantle-origin pyroxenites.

CONCLUSIONS

Cumulate ultramafic bodies occur close to the Main Mantle Thrust location near Domel, and are mainly clinopyroxenites with limited amounts of cumulus orthopyroxene and olivine. Similar clinopyroxenite, and dunite bodies occur in the Kinari gorge. Basement gneisses of the Indian plate mainly display medium to high grade Barrovian type metamorphism; that increases progressively from SE towards NW, producing kyanite- grade gneiss near Domel. Quartz-rich mylonitic gneisses occur westwards from Sohch and near Dhamdama. Their deep-seated ductile deformation seem to have been followed by shallower deformation and retrograde metamorphic changes. Along the main Kaghan valley traverse, the garnet paragneisses occur interbedded with marble, and tabular amphibolites showing gross-banding reflecting protolith compositions. Gneisses of the three sections examined indicate sedimentary protoliths; but the granitic gneiss near Sohch may have a magmatic origin indicated by very large potash feldspar crystals, their alignment, more felsic appearance and mafic enclaves.

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Table 2
Whole rock analyses of samples from Sohch area.

Analysis	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Sample no.	**D-7**	**D-10**	**D-12**	**D-16**	**D-17**	**D-22**	**D-23**	**D-25**	**D-28**	**D-29**	**D-31**	**D-32**
SiO_2	57.30	51.51	55.29	46.28	58.66	46.15	48.48	72.13	64.41	64.95	46.10	25.00
TiO_2	0.18	0.30	1.45	2.49	4.40	0.10	0.10	0.10	0.27	0.52	1.93	0.22
Al_2O_3	17.19	17.25	14.27	14.27	12.57	2.57	7.09	13.32	14.17	15.17	16.46	9.22
Fe_2O_3	6.89	6.29	6.31	5.93	5.45	1.97	2.32	<0.10	2.50	3.53	3.88	5.81
FeO	1.68	6.64	7.44	7.92	4.00	2.56	2.16	1.92	2.16	3.28	7.92	3.12
MnO	0.12	0.10	0.17	0.12	0.12	0.13	0.10	0.10	0.10	0.10	0.12	0.12
CaO	4.00	1.39	1.78	3.61	2.97	13.42	14.69	0.10	7.52	0.38	7.96	28.05
MgO	1.23	4.46	6.88	14.15	6.88	27.67	3.85	0.32	0.86	1.85	8.76	1.21
Na_2O	0.88	1.65	1.53	1.95	1.72	0.76	0.86	1.94	1.77	2.69	1.77	0.74
K_2O	1.68	1.61	1.31	0.40	1.22	<0.10	1.90	5.98	4.34	2.70	0.56	1.54
P_2O_5	0.04	0.03	0.07	0.03	<0.01	0.05	0.03	0.09	0.06	0.07	0.09	0.05
H_2O	0.50	0.60	0.50	0.54	0.33	0.61	0.61	0.34	0.49	0.63	0.70	0.55
H_2O	0.80	0.40	0.50	0.36	0.57	0.39	0.34	0.56	0.46	0.22	0.20	0.24
CO_2	7.52	5.46	1.21	1.21	0.40	0.62	18.22	0.48	0.55	0.59	0.62	23.36
Total	100.01	97.69	98.71	99.26	99.29	97.00	100.75	97.38	99.66	96.68	97.07	99.23
p. p. m. :												
U_3O_8	8	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	6	11	1	n.d.
Th*	22	12	<10	<10	<10	<10	14	<10	38	38	<10	<10
V	153	348	363	457	434	87	87	54	95	86	393	130
Co	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Cr	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.92	0.74	< 0.1
Ni	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Sr	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

n.d. = Not determined.

Table 3
Analyses of orthopyroxenes from clinopyroxenites

Sample #.	**D1**	**D1**	**D22**	**D22**	**D22**	**D21**
Anal. #	**D1-p82**	**D1-p88**	**D22-151**	**D22-157**	**D22-141**	**D21-127**
SiO_2	45.60	47.46	50.22	50.17	50.72	54.12
TiO_2	0.00	0.00	0.01	0.00	0.00	0.00
Al_2O_3	4.02	2.33	0.50	0.59	1.11	2.24
$C_{r2}O_3$	0.07	0.01	0.01	0.52	0.39	0.19
Fe O*	17.44	15.78	11.79	11.27	10.66	2.63
MnO	0.40	0.33	0.34	0.30	0.23	0.05
MgO	30.43	31.87	35.49	35.57	34.31	40.40
CaO	0.00	0.29	0.13	0.29	1.29	0.00
NiO	0.11	0.17	0.19	0.01	0.11	0.07
Total	98.07	98.24	98.68	98.72	98.82	99.70

Fe O*= Total iron as FeO.

Table 4
Analyses of clinopyroxenes from clinopyroxenites of Domel

	Augite					Ferroaugite				Diopside				
Sample #.	D1	D1	D1	D2	D2	D4	D4	D4	D4	D2	D2	D2	D22	D22
Anal.#	D1-p83	D1-89	D1-p92	D2-p1	D2-p4	D4-107	D4-108	D4-115	D4-118	D2-p2	D2-p3	D2-p5	D22-137	D22-147
SiO_2	57.75	57.56	58.05	59.66	56.93	57.04	57.25	55.35	54.99	54.35	53.15	54.53	52.74	53.27
TiO_2	0.04	0.05	0.08	0.01	0.03	0.02	0.01	0.04	1.88	0.00	0.03	0.05	0.05	0.03
Al_2O_3	0.00	1.14	0.00	0.08	2.21	1.47	0.80	1.25	1.76	0.67	0.38	0.62	0.74	0.20
Cr_2O_3	0.08	0.23	0.01	0.22	0.46	0.03	0.02	0.01	0.00	0.44	0.57	0.56	0.44	0.04
Fe O*	5.90	6.15	5.37	4.82	4.45	10.32	9.71	10.94	11.35	2.91	3.74	3.13	3.34	2.85
MnO	0.14	0.18	0.14	0.28	0.08	0.26	0.26	0.19	0.19	0.04	0.08	0.08	0.07	0.08
MgO	19.69	20.49	19.94	20.55	20.25	16.56	17.50	16.89	15.04	16.08	17.07	16.44	15.51	15.88
CaO	15.70	13.53	15.82	13.82	15.02	13.09	13.35	13.99	14.49	25.14	24.47	24.20	26.71	27.23
NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.10
Total	99.30	99.33	99.41	99.44	99.43	98.79	98.90	98.66	99.70	99.63	99.49	99.61	99.63	99.68

Na_2O and K_2O yielded zero values for all of the analyzed samples.
Fe O* = Total iron as FeO.

Table 5.

Analyses of garnet hosted by kyanite-grade (D-7) and garnet-grade (D-10) gneisses of Domel- Sohch section

Sample #	D7	D7	D10	D10	D10	D10	D10	D10	D10
Anal. #	D7-p1	D7-p3	D10-58	D10-57	D10-56	D10-55	D10-54	D10-53	D10-52
SiO_2	37.01	36.06	36.24	36.80	36.07	36.20	36.64	36.24	36.79
TiO_2	0.03	0.04	0.02	0.05	0.00	0.06	0.00	0.03	0.04
Al_2O_3	19.74	19.32	19.41	19.49	19.22	19.20	19.28	19.17	19.43
Cr_2O_3	0.04	0.00	0.00	0.01	0.00	0.06	0.04	0.02	0.01
FeO*	29.13	31.22	31.84	30.16	31.93	31.34	30.58	30.75	31.03
MnO	1.21	1.20	0.28	0.45	0.61	0.71	0.54	0.43	0.26
MgO	3.69	3.24	5.60	4.30	4.21	4.12	3.80	3.76	5.75
CaO	5.78	5.41	2.94	5.38	4.37	4.74	5.70	6.08	2.91
Na_2O	0.06	0.02	0.00	0.00	0.03	0.02	0.01	0.03	0.26
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Total	96.69	96.51	96.33	96.63	96.44	96.45	96.59	96.51	96.50

`FeO* = Total iron as FeO. Low total of analyses indicate partly Fe may be present as Fe_2O_3. NiO was below detection level in all analyses.

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