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Stratigraphy and structure of the Precambrian to Mesozoic, especially Precambrian (?) to Lower Cambrian phosphorite-bearing formations, in Abbottabad, northern Pakistan

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Abstract: Metamorphic and sedimentary rocks in the Abbottabad area, northern Pakistan, are divided into the Precambrian, Precambrian (?) to Lower Cambrian, and Jurassic to Cretaceous systems. The Precambrian (?) to Lower Cambrian system consists of two phosphorite-bearing formations: the Abbottabad and Hazira Formations. The Sirban Dolomite Member in the upper part of the Abbottabad Formation is about 600m thick, and subdivided into three units: the Lower, Middle, and Upper. The Lower and Middle Units consist mainly of micritic dolomite, and dolomite and quartzite, respectively. The Upper Unit is characterized by numerous chert intercalations within the dolomite. At least three horizons of economically important phosphorite deposits are recognized in the top part of the Upper Unit. The phosphorite horizons are of variable thickness, reaching a maximum of 5m.

The Hazira Formation is 125m thick and disconformably overlies the Abbottabad Formation. Two lithologic facies are recognized in the formation: the Hazira and Galdanian Facies. The Hazira Facies is characterized by glauconite-bearing calcareous mudstone and sandstone, while the Galdanian Facies is composed of hematitic red mudstone, siltstone and chert breccia. Thin phosphorite beds occur in the lower part of the formation.

The study area is characterized by a number of thrust sheets, and divided into four structural domains: Domains α, β, γ, and δ. Two phases of deformation are recognized: thrusting followed by bending and westward overturning. Phosphorite deposits are generally confined to the Hazira Facies dominant-domain, Domain β, while the other domains are poor in phosphorite.

A drastic facies change from carbonate to clastic rocks is observed around the boundary between the Abbottabad and Hazira Formations. This change with associated deposition of phosphorite and ferruginous sediments indicates the widespread rapid transgression along the northern margin of Gondwana including the study area.

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1. Introduction

One of the most significant phosphogenic episode in geologic time has been recognized in the transition between Precambrian and Cambrian. Representative phosphorite

Keywords : Precambrian, Lower Cambrian, Jurassic, Cretaceous, phosphorite, Gondwana, stratigraphy, structure, Abbottabad Formation, Hazira Formation, Abbottabad, Pakistan

deposits occur worldwide, especially along the northern margin of Gondwana (Cook and Shergold, 1986; Brasier, 1989; 1990; Donnelly *et al.*, 1990; Cook, 1992), and includes the phosphorite deposits in the Abbottabad area, Hazara Division, northern Pakistan. The phosphorite deposits in the Abbottabad area were discovered by Latif (1970; 1972a) in the late 1960's. Exploration for phosphorites was initiated in 1976 by the Sarhad Development Authority, with production of 200tons a day beginning in 1984 (Hasan, 1989; Hirayama *et al.*, 1995).

The Abbottabad area has been studied by numerous workers not only from an economic interest in phosphorite and other mineral resources but also from an academic interest in the stratigraphy and geologic structure of this area located in the Himalayan fold and thrust belt. Although detailed geologic maps in the Hazara area have been published at a scale of 1: 24,000 and smaller by several authors (Marks and Ali, 1961; Gardezi and Ghazanfar, 1965; Latif, 1970; Calkins *et al.*, 1975; Ghaznavi and Karim, 1978; 1979; Hasan and Ghaznavi, 1980), most were published before the discovery of phosphorite deposits. The remainder are too insufficient for tracing the phosphorite deposits in the Abbottabad area.

The Geoscience Laboratory, Geological Survey of Pakistan, has been engaged since 1991 in the re-examination of mineral resources and geology in the Hazara Division including the Abbottabad area. Subsequently, a mapping project in the Abbottabad phosphorite area was initiated in 1993 as one of the Technical Cooperation Project between Geological Survey of Pakistan (GSP) and Japan International Cooperation Agency (JICA). Tentative results of the mapping project were reported in internal circulars of the Geoscience Laboratory (Karim, 1993; Warraich *et al.*, 1993; Aslam and Kaneda, 1993; Hirayama *et al.*, 1995; Naka *et al.*, 1995; etc.).

In this paper, we summarize the results of the mapping project . The purpose is to describe the Precambrian to Cretaceous lithostratigraphy and geologic structure in the Abbottabad area, and to discuss the litho-logical and environmental changes around the Precambrian-Cambrian transition. In the present work, detailed maps at a scale of 1: 5,000 to 1: 6,000 were made along various traverses in order to understand the lithostratigraphy and structure of the area. Field data were transferred onto a topographic map at a scale of 1: 10,000 prepared by the Sarhad Development Authority. The attached geologic map and cross sections (Figs. 10 and 11) were reduced from an original scale of 1: 10,000 to a scale of 1: 25,000.

2. Geological setting and previous work

The study area (about 70km^2) is situated between longitudes 73°15′ E to 73°20′ E and latitudes 34°10′ N to 34°19′ N (Fig. 1). It covers part of toposheets Nos. 43F/8 and F/7, published by the Survey of Pakistan.

The collision between the Indian sub-continent and the Asian continent occurred during the Paleocene to Eocene (Coward and Butler, 1985; Beck *et al.*, 1995). The collision resulted in an extensive southward-directed thrust system involving Precambrian to Early Eocene sedimentary cover onto the Indian sub-continent. This system called the Himalayan fold and thrust belt (Fig. 1) is bounded by the Main Mantle Thrust to the north and by the Salt Range Thrust to the south. The study area is located in the northwestern part of the Hazara Arc (Yeats and Hussain, 1987), which forms the western limb of the Hazara-Kashmir Syntaxis (Fig. 1). The arc thrusts southward onto the Miocene to Pliocene post-collision sediments along the Main Boundary Thrust. To the north, the Hazara Arc is bounded by the Panjal Thrust with Precambrian strata and Cambrian granitic rocks.

Pioneer works in the Hazara Division were made by Waagen and Wynne (1872) and Middlemiss (1896). They published geological descriptions accompanied by small-scaled geologic maps covering part of the Hazara Division, which served as a base for subsequent work. Marks and Ali (1961) prepared a geologic map of the area around Abbottabad, and divided the rock sequence into several litho-

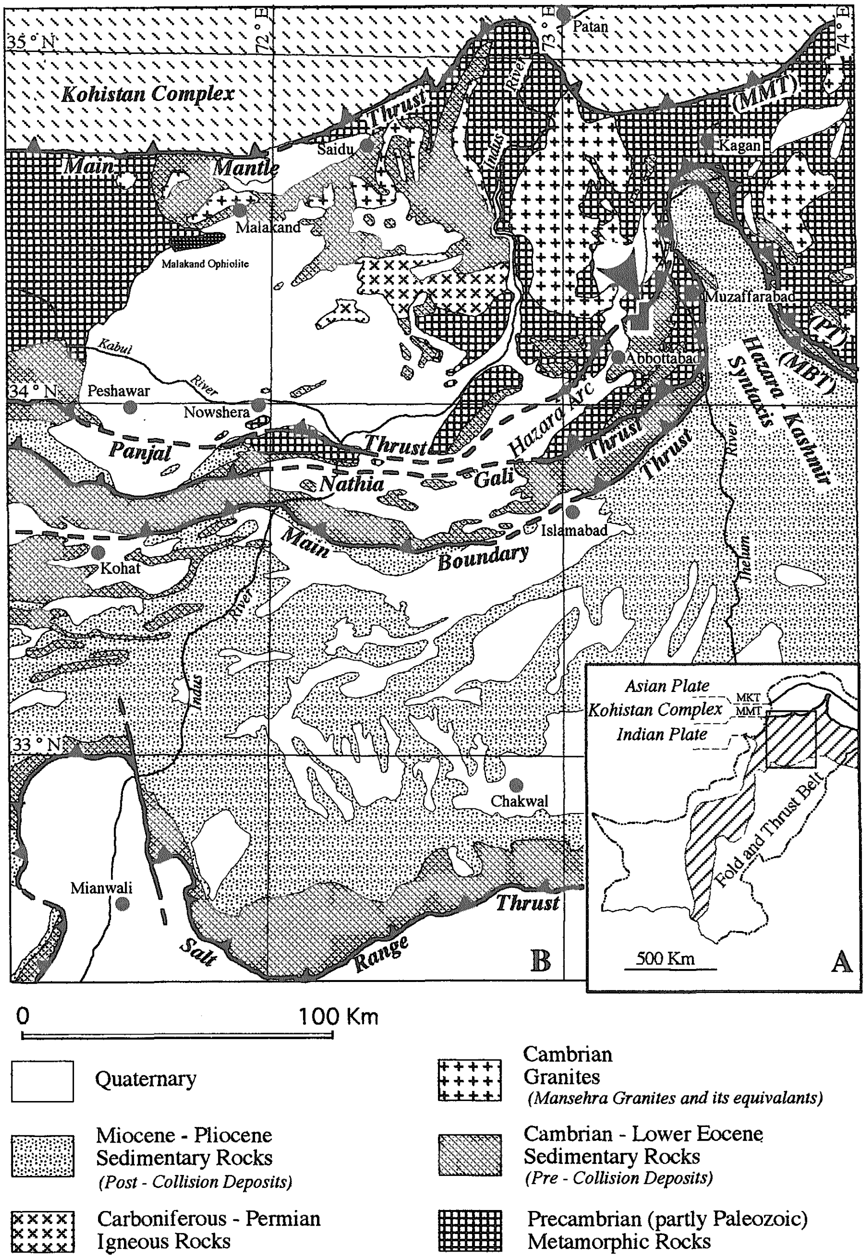


Fig. 1-A Simplified tectonic map of Pakistan showing the Himalayan fold and thrust belt. Study area denoted by rectangle in the figure. MKT, Main Karakoram Thrust; MMT, Main Mantle Thrust.

1-B Geotectonic map of northern Pakistan showing major thrusts (barbs on hanging wall). Black arrow points to the study area. Compiled from Hylland *et al.* (1988), Khan and Humayun (1991) and Qureshi *et al.* (1993).

Table 1 Comparison of the stratigraphy of previous workers with this study.

This study *	Marks and Ali (1961 *; 1962)	Gardezi and Ghazanfar (1965) *	Calkins and Matin (1968) *, Calkins et al. (1969; 1975) *	Latif (1970; 1974a)*
Samana Suk Fm.	Triassic System: Upper Fm.	Jurassic Limestone Fm. and Maira Fm.	Samana Suk Fm.	Thandiani Gr.
Hazira Fm.: Hazira Facies	Triassic System: Lower Fm.: Hematitic Sandstone Mem.	Hazira Fm.	Datta Fm.	Tarnawai Fm.: Hazira Mem.
Hazira Fm.: Galdanian Facies	Triassic System: Lower Fm.: Rhyolitic Mem.	Hematite Fm.		Tarnawai Fm.: Galdanian Mem.
Abbottabad Fm.: Sirban Dolomite Mem.: Upper Unit	Abbottabad Fm.: Upper Dolomite Mem.	Abbottabad Fm.	Kingriali Fm.	Abbottabad Gr.: Sirban Fm.
Abbottabad Fm.: Sirban Dolomite Mem.: Middle Unit				
Abbottabad Fm.: Sirban Dolomite Mem.: Lower Unit				
Abbottabad Fm.: *Not exporsed*	Abbottabad Fm.: Upper Shale and Sandstone Mem.			Abbottabad Gr.: Kakul Fm.: Mirpur Sandstone
	Abbottabad Fm.: Lower Dolomite Mem.			Abbottabad Gr.: Kakul Fm.: Mahmdagali Mem.
	Abbottabad Fm.: Lower Shale and Sandstone Mem.			Abbottabad Gr.: Kakul Fm.: Sangargali Mem.
	Abbottabad Fm.: Basal Conglomerate Mem.			Abbottabad Gr.: Kakul Fm.: Tanakki Conglomerate
Hazara and Tanawal Fms.	Tanol Fm.	Hazara Slate / Metamorphics	Tanawal Fm.	Tanol Fm.
	Hazara Slate Fm.		Hazara Fm.	Hazara Gr.

This study *	Butt (1970; 1972; 1989)	Stratigraphic Committee of Pakistan (Shah, 1977)	Hasan (1986; 1989)*	Ashraf and Chaudhry (1987) *
Samana Suk Fm.	Samana Suk Fm.	Samana Suk Fm.	Samana Suk Fm.	
Hazira Fm.: Hazira Facies	Hazira Fm.	Hazira Fm.	Hazira Fm.: Hazira Facies	Hazira Fm.
Hazira Fm.: Galdanian Facies	Shekhan Bandi Fm.		Hazira Fm.: Galdanian Facies	Galdanian Fm.
Abbottabad Fm.: Sirban Dolomite Mem.: Upper Unit	Abbottabad Fm.: Sirban Mem.	Abbottabad Fm.	Abbottabad Fm.: Upper Dolomite Mem.	Hazara Phosphate Fm.
Abbottabad Fm.: Sirban Dolomite Mem.: Middle Unit			Abbottabad Fm.: Middle Quartzose Sandstone Mem.	Abbottabad Fm.
Abbottabad Fm.: Sirban Dolomite Mem.: Lower Unit			Abbottabad Fm.: Lower Dolomite Mem.	
Abbottabad Fm.: *Not exporsed*	Abbottabad Fm.: Mirpur Mem.			
	Abbottabad Fm.: Mahmdagali Mem.			
	Abbottabad Fm.: Sangargali Mem.			
	Abbottabad Fm.: Tanakki Mem.		Abbottabad Fm.: Tanaki Conglomerate Mem.	
Hazara and Tanawal Fms.	Tanol Fm.	Tanawal Fm.	Tanawal Fm.	
	Hazara Fm.	Hazara Fm.	Hazara Fm.	

Abbreviation : Gr., Group; Fm., Formation; Mem., Member, * : attached with original geological map and/or stratigraphic column

Stratigraphic relationship : fault, ———

conformiy, ——— lateral change, ·········

unconformity or break of sedimentation, —·—·—·—

stratigraphic units. Gardezi and Ghazanfar (1965) compiled a geologic map covering the area between Abbottabad and Lagarban. In the late 1960's to 70's, phosphorite deposits and Cambrian fossils were discovered in the Abbottabad area (Latif, 1972a; 1972b; Fuchs and Mostler, 1972; Rushton, 1973). At the same time, the knowledge on stratigraphy and structure of the Hazara Division rapidly increased mainly from works by Latif (1970; 1972a; 1972b; 1974a; 1974b), Calkins (Calkins and Matin, 1968; Calkins *et al.*, 1969; Calkins *et al.*, 1975), and the staff of Geological Survey of Pakistan (Bhatti *et al.*, 1972;

Hasan, 1974; Ghaznavi and Karim, 1978; 1979; Hasan and Ghaznavi, 1980). Subsequently, intensive explorations of the phosphorite deposits, including topographic and geologic mapping, drilling, aditting, and trenching, were carried out in the Kakul-Lagarban area between 1976 and 1994 by the Sarhad Development Authority with technical cooperation from the British Government (Hirayama *et al.*, 1995). Unfortunately, the exploration data remains unpublished. A new classification and nomenclature of the rock units was also proposed (Butt, 1970; 1972; 1989; Shah, 1977; etc.). Although several stratigraphic, structural, and geochemical studies have been undertaken between 1980 and 1994 (Coward *et al.*, 1982; Ashraf and Malik, 1983; Bhatti, 1983; Bossart *et al.*, 1984; Coward and Butler, 1985; Shaw and Wasserburg, 1985; Husain *et al*., 1987; Ashraf and Chaudhry, 1987; Ghazanfar *et al.*, 1987; Treloar, 1989; Treloar *et al.*, 1989; Donnelly *et al.*, 1990; Husain *et al.*, 1990; 1994), the geological interpretations established by Latif, Calkins, and GSP have undergone no basic changes. Several reviews were also made on the geology and the phosphorite deposits by Bhatti (1983), Hasan (1986; 1989), Butt (1988; 1989), and Khan and Humayun (1991).

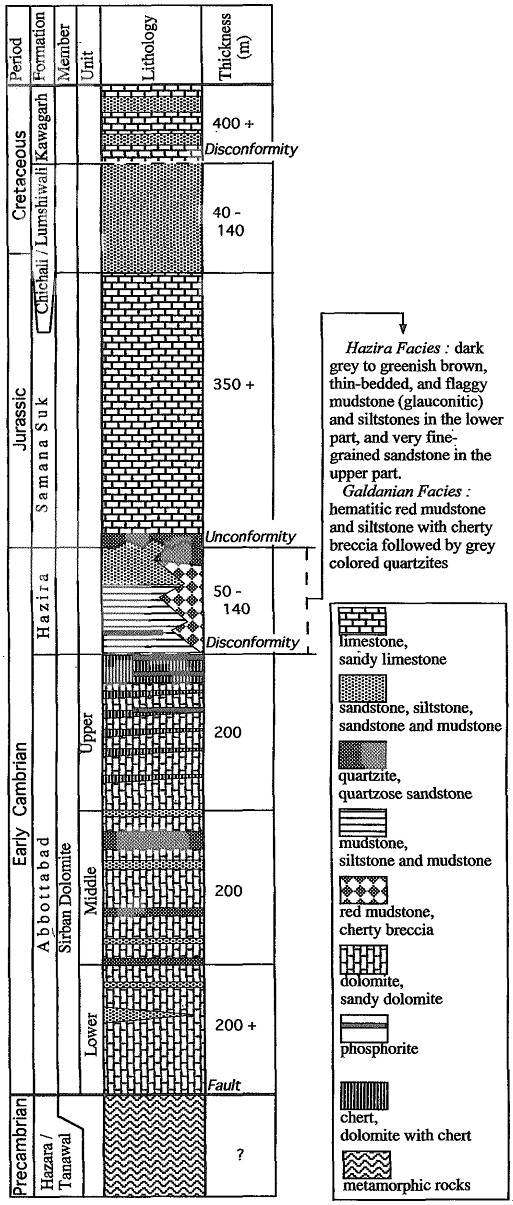
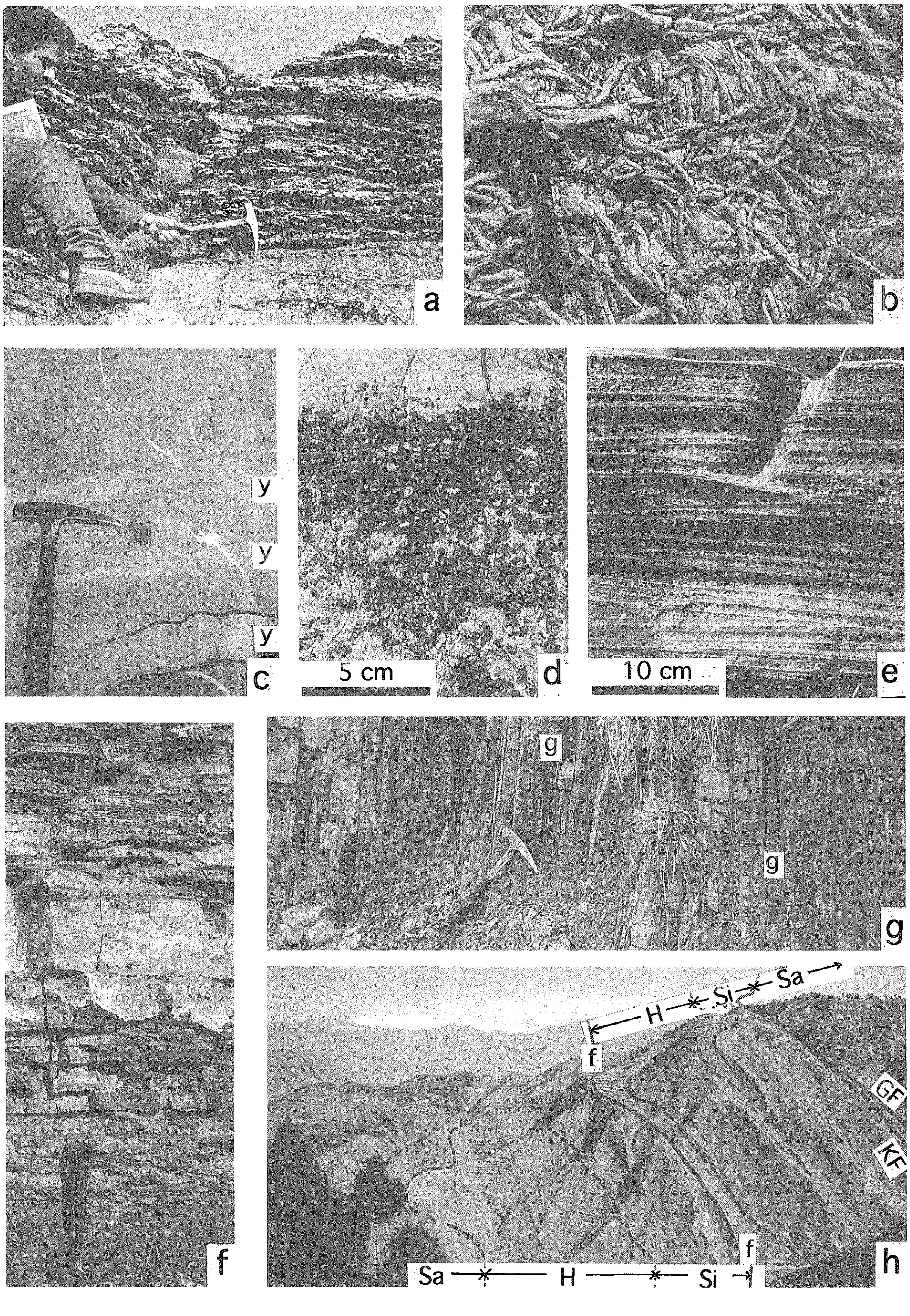


Fig. 2 Generalized stratigraphic column of the study area, Abbottabad, northern Pakistan.

3. Stratigraphy

The rock sequence in the study area is divided into the following three systems: the Precambrian, Precambrian (?) to Lower Cambrian, and Jurassic to Cretaceous (Fig. 2). The Precambrian is composed of variously metamorphosed rocks, and consist of the Hazara and Tanawal Formations. The Precambrian (?) to Lower Cambrian composed predominantly of carbonate and clastic sedimentary rocks, is divided into the Abbottabad and Hazira Formations in ascending order. Only the uppermost member of the Abbottabad Formation, the Sirban Dolomite Member (redefined here), is exposed in the study area. The Jurassic to Cretaceous sedimentary system is divided in ascending order into the Samana Suk, Chichali and Lumshiwal, and Kawagarh Formations. Although the classification and nomenclature of rock units in the study area have been under discussion, this paper basically follows the Stratigraphic Committee of Pakistan (Shah, 1977). Table 1 shows the correlation of the classification and nomenclature between previous workers and this study.


a
b
y
y
y
c
5 cm
d
10 cm
e
g
g
g
f
H
Si
Sa
f
GF
KF
f
Sa
H
Si
h

Phosphorite deposits occur in the Abbottabad and Hazira Formations in the study area. They can be traced to the north and south (Ashraf, 1974; Hasan and Ghaznavi, 1980).

3.1 Hazara and Tanawal Formations (Calkins and Matin, 1968)

Name: The formation names of Hazara and Tanawal are derived from the district and the location names, respectively.

Historical background: Several names have been given to the thick widespread metamorphic to weakly metamorphosed rocks in the Hazara Arc (Table 1). The formation names of Hazara and Tanawal were introduced by Calkins and Matin (1968), and the Stratigraphic Committee has approved the names (Shah, 1977).

Stratotype: The stratotypes of the formations have not been designated by any author.

Distribution: The Hazara and Tanawal Formations are distributed in the western portion of the study area (Fig. 10), and are widely distributed over the Hazara Arc. The base of the formations are not exposed in the study area.

Thickness: Not measured due to complex structure, but estimated to be more than several hundred meters.

Lithology: The Hazara Formation consists mainly of slate, while the Tanawal Formation is composed largely of quartzose schist (Calkins *et al.*, 1975). In this study, we did not divide the Hazara and Tanawal Formations, and thus combined them as one unit in the geologic map (Fig. 10), due to the complicated structure and various metamorphic grade. The formations consist of various kind of metamorphic rocks, including pelitic, psammitic, micaceous, and carbonaceous schists. In Banda Pir Khan, gneissose schists are found. Their metamorphic grade appears to decrease northward in the study area.

Stratigraphic relationship: The formations are clearly truncated with the Precambrian (?) to Cambrian and Jurassic rocks by the Panjal Thrust.

Age: No fossils have been reported from the formations. Crawford and Davies (1975; recalculated in Baig *et al.*, 1988) reported Rb/Sr whole rock ages of 739±9 Ma and 951±8 Ma for the Hazara Formation. The Tanawal

←Fig. 3 Field photographs.

a. Chert bands in the Upper Unit, Sirban Dolomite Member of the Abbottabad Formation showing protruded weathering surfaces; Kakul Mine.

b. Burrows found on the bed surface of grey mudstone, Galdanian Facies, Hazira Formation; near Gali Beha.

c. Medium to thick-bedded Samana Suk Formation showing yellow patches and layers (shown as y) consisting of calcareous sandstone and/or sandy limestones; near the Kakul Mine.

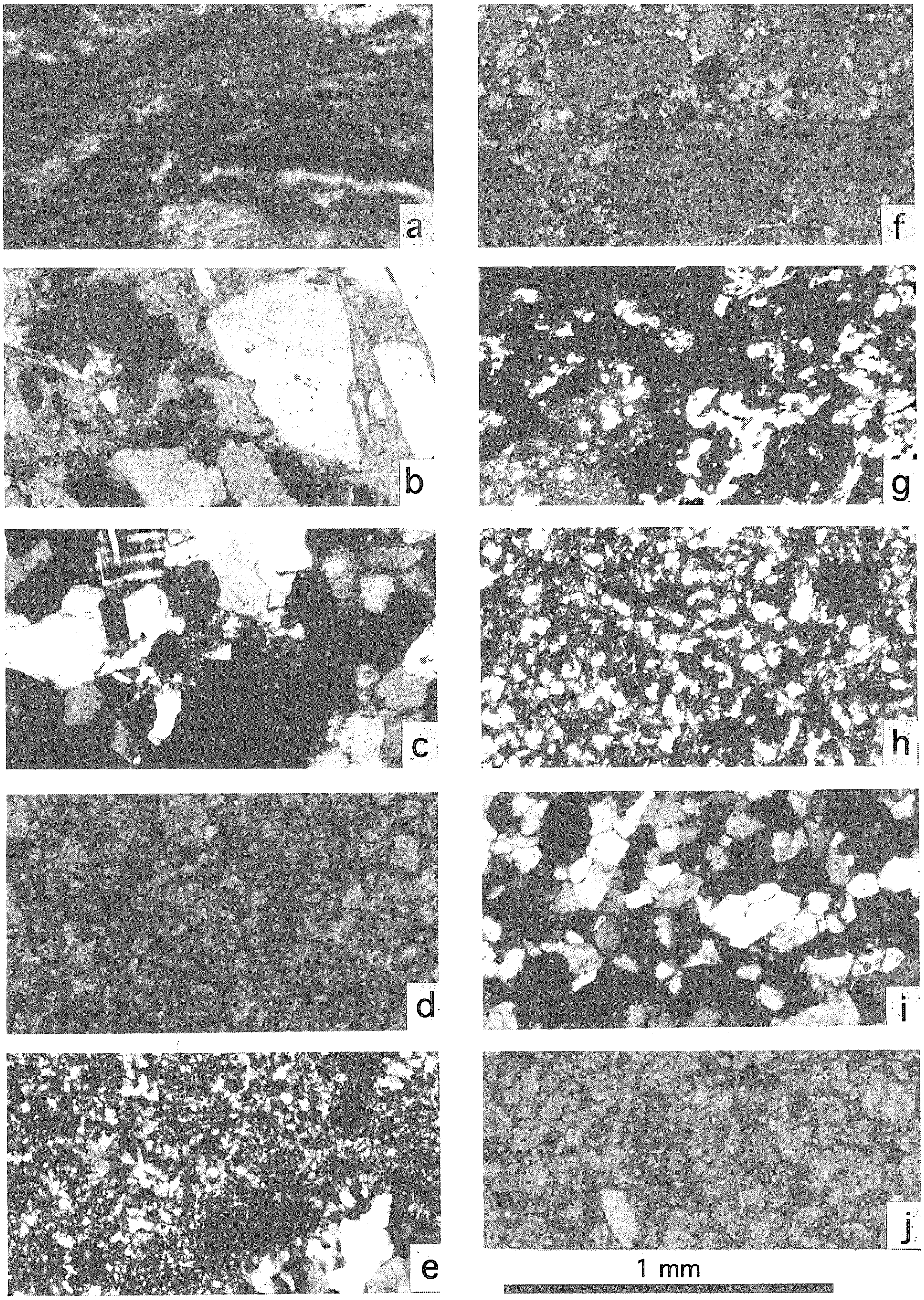
d. Close-up view of a conglomerate containing chert granules of the Upper Unit, Sirban Dolomite Member of the Abbottabad Formation; near the Kakul Mine. Angular chert grains are dispersed in a dolomite matrix.

e. Graded and cross-bedded dolomitic sandstone found in the Middle Unit, Sirban Dolomite Member of the Abbottabad Formation; NW of the Kakul Mine.

f. Close-up view of phosphorite deposits in the Kakul Mine. Black to greyish black phosphorite layers are rhythmically interbedded with the whitish grey dolomites. Upper Unit, Sirban Dolomite Member of the Abbottabad Formation; Kakul Mine.

g. Medium- to thin-bedded and dark-grey colored siltstones intercalated with thin-bedded greenish-brown glauconitic mudstones (distinct layers are labeled "g") in the lowermost part of the Hazira Facies, Hazira Formation; near the Kakul Mine.

h. Panoramic view of part of the survey area, Tarnwai. The picture was taken from S to N. The Samana Suk Formation (Sa), Upper Unit of the Sirban Dolomite Member, Abbottabad Formation (Si), and the Hazira Formation (H) are repeated by thrust faults (f, KF, and GF). The Hazira mudstone forms small topographic depressions. Note that formations distributed on the left side of the thrust faults (GF and KF) are overturned westward. GF, Galdanian Fault; KF, Kakul Fault.


a
b
c
d
e
f
g
h
i
j
1 mm

Formation is intruded by the Mansehra Granite near Mansehra (Calkins *et al.*, 1975; see Fig. 1), which has yielded a Rb/Sr whole rock age of 516±16 Ma (Le Fort *et al.*, 1980). Thus, the Hazara and Tanawal Formations are assigned to the Precambrian.

3.2 Abbottabad Formation (Marks and Ali, 1962), Sirban Dolomite Member (redefined from Latif, 1974a)

Name: The formation name is derived from the city of Abbottabad. The member name is derived from a hill, situated to the south of Abbottabad. Although the hill name is written as Sarbun on toposheet No. 43 F/4, the member name has been spelled as Sirban since the member was established (Latif, 1970).

Historical background: Marks and Ali (1962) proposed the name Abbottabad Formation for the dolomite and sandstone sequence in the Sarbun Hill, and divided it into five members (Table 1). Subsequently, various names and stratigraphic divisions were given to the formation by many workers (Table 1).

Stratotype: The stratotype of the formation is in Sarbun Hill, south of Abbottabad (Marks and Ali, 1961; Latif, 1974a).

Distribution: The formation is widely distributed in the Hazara Arc, including the study area. Only the upper part of the formation, the Sirban Dolomite Member is exposed in the study area. The base of the Sirban Dolomite Member is not exposed.

Redefinition and correlation: The Sirban Dolomite Member is here redefined as the dolomite dominant sequence of the uppermost part of the Abbottabad Formation. In comparison with stratigraphic descriptions from previous works, the Sirban Dolomite Member in this paper corresponds with the "Upper Dolomite Member" of Marks and Ali (1961;

←Fig. 4 Microscopic photographs. Scale bar is 1mm long for all photographs. Chemical composition of samples are listed in Table 2. All samples were collected in and around the Kakul Mine.

a. Stromatolitic dolomite. A thin, upward-curved cyanobacterial mat in dolomite. Lower Unit, Sirban Dolomite Member of the Abbottabad Formation. Open nicol. Sample No.: KA-14.

b. Dolomitic sandstone. Fractured quartz grains filled with dolomite. Middle Unit, Sirban Dolomite Member of the Abbottabad Formation. Crossed nicol. Sample No.: KA-11.

c. Quartzite. Quartz grains display a typical mosaic texture. Matrix is very poor. A few grains of microcline and tourmaline can be observed. Middle Unit, Sirban Dolomite Member of the Abbottabad Formation. Crossed nicol. Sample No.: KA-12.

d. Dolomite. Fine-grained dolomite associated with rhomboid shaped crystals. Upper Unit, Sirban Dolomite Member of the Abbottabad Formation. Open nicol. Sample No.: KA-5.

e. Chert. Cryptocrystalline to very fine micro- quartz in chert layer from the Upper Unit, Sirban Dolomite Member of the Abbottabad Formation. No biological features are observed, probably due to recrystalization. Crossed nicol. Sample No.: KA-5b (chert part of the KA-5).

f. Glauconitic mudstone. Ooids and pellets of glauconite occurs in a quartz-hematite-clay mineral matrix. Hazira Facies of the Hazira Formation (lower Part). Crossed nicol. Sample No.: KA-7.

g. Hematitic rock. Irregular shaped hematite (black color) and quartz (white color) are observed. A glauconitic ooid is also contained (lower left). Lower part of the Galdanian Facies, Hazira Formation. Crossed nicol. Sample No.: KA-3.

h. Siltstone. Sub-angular to sub-rounded detrital grains of quartz and feldspar dispersed in a clay matrix. Mica is also observed. Lower part of the Hazira Facies of the Hazira Formation. Crossed nicol. Sample No.: KA-6.

i. Quartzite. Subrectangular to polygonal shaped quartz grains weakly tectonized. At the base of Samana Suk Formation. Crossed nicol. Sample No. :KA-11.

j. Limestone. Some micro-fossils and detrital quartz grain (lower left) are observed. Samana Suk Formation. Open nicol. Sample No. :KA-1.

Table 2 Results of XRF analysis of representative samples collected from the Kakul Mine area. Microphotographs of some are shown in Fig. 4.

Sample No.	KA-14	KA-11	KA-13	KA-12	KA-5	KA-6	KA-7	KA-8	KA-3
Lithology	dol	dol ss	dol ss	qz	ch. dol	ms	ms	ss	iron ms
Formation	Abb.	Abb.	Abb.	Abb.	Abb.	Hazira	Hazira	Hazira	Hazira
Unit or Facies	Lower	Middle	Middle	Middle	Upper	Hazira	Hazira	Hazira	G
SiO_2	0.32	60.97	72.39	95.91	10.53	50.31	67.19	69.19	33.97
TiO_2	0.01	0.03	0.02	0.04	0.01	0.64	0.55	0.86	0.56
Al_2O_3	0.42	1.18	1.31	2.24	0.48	9.70	9.55	12.78	13.14
Fe_2O_3	0.81	0.60	0.53	0.18	0.17	4.86	6.85	3.98	36.45
MnO	0.07	0.08	0.07	0.02	0.06	0.15	0.08	0.08	0.01
MgO	22.07	2.58	4.66	0.07	19.89	5.89	1.86	2.17	0.56
CaO	29.94	17.69	8.69	0.06	26.82	9.27	3.77	0.93	4.22
Na_2O	0.00	0.01	0.07	0.09	0.00	0.04	0.05	0.05	0.00
K_2O	0.02	0.31	0.47	1.11	0.03	4.84	4.85	6.71	3.04
P_2O_5	0.03	0.19	0.17	0.01	0.01	0.38	1.39	0.50	4.73
LOI	46.31	16.37	11.63	0.29	42.01	13.94	3.87	2.75	3.31
Total	100.00	100.01	100.01	100.02	100.01	100.02	100.01	100.00	99.99

Sample No.	KA-9	KA-10	KA-1	KA-2
Lithology	qz	qz	ls	ls
Formation	Samana	Samana	Samana	Samana
SiO_2	96.88	96.98	5.65	2.49
TiO_2	0.01	0.26	0.12	0.04
Al_2O_3	0.76	1.26	2.30	1.11
Fe_2O_3	0.70	0.57	1.20	0.36
MnO	0.04	0.02	0.12	0.04
MgO	0.20	0.09	5.25	0.30
CaO	0.64	0.20	44.32	53.32
Na_2O	0.00	0.00	0.01	0.00
K_2O	0.06	0.24	0.57	0.23
P_2O_5	0.02	0.00	0.02	0.02
LOI	0.71	0.38	40.45	42.09
Total	100.02	100.00	100.01	100.00

Abbreviation :
dol ; dolomite
dol ss ; dolomitic sandstone
qz ; quartzite
ch. dol ; cherty dolomite
ms ; mudstone
ss ; sandstone
ls; limestone
LOI ; loss of ignition
Abb. ; Abbottabad
Samana ; Samana Suk
G ; Galdanian

1962), the "Sirban Formation" of Latif (1974 a), the "Sirban Member" of Butt (1970; 1972; 1989), and the upper part of the "Lower Dolomite Member", "Middle Quartzose Sandstone Member" and "Upper Dolomite Member" of Hasan (1986; 1989) (Table 1).

Thickness: The total thickness of the formation in the type section is 2200feet (about 660 m) measured by Marks and Ali (1961), 1460 to 2630feet (about 438m to 789m) by Latif (1974 a), and 525.6m by Hasan (1986). The Sirban Dolomite Member attains a thickness of 600m$^+$ in the study area (Table 3).

Lithology: The formation is composed mainly of dolomite and sandstone. The Sirban Dolomite Member consists largely of dolomite, and is subdivided into three units in this paper: the Lower, Middle, and Upper Units (Fig. 2; Table 1).

Stratigraphic relationship: Outside the map area, the Sirban Dolomite Member conformably overlies the Mirpur Member (Marks and Ali, 1961; Latif, 1974a). To the south of Abbottabad, the Tanakki Conglomerate Member at the base of the Abbottabad Formation unconformably overlies the Hazara Formation (Baig *et al.*, 1988).

Age: Shah (1977) reported the occurrence of Early Cambrian phosphatic fossils, *Hyolithellus* spp. and *Hyolithes* spp., in the upper part of the Abbottabad Formation, which corresponds with the Upper Unit of the Sirban Dolomite Member in this paper. A Precambrian Sm-Nd age has been reported from the phosphorites in the Upper Unit of the Sirban Dolomite Member (Shaw and

Table 3 Thickness of rock units measured along various cross-sections in the study area. Section lines and distribution of structural domains are given in Fig. 7. Fm., Formation; C/L Fm., Chichali and Lumshiwal Formations; Abb., Abbottabad; Dol., Dolomite.

Domain		Section	Kawagah Fm.	C/L Fm.	Samana Suk Fm.	Hazira Fm.		Abb. Fm., Sirban Dol. Mem.		
						Galdanian	Hazira	Upper	Middle	Lower
α	α–1	M-N						# 70		
		E-F						# 70		
		X-Y						# 100		
	α–2	E-F			# 240					
		G-H			? 20	**80**		# 50		
		X-Y			# 220	**80**		? 0 - 200		
β	β–1	I-J			? 250		**140**	# 30		
		A-B			# 180		# 100	# 20		
		K-L			# 300		# 60			
		C-D			? 120		? 100			
	β–2	I-J			# 80		**100**	? 120		
		A-B			# 40		**100**	? 100 - 200		
		K-L					# 100	# 100 - 200		
		C-D			? 330		? 100			
		M-N			? 240					
		G-H			# 70		**120**	? 200	? 200	
		O-P					? 120	**200**	? 200	
		X-Y					# 120	**200**	**200**	? 200
	β–3	I-J			? 130 -280	**50**		? 50-100		
		A-B			? 60		**50**	? 160-200		
		K-L					# 50	# 200		
		C-D			? 120		? 50	# 100		
		M-N			? 220		# 50			
		E-F			? 150		**100**	? 60 -200		
		G-H			# 80		**120**	# 200		
		O-P						? 200		
γ	γ–1	A-B				# 70		# 90 - 200		
		K-L						# 120		
		C-D				# 20		# 180		
		M-N			# 350	? 70				
		E-F			? 80	**80**		# 120		
		G-H			? 120	**80**		# 200		
		O-P			# 20	# 20		# 60		
	γ–2	K-L				# 60		? 200		
		C-D			? 20	**80**		# 180		
		M-N			? 150	? 80				
		E-F			# 110	**60**		# 120		
		G-H			# 20					
δ	δ–1	I-J		?	? 300					
	δ–2	A-B				**30 - 70**				
	δ–3	A-B			# 300	70		? 100		
		K-L			? 140	**60**		# 140		
		C-D				? 70		# 80		
		M-N			? 350	# 70		# 20		
	δ–4	K-L			# 200	**80**		? 80		
		C-D			# 60	**80**		# 50		
		M-N				# 60		# 80		
	δ–5	C-D	?	**40**	? 150					
		M-N	? 400	**50**	? 120					
	δ–6	E-F	? 180	**140**	? 300					
		G-H			? 300					

Gothic : confirmed thickness, # : bounded by fault, ? : estimated

Wasserburg, 1985), but the age is inconsistent with the fossil age. The Abbottabad Formation unconformably overlies the Precambrian Hazara Formation (Baig *et al.*, 1988). Thus, the Upper Unit of the Sirban Dolomite Member is assigned to the Early Cambrian, but the main part of the Abbottabad Formation may be part of the Late Precambrian (see discussion).

1) Lower Unit

Distribution: The unit is distributed in the southwestern part of the study area, around Mirpur (Fig. 10).

Thickness: $200m^{+}$thick (Table 3). The base of the unit is not exposed in the study area.

Lithology: The Lower Unit is characterized by medium- to thick-bedded alternations of grey to dark grey dolomite and pink-colored dolomite, intercalated with thin sandstone. The grey to dark grey dolomite predominates over the pink-colored dolomite. The dolomites are hard and micritic, displaying chop-board weathering surfaces. XRD analysis indicates that the pink-colored dolomite consists mainly of ferroan dolomite (Aslam and Kaneda, 1993). In the grey to dark grey dolomite, especially in weakly dolomitizaized portions, cyanobacterial mats are recognized (Fig. 4a). The chemical composition of the grey-colored dolomite is shown in Table 2. Assuming that the loss of ignition (LOI) represents CO_2, the chemical composition of this sample indicates that it consists of 97.02% dolomite, with minor amounts of CaO and MgO, probably derived from other silicate minerals. Furthermore, thin sandstone beds are intercalated in the upper part of this unit. The sandstone is a fine- to medium-grained quartzose sandstone, and displays a beige color on fresh portion and a brownish grey color on the weathered surface.

2) Middle Unit

Distribution: The unit is mainly distributed in the southwestern part of the study area, around Mirpur. Small outcrops are also recognized to the north of Mohara (Fig. 10).

Thickness: 200m thick (Table 3).

Lithology: This unit consists of medium- to thick-bedded alternations of dolomite, dolomitic sandstone and quartzite. The unit is subdivided into the lower and upper parts. The lower part is dominated by whitish grey to grey dolomite, whilst the upper part is prevailed by brown-colored dolomitic sandstone and quartzite. The dolomite is micritic. The dolomitic sandstone is medium- to coarse-grained, occasionally showing cross-bedding (Fig. 3e) and protruded weathering surfaces. The base of the upper part is marked by a 20 m-thick band of medium- to thick-bedded quartzite, which is of creamy white color and fine- to medium-grained.

The mineral species composing the dolomite and dolomitic sandstone units identified by XRD, consist predominantly of dolomite, ferroan dolomite, with small amounts of quartz and calcite (Aslam and Kaneda, 1993). Under the microscope, the dolomite and dolomitic sandstone are composed of quartz angular to sub-angular grains dispersed in a matrix of dolomite with minor amounts of goethite, hematite, and calcite (Fig. 4b). Altered minerals such as chlorite and sericite are also found. Petrographically the quartzites display a perfect mosaic texture, and are fine- to medium- grained (Fig. 4c). A few microcline and tourmaline grains are observed in quartzites. The chemical composition of three samples from the unit are shown in Table 2. Assuming that the loss of ignition (LOI) represents CO_2, a norm- calculation of sample KA-11 indicates that it consists of 60.97% quartz, 11.08% dolomite, and 22.49% calcite, with minor remnants of CaO and MgO, probably derived from other silicate minerals. Similarly, sample KA-13 is composed of 72.39% quartz and 24.37% dolomite with a minor amount of unconsumed CaO derived from other minerals, while sample KA-12 comprises 95.91% quartz, and less than 1% dolomite and calcite.

3) Upper Unit

Distribution: The Upper Unit is widely distributed throughout the map area (Fig. 10).

Thickness: 200m thick (Table 3).

Lithology: The Upper Unit is the most important phosphorite-bearing rock unit. The unit is composed of medium- to thick-bedded, grey to light grey dolomite interbedded with chert layers. The chert layers vary in thickness from 3 to 35cm (Fig. 5), at times display lenticular shape, and have protruded weathering surfaces (Fig. 3a). Petrographically, the chert consists of micro-quartz, without biological features (Fig. 4e). The dolomite features typical chop-board type of weathering. At times thin intercalations of purple- to chocolate-colored siltstone are found within the dolomite. Examination of the dolomite by XRD exhibits dolomite, ferroan dolomite, calcite, quartz, and phosphorite minerals (Aslam and Kaneda, 1993). The dolomite

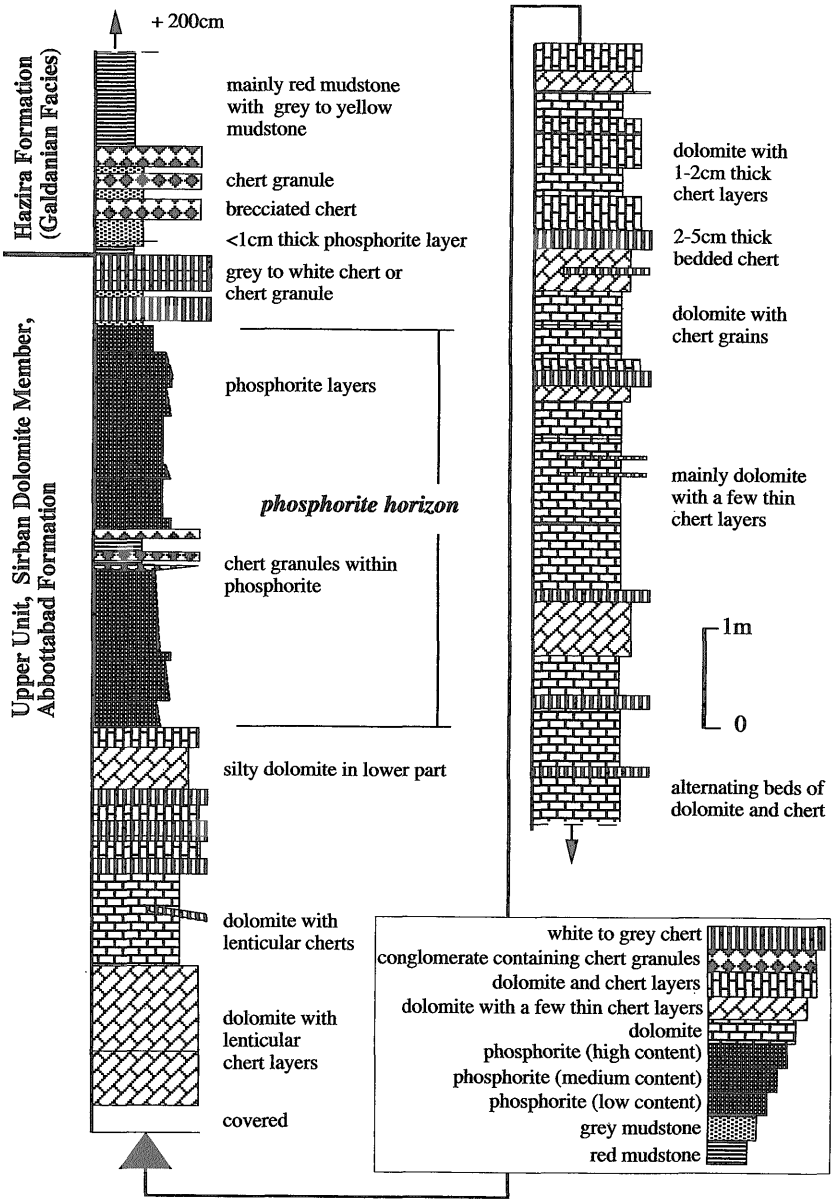


Fig. 5 A columnar section of the KM-I Section, Kakul Mine, showing lithologic change from the Abbottabad Formation to the Galdanian Facies of the Hazira Formation. Location of the section is shown in Fig. 7.

consists of fine-grained dolomite, with minor amounts of quartz, hematite, goethite, and calcite (Fig. 4d). The chemical composition of the dolomite is shown in Table 2. A norm-calculation indicates that it consists of 10.53% quartz and 88.04% dolomite with minor remnants of CaO and MgO, probably derived from other silicate minerals.

At least three to four sedimentary phosphorite horizons are intermittently traceable in the upper part of this unit (Figs. 2 and 10). A detailed stratigraphic column showing the uppermost horizon of phosphorite in the unit is given in Fig. 5. Each of the phosphorite horizons, ranging in thickness from 1 to 5m thick, is composed of 1 to 15cm thick phosphorite beds intercalated with dolomite (Fig. 3f), chert, and conglomerate. The conglomerate consist of angular to subangular chert grains dispersed in a dolomite matrix (Fig. 3d). All of the phosphorite deposits display characteristic pelletal and oolitic textures. The pellets and oolites vary in size from 0.1 to 1mm in length and 0.2 to 0.5mm in width. The oolites are often composite. The phosphate content in both the phosphorite layers and associated dolomites varies from place to place ranging from a minimum of 1 to 5% to a maximum 50% or grater (Latif, 1974 b; Hasan and Ghaznavi, 1980; Hasan, 1986; 1989; Husain *et al.*, 1990).

3.3 Hazira Formation (Gardezi and Ghazanfar, 1965; redefined by Shah, 1977)

Name: The formation is named after the village of Hazira, located in the northwestern part of the study area.

Historical background: The Hazira and Hematite Formations were introduced by Gardezi and Ghazanfar (1965) for the mudstone dominant unit between the Abbottabad and Samana Suk Formations. Only the Hazira Formation however has been approved for the unit by the Stratigraphic Committee of Pakistan (Shah, 1977; Table 1). Ghaznavi *et al.* (1983) and Hasan (1986; 1989) recognized two facies within the formation, the Hazira Facies for the grey mudstone and sandstone dominant sequence, and the Galdanian Facies (equivalent to the Hematite Formation by Gardezi and Ghazanfar, 1965) for the hematitic red mudstone dominant sequence (Table 1). We support the opinion of Ghaznavi *et al.* (1983) and Hasan (1986; 1989).

Stratotype: The type section has been chosen near the village of Hazira in the northern part of the study area (Gardezi and Ghazanfar, 1965; Shah, 1977).

Lithofacies: The formation consists mainly of weakly undulated mudstone and sandstone, so that it forms valleys and saddles as shown in Fig. 3h. As indicated above, the formation has two facies: Hazira and Galdanian Facies (Table 1; Fig. 2). The two facies are generally separated from each other by faults (see Fig. 10), however a lateral lithologic change is observed between both facies near Riala (Fig. 6). Figure 6 shows the interfingering relation ships between the red mudstone of the Galdanian Facies, and the grey mudstone and sandstone of the Hazira Facies.

Distribution: The formation is widely distributed throughout the area (Fig. 10).

Thickness: 50 to 140m thick for the Hazira Facies and 50 to 80m thick for the Galdanian Facies (Table 3).

Lithology: The Hazira Facies is composed of dark grey to greenish brown, finely-laminated calcareous mudstone and siltstone in the lower part (Fig. 3g) and dark grey-colored, very fine-grained sandstone in the upper part. The mudstone and siltstone are flaggy, with intercalation of thin glauconite layers (Fig. 3g). The glauconites are pelletal in shape and range in length from 0.1 to 1mm (Fig. 4f). The sandstone is dark grey- to brown-colored and blocky on weathered surfaces. The siltstone and sandstone consist fine-grained aggregates of quartz, calcite, and small amounts of hematite and mica in a clayey matrix (Fig. 4 h).

The Galdanian Facies is characterized by red- and chocolate-colored hematitic mudstone and siltstone in the lower part and grey to reddish brown, fine- to medium-grained quartzite in the upper part. Massive, hard breccias occasionally occur in the upper part, and are composed of cherty to quartzitic fragments in a matrix of red siltstone. The hematitic mudstone occasionally contains concentrations of worm burrows (Fig. 3b). A few phosphorite layers are intercalated in the lower part of the Galdanian Facies near Galdanian (Fig. 10). The phosphorites are microscopically similar to those in the Sirban

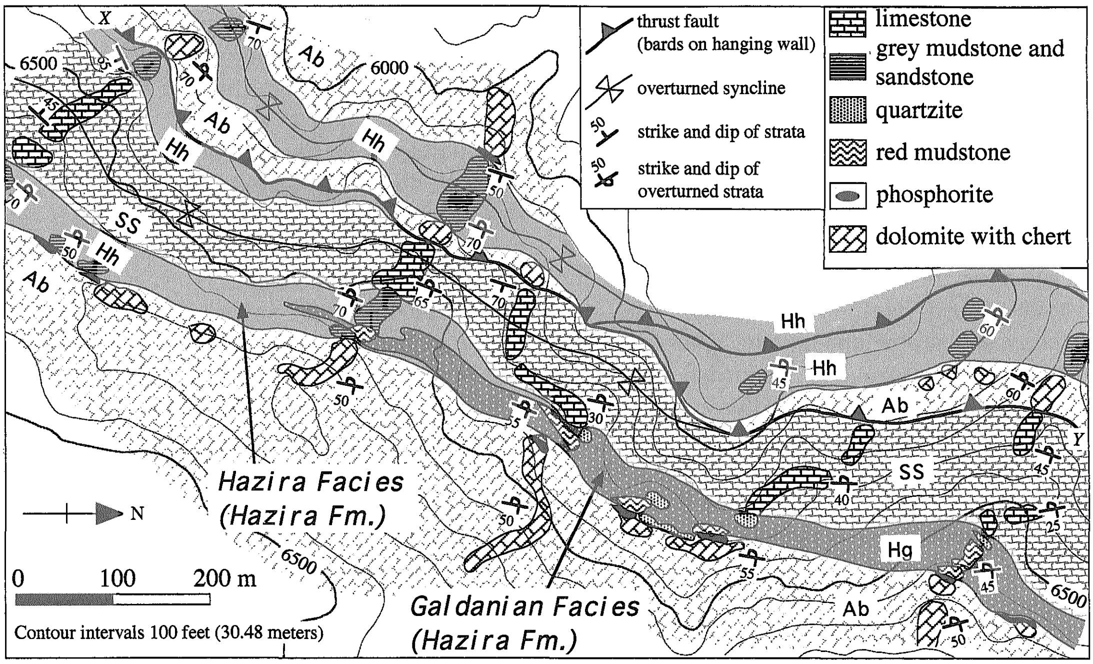


Fig. 6 Traverse map near Riala showing the interfingering relationship between the Hazira and Galdanian Facies of the Hazira Formation. Red mudstone represents the Galdanian Facies laterally changing into grey mudstone and sandstone in the central part of the figure. A thrust running from "X" to "Y" bounds the structural sub-Domain β-2 on the west from β-3 on the east. Location of the map is shown in Fig. 7. Ab, Sirban Dolomite Member of the Abbottabad Formation; Hh, Hazira Facies of the Hazira Formation; Hg, Galdanian Facies of the Hazira Formation; SS, Samana Suk Formation.

Dolomite Member. Petrographically, the red mudstones are highly oxidized, and include quartz grains in a matrix of hematite and goethite, chlorite, glauconite, and sericite (Fig. 4g).

Chemical compositions indicate that rocks of the Hazira Facies are richer in SiO_2 and poorer in Fe_2O_3 than those of the Galdanian Facies (Table 2). Although rhyolite has been reported from the formation (Middlemiss, 1896; Marks and Ali, 1961; Hasan and Ghaznavi, 1980), no evidence of volcanic material was found in the formation in the study area.

Stratigraphic relationship: The formation disconformably overlies the Abbottabad Formation (see discussion).

Age: Early Cambrian phosphatic fossils including *Allonnia tripodophora* are found in the lower part of the Hazira Facies of the Hazira Formation in the Sarbun Hill area (Latif, 1972 b; Fuchs and Mostler, 1972; Rushton, 1973). As a result, the lower part of the formation is assigned to the Early Cambrian.

3.4 Samana Suk Formation (Fatmi, 1977)

Name: The formation name is derived from the Samana Range in the North West Frontier Province.

Stratotype: The type section is in Shinawari, Samana Range.

Distribution: The formation is widely distributed in the study area (Fig. 10).

Thickness: $350m^{+}$thick (Table 3). In the type section, the formation is 190 to 366m thick (Iqbal and Shah, 1980).

Lithology: The formation consists of thick-bedded fossilferous limestone and oolitic limestone with dolomite, calcareous sandstone, and ferruginous sandy limestone. The base of the formation is marked by a 5m-thick, whitish grey, very fine-grained quartzite beds, intercalated with calcareous sandstone. The quartzite exhibits a mosaic texture under the microscope (Fig. 4i). The fossilferous and oolitic limestones are light to dark grey and micritic. They include a large quantity of shell debris and gastropods with minor amounts of detrital quartz and feldspar grains (Fig. 4j). The limestone beds range in thickness from 10 to 30cm or more, and are characterized by groove-shaped weathering surfaces. The calcareous sandstone and sandy limestone are medium to fine-grained, yellowish brown in color, interbedded with fossilferous limestone (Fig. 3c), and occasionally shows graded bedding and cross-laminations. The calcareous sandstone bed varies between 1 and 10cm in thickness. Intense bioturbation has transformed the sandstone intercalations to yellow-colored patches scattered in a grey-colored matrix of limestone.

Stratigraphic relationship: The Samana Suk Formation unconformably overlies the Hazira Formation. Despite a large time gap, the boundary surface between the Hazira and Samana Suk Formations is nearly parallel to the bedding planes of both formations.

Age: Well preserved micro- and mega-fossils are found in the study area. The formation has been assigned to the Middle Jurassic (Fatmi, 1977).

3.5 Chichali and Lumshiwal Formations (Fatmi, 1977)

Name: The formation names are derived from the names of a pass located in the Surghar Range, and a nala (river) in the Salt Range, Punjab Province, respectively.

Stratotype: Type sections of the formations are located in the Chichali Pass, Surghar Range, and the Lumshiwal Nala, Salt Range, respectively.

Historical background: The Chichali and Lumshiwal Formations in the study area were described as the Spiti shale and Giumal sandstone by Latif (1970). Calkins *et al*. (1975) and Hasan and Ghaznavi (1980) combined both formations into one unit, because they are not very thick in the area. We follow the opinion of these.

Distribution: The formations are exposed near Lagarban, Maira, and Balolia in the western part of the study area (Fig. 10).

Thickness: 40 to 50m thick in Maira and 140 m thick in Balolia (Table 3).

Lithology: The Chichali and Lumshiwal Formations consist predominantly of glauconitic sandstone, associated with minor nodular silty calcareous phosphorite and glauconitic sandy mudstone. The sandstone is greenish grey to light grey in color, soft, and massive. The sandy mudstone is black to grey, very soft, and massive.

Stratigraphic relationship: The Chichali Formation conformably overlies the Samana Suk Formation.

Age: Poorly preserved ammonites and belemnites are found in the sandy mudstone. The formations are assigned to the Tithonian (Latest Jurassic)-middle Albian (Early Cretaceous) by Fatmi (1977).

3.6 Kawagarh Formation (Fatmi, 1977)

Name: The formation is named after a hill located in Punjab Province.

Stratotype: The type section is in Kawagarh Hill, Punjab Province (Fatmi, 1977).

Historical background: The Kawagarh Formation in the study area was originally designated the Chanali limestone by Latif (1970). Subsequently, Calkins *et al*. (1975) and Hasan and Ghaznavi (1980) correlated this unit with the Kawagarh Formation.

Distribution: The formation is distributed in the eastern part of the study area (Fig. 10).

Thickness: $400m^{+}$thick (Table 3).

Lithology: The formation is composed largely of thin- to thick-bedded, brownish grey to grey limestone, intercalated with sandstone. As mentioned by Hasan and Ghaznavi (1980), it is rather difficult to distinguish in the field the Kawagarh Formation from the Samana Suk Formation. The Kawagarh Formation however lacks the yellow patches, the layers of bioturbated sandstones and the oolites characteristic of the Samana Suk Formation.

Stratigraphic relationship: Though the relationship between the Kawagarh Formation and the underlying Chichali and Lumshiwal Formations seems to be conformable, Hasan and Ghaznavi (1980) regarded it as disconformable on the basis of missing fossils representing Cenomanian and Turonian.

Age: Latif (1970) reported foraminifers ranging in age from the late Coniacian to Campanian (Late Cretaceous).

4. Structure

The study area is located between two major faults, the Panjal Thrust to the NNW and the Nathia Gali Thrust to the SSE (Fig. 1). Metamorphic and sedimentary sequences in the study area were strongly deformed yielding complicated structure. To date, the complicated structure has been attributed to the presence of a major syncline associated with a number of minor thrust faults (Calkins *et al.*, 1975; Hasan, 1986; etc.). However, we recognized in the study area the development of large-scale stacked thrust sheets (Figs. 10 and 11). Folds are mostly developed in relation to thrusting, but some deformed the thrust sheets. The study area is subdivided from west to east into four major domains (thrust sheets), namely the Domain α, β, γ, and δ, based on the amount of phosphorite and facies characteristics of the Hazira Formation. The Domains are separated by the Nare Di Gali, Kakul, and Galdanian Faults, which are newly proposed in this study. A simplified structural map showing the distribution of structural domains and major faults and folds is given in Fig. 7.

4.1 Fault

In the study area, the sequence of the Abbottabad, Hazira, and Samana Suk Formations is repeated several times by layer-parallel to -subparallel thrusts (Figs. 7, 10 and 11). An example of the repetition of the sequence is shown in Figs. 3h and 6. Thrust faults in the northern and southeastern parts generally strike NNE-SSW and dip moderately to steeply, whilst in the southwestern part they strike NW-SE to E-W, and dip moderately to the north. The attitude of the thrust faults generally coincides with that of the two major faults, the Panjal and the Nathia Gali Thrusts. There are some thrusts obviously truncating bedding with an angle of less than 30°. Several high-angle normal faults, which generally strike E-W, are also recognized in the study area. The normal faults clearly cut the thrust faults, as indicated in Maira and Gali Beha (Figs. 7 and 10). Major faults separating the structural domains are described below.

1) Panjal Thrust (Calkins and Martin, 1968)

The Panjal Thrust, which is one of the most important thrust faults in the Hazara Arc, separates the Hazara and Tanawal Formations in the hanging wall from Precambrian (?) to Cretaceous sedimentary rocks in the foot wall. The fault is known by various names such as the Panjal Thrust (Calkins and Martin, 1968; Latif, 1970; 1974b; Yeats and Hussain, 1987), Tarnawai Fault (Hasan and Ghaznavi, 1980), and Tarnawal Fault (Hasan, 1986; 1989).

In the southwestern part of the study area, the Panjal Thrust strikes NW-SE to E-W, and dips moderately to the north. The trend of the thrust abruptly changes to NNE-SSW or N-S in the northern part of the area (Fig. 10). Thus, the thrust forms a convex shape toward the south. Moreover, the thrust has been entirely overturned towards the west in the northern part. The thrust plane observed along a road side exposure in Tarnwai strikes N 60°E, and dips 60° SE. At this location, the Hazara and Tanawal Formations appears to be at the foot wall of a normal fault. However, the younger sequence distributed to the east of the fault is totally overturned (A-B section in Fig. 11). Therefore in the northern part of the field, this fault plane is considered to have been overturned to the west along with the overlying rock sequence.

2) Nare Di Gali Fault (newly proposed)

The fault is located to the south of the southward convex of the Panjal Thrust and bounds Domain α to the north from Domain β to the south. The fault plane gently dips north, and is nearly parallel to the bedding planes of both the hanging and foot walls (cross section G-H in Fig. 11). The Nare Di Gali Fault plane has been truncated by a NNE -trending thrust fault, and folded into open

Table 4 Comparison of the characteristic features of the four structural domains.

Domain	α	β	γ	δ
Abundance of phosphorite	very poor	abundant	moderate (Kakul Mine)	none
Facies type of Hazira Formation	Galdanian Facies	Hazira Facies partly Galdanian Facies	Galdanian Facies	Galdanian Facies
Fold type	open	open (southern part) tight (northern part)	tight	tight and open

folds (cross sections E-F and G-H in Fig. 11).

3) Kakul Fault (newly proposed)

The fault bounds the Domain β from Domain γ. The fault runs in a NNE-SSW direction and dips moderately to steeply to the northwest. The Kakul Fault is oblique to the Panjal Thrust in the southern area, but turns to be parallel to it northward.

4) Galdanian Fault (newly proposed)

The Galdanian Fault separates Domain γ to the west from Domain δ to the east. The fault plane steeply dips to the east or west. In the northern part of the area, the fault joins with the Kakul Fault.

4.2 Fold

Two types of folds are recognized in this area: tight and open folds. Tight folds are developed in the eastern and northern parts of the study area, and show asymmetrical profiles. The half wavelength of the folds varies from 100 to 300m. Their fold axes are generally parallel to the thrust planes in the northern part, trending NNE-SSW, but are oblique to the thrust planes in the southern part. The eastern or southeastern limbs of folds are mostly truncated by thrust faults. Their fold axes plunge moderately to the north or south. The fold axial planes dip to the east or west (cross section A-B in Fig. 11).

Open folds are recognized in the southwestern part of the area, and display symmetrical profiles with mostly vertical axial planes. Their full wavelength is about 500 to 1000m (cross-section G-H in Fig. 11). Their axes plunge gently to the north. The open folds have obviously deformed the Panjal Thrust and Nare Di Gali Fault.

4.3 Structural domain

1) Domain α

Domain α is sandwiched between the Panjal Thrust and the Nare Di Gali Fault. It is marked by the very poor occurrence of phosphorite, the predominance of the Galdanian Facies in the Hazira Formation, and the development of open folds. The domain is further subdivided by a thrust into two sub-domains: α-1 and α-2.

2) Domain β

Domain β is characterized by the abundance of phosphorite deposits and the prevalence of the Hazira Facies. Tight folds are developed in the northern part of the domain, while open folds are observed in the southern part. The domain is subdivided by thrust faults into three sub-domains: β-1, β-2, and β-3.

3) Domain γ

Domain γ is marked by the moderate development of phosphorite deposits including the Kakul Mine, the predominance of the Galdanian Facies, and tight folds. The domain is further divided into two sub-domains: γ-1 and γ-2.

4) Domain δ

Domain δ is featured by the lack of phosphorite, the predominance of the Galdanian Facies, and the development of tight folds. The domain is subdivided into six sub-domains δ-1 to δ-6.

5. Discussion

5.1 Correlation of the Precambrian to Cambrian formations with counterparts of China, India, and Iran

Both the Abbottabad and Hazira Formations have been assigned to the Early Cambrian based on fossil evidence (Shah, 1977; etc.). However, fossils are found in a few limited horizons: the Upper Unit of the Sirban Dolomite Member, Abbottabad Formation,

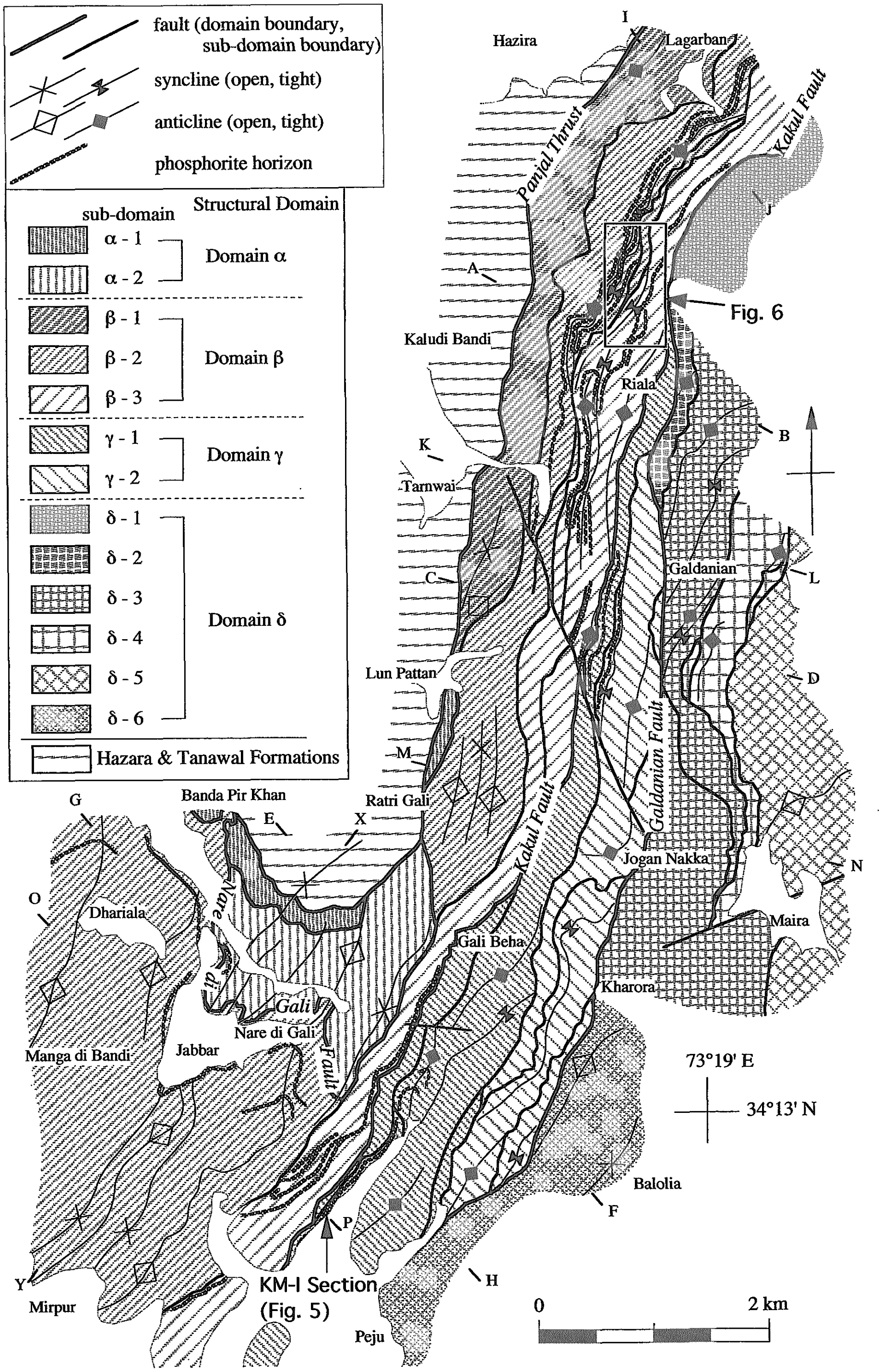


Fig. 7 Diagram showing the distribution of structural domains in the study area.

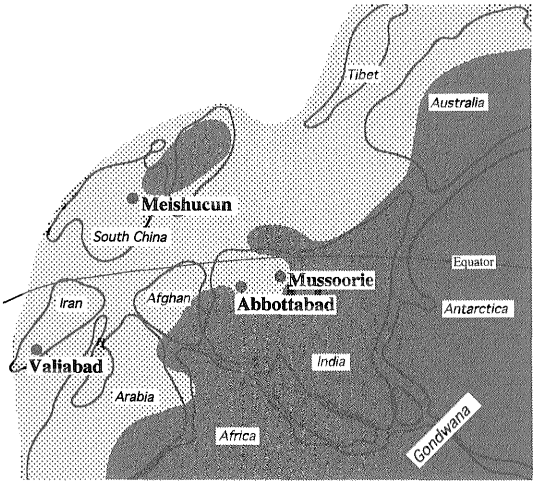


Fig. 8 Early Cambrian paleogeography around the Indian sub-continent showing major phosphorite occurrences (solid circles). Dark shading = land, light shading = shelf. Modified from Parrish *et al.* (1986), Aharon *et al.* (1987), McKerrow *et al.* (1992), Brasier (1992), and Dalziel *et al.* (1994).

and the lower part of the Hazira Formation. Therefore, precise ages of both formations and the Precambrian/Cambrian boundary have not been determined. In this section, we discuss the ages of both formations based on lithostratigraphical correlation with a Chinese section, where the age has been studied greater.

A remarkable facies change from a carbonatic to a clastic formation is recognized at the boundary between the Abbottabad and Hazira Formations (Fig. 2). A accompanying the facies change is the formation of phosphorite, and hematitic and glauconitic mudstones. Similar lithologic changes from calcareous to clastic sediments with phosphorite have been recognized along the northern margin of the Gondwanaland from China to Iran, occurring the transitional period from Precambrian to Cambrian age (Figs. 8 and 9; Cook and Shergold, 1986; Brasier, 1989). In the Meishucun section in China, which represents a standard section of the Gondwana region, the lithostratigraphy and biostratigraphy of the Precambrian and Early Cambrian sequence has been studied in detail (see Brasier, 1989). This sequence is divided into six bio-zone, Chinese Bio-Zones 0 to V (Brasier, 1989), and the Precambrian/Cambrian boundary is placed at the base of Zone I (Landing, 1994; Fig. 9).

The lithostratigraphic and biostratigraphic correlation between the northern margin of Gondwana (China, India, and Iran) and the study area is demonstrated in Fig. 9. The Sirban Dolomite Member, which is characterized by the dominance of dolomite with phosphorite, is lithostratigraphically correlative with the succession from Zones 0 to II in China. A noteworthy point is that chert layers are frequently intercalated in the Upper Unit of the Sirban Dolomite Member and the sequence of Zones I and II in China, which corresponds to the Earliest Cambrian (Brasier, 1989; 1990). Phosphatic fossils from the Upper Unit of the Sirban Dolomite Member indicates an Early Cambrian age (Shah, 1977). Thus, the Upper Unit of the Sirban Dolomite Member is confidently correlated with the sequence of Zones I and II in China. The lithostratigraphic correlation suggests that the Precambrian/Cambrian boundary represented by the base of the Chinese Bio-Zone I is placed within the Sirban Dolomite Member. Although no fossil evidence indicates the exact horizon of the boundary, the main part of the Abbottabad Formation may range down to the Late Precambrian.

In contrast, a Sm-Nd age of 610±30 Ma has been reported from the phosphorite of the Upper Unit of the Sirban Dolomite Member (Shaw and Wasserburg, 1985). The age of the Precambrian/Cambrian boundary was estimated at 570 Ma (Harland *et al.*, 1990; Yang *et al.*, 1996) or 544 Ma (Brasier *et al.*, 1994). The radiometric age suggest a Precambrian age for the Upper Unit of the Sirban Dolomite Member, however the radiometric age is not accepted because of the Cambrian fossil age and the lithostratigraphic comparison with the Chinese section discussed above.

The Hazira Formation in the study area is correlated with the sequence of Zones III to IV in China based on lithostratigraphic similarity (Fig. 9). Both sections are characterized by

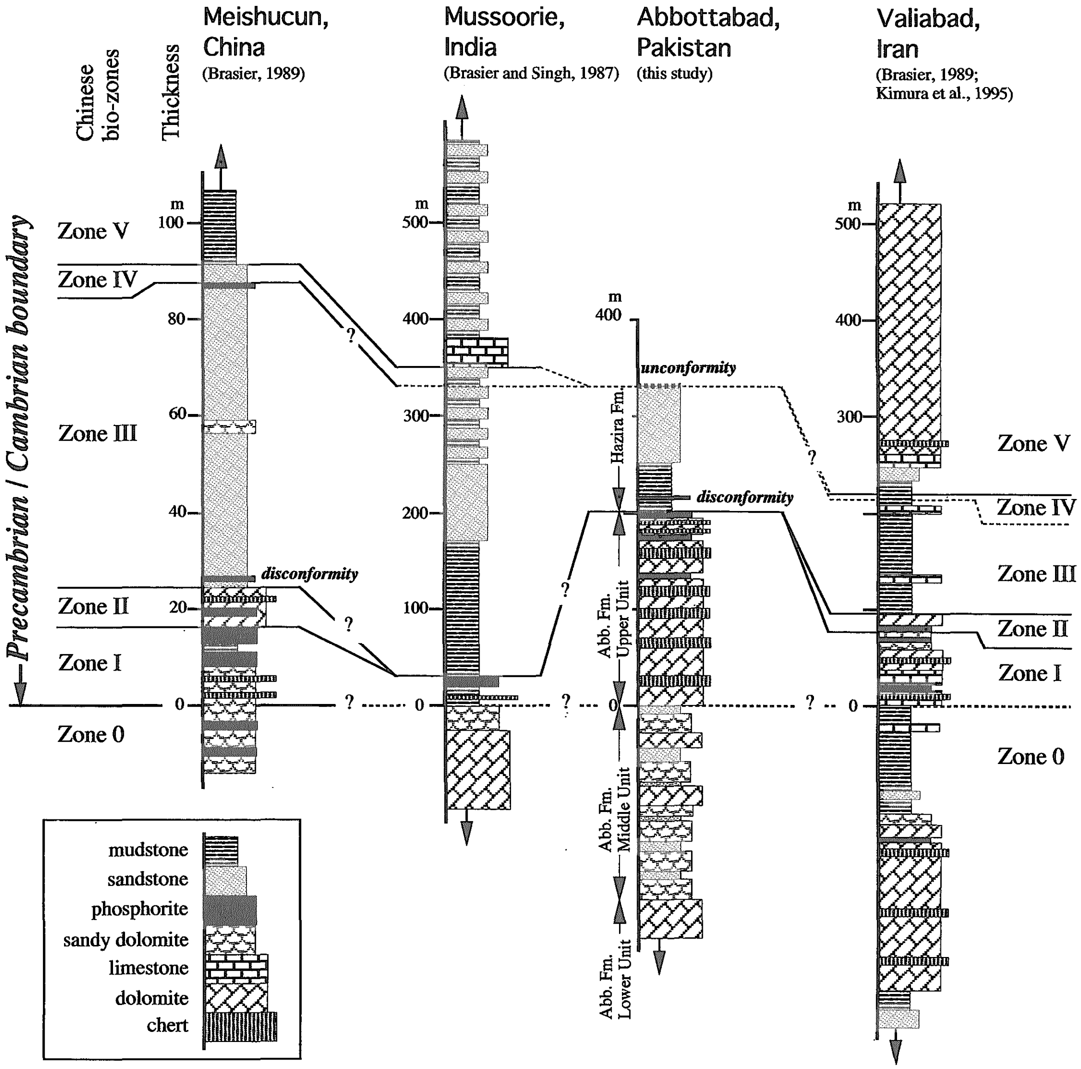


Fig. 9 Generalized stratigraphic columns of the Precambrian-Cambrian transition sections in Meishucun, China (Brasier, 1989), Mussoorie, India (Brasier and Singh, 1987), Abbottabad, Pakistan (this study), and Valiabad, Iran (Brasier, 1989; Kimura *et al.*, 1995). All localities are shown in Fig. 8. The biostratigraphic correlation between the Chinese bio-zones and each sections is according to Brasier (1989).

the dominance of mudstone and sandstone. The fauna from the lower part of the Hazira Formation (Latif, 1972b; Fuchs and Mostler, 1972; Rushton, 1973) also supports the litho-stratigraphic correlation with the Zones III to IV Early Cambrian age (Brasier, 1989). Thus, the Hazira Formation is assigned to the Early Cambrian.

5.2 Stratigraphic relationship and environmental change between Abbottabad and Hazira Formations

The stratigraphic relationship between the Abbottabad and Hazira Formations has been argued over the years (Table 1). Hasan and Ghaznavi (1980) and Hasan (1986) regarded the relationship as conformable based on the structural concordance between both formations. Whilst Latif (1974a), Marks and Ali (1961), and Ashraf and Chaudhry (1987) regarded it as disconformable or unconformable based on the abrupt lithological change from calcareous to clastic sediments.

We regard the relationship as disconformable based on the following criteria: (i) an abrupt facies change between the Abbottabad and Hazira Formations, (ii) the occurrence of glauconite, indicative of a sedimentary break at the base of the Hazira Formation, (iii) the close similarity in the lithostratigraphic sequence with the Meishucun section in China (Fig. 9).

The lithologic change from calcareous to clastic sediments recognized along the northern margin of Gondwanaland at the Precambrian/Cambrian boundary has been explained to have been caused by a global environmental change (Cook and Shergold, 1986; Brasier, 1989; 1992, etc.). Brasier (1992) suggested that a change from icehouse condition in the Precambrian to a greenhouse condition in the Cambrian triggered a widespread transgression, which brought un-mixed, nutrient rich bottom waters onto the shelf and triggered the formation of phosphorite and ferruginous mudstone. The facies change from the Abbottabad to Hazira Formations and its close association with the formation of phosphorite and ferruginous sediments probably represents the widespread rapid transgression that occurred in the Early Cambrian along the northern margin of Gondwana including the study area.

5.3 Significance of the Structural Domain

As previously mentioned, the study area is divided into four structural domains. It is noticeable that the phosphorite deposits are abundant in Domain β, characterized by the Hazira Facies of the Hazira Formation, whereas the Galdanian Facies-dominated domains are generally poor in phosphorite (Table 4). Thus, the trace of each domain provides basic information useful for the exploitation of phosphorite deposits.

The formation of phosphorite and ferruginous sediments were probably caused by the widespread rapid transgression as discussed above. However, the differences in abundance of phosphorite and the lithologic facies of the Hazira Formation in each domain are probably due to differences in local depositional environments. Details of the local depositional setting and dislocation of each domain-bounded faults should be further studied.

The structural domains were bent by open folds in the southern part, whereas they were overturned in the northern area (Figs. 10 and 11). Two schools of interpretations have been proposed to explain the bending and overturning. In Coward and Butler (1985) and Butler and Coward (1989), who studied the structure of northern Pakistan, argued that gently dipping thrusts could turn and overturned through the mechanism of a passive back-rotation due to an obstacle in the frontal part of the thrust sheets. In contrast, Bossart *et al*. (1984; 1988) proposed that the Hazara-Kashmir Syntaxis was generated by at least two phases of tectonic movements: first, the formation of a series of thrust sheets, followed by the secondary deformation of these thrust sheets by a left-lateral shearing. The structural investigations in the study area support the interpretation by Bossart *et al*. (1984; 1988). The mechanism proposed by Coward and Butler (1985) and Butler and Coward (1989) cannot change the trend of the thrusts, which was caused by folding.

6. Conclusions

On the basis of detailed geologic mapping, we have described the lithostratigraphy and structure of the Precambrian, Precambrian (?) to Lower Cambrian, and Jurassic to Cretaceous systems in the Abbottabad area. The following facts have been clarified:

(1) The Sirban Dolomite Member in the upper part of the Abbottabad Formation is subdivided into three units: the Lower, Middle and Upper Units.

(2) The Hazira Formation consists of the two facies, the Hazira and Galdanian Facies.

Both facies laterally change.

(3) The economically important phosphorite deposits are recognized in at least three levels in the upper part of the Upper Unit of the Sirban Dolomite Member. Thin phosphorite beds also occur in the lower part of the Galdanian Facies of the Hazira Formation. The phosphorite horizons are variable in thickness, reaching a maximum of 5m.

(4) The map area is characterized by many thrust sheets, and is divided into four major domains: Domain α, β, γ, and δ. Two types of folds, open and tight are recognized in the area. The open folds deformed the domain bounded faults.

(5) The Sirban Dolomite Member of the Abbottabad Formation and the Hazira Formation are lithostratigraphically correlated with the sequence of Zones 0 to II (Precambrian to Early Cambrian) and Zones III to IV (Early Cambrian) in China, respectively.

(6) The stratigraphic relationship between the Abbottabad and Hazira Formations is disconformable based on the abrupt lithological change from carbonatic facies to clastic facies. This change is associated with the deposition of phosphorite and ferruginous sediments, indicating a widespread rapid transgression along the northern margin of Gondwana.

(7) Many phosphorite deposits are recognized in the Hazira facies dominated domain, Domain β. On the other hand, the Galdanian Facies-dominated domains, Domain α, γ, and δ, are generally poor in phosphorite.

(8) The overturning and bending of the structural domains in the study area indicate two phases of tectonic movements: thrusting to form a series of thrust sheets, followed by deformation of the thrust sheets probably related to the formation of the Hazara - Kashmir Syntaxis.

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パキスタン国北部，アボッタバート地域の先カンブリア系－中生界，特に含リン灰石先カンブリア系（？）－下部カンブリア系，の層序と構造

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要　旨

パキスタン国北部，アボッタバード地域にはプレカンブリア系・プレカンブリア（？）-下部カンブリア系・ジュラ-白亜系が分布する．これらの層序と構造を本論で記載し，特にプレカンブリア(？)-下部カンブリア系を詳述した．

プレカンブリア(？)-下部カンブリア系は，主として炭酸塩岩と砕屑岩より成り，リン灰石層を挟む．下位よりアボッタバード層とハジラ層に区分される．アボッタバード層上部は，層厚約600mでシルバンドロマイト部層と呼ばれ，これはさらに下部・中部・上部の3ユニットに区分できる．下部と中部ユニットはそれぞれ，ミクライト質ドロマイトと，ドロマイトと石英質砂岩から構成される．上部ユニットはドロマイト中に多数のチャート層を挟むことで特徴づけられる．経済的に重要なリン灰石鉱床は，上部ユニットの上部に少なくとも3層準認められる．リン灰石層の厚さは様々であるが，最大で5mに達する．

ハジラ層は125mの厚さを持ち，アボッタバード層の上位に非整合関係で重なる．ハジラ層には，ハジラ相とガルダニアン相の2相が識別される．ハジラ相は，海緑石を含む石灰質泥岩と砂岩で特徴づけられ，ガルダニアン相は赤鉄鉱質赤色泥岩・シルト岩・チャート角礫岩からなる．リン灰石の薄層が，ハジラ層の下部に挟まれる．

調査地域は，多くのスラストシートの発達で特徴づけられ，主要な断層で境された4つの構造ドメイン，ドメインα・β・γ・δ，に区分することができる．2回の変形が本地域に認められる．それは最初の衝上運動と，続いてのスラストシートを曲げ，そして西向きに逆転させる運動である．リン灰石の産出は，ハジラ相の卓越するドメインβにおおむね限られ，他のドメインは通常リン灰石層に乏しい．

アボッタバード層とハジラ層の境界付近には，炭酸塩岩相から砕屑岩相への急激な岩相変化，リン灰石の形成と含海緑石・赤鉄鉱泥岩の堆積，という顕著な現象が観察される．このことは，2層の境界付近の時代において，急激な海進が，調査地域を含むゴンドワナ大陸北縁部で広範囲に生じた結果であると推察される．

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