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Lithofacies Interpretation of the Early Cambrian Abbottabad Formation, Thandiani, Pakistan

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1.0 Introduction:

The Early Cambrian Abbottabad Formation is exposed at Mera Rehmat Khan section (Thandiani), constitutes of a) Dolomite, b) Sandstone, c) Shales, and d) Conglomerate. At that particular section in Mera Rehmat Khan, the only lower part of Abbottabad Formation is exposed whose upper contact is conformable with SamanaSuk Formation. In the study area, about 80m of strata are covered by the lower part of Abbottabad formation and mainly composed of sandstone with subordinate shales, massive sandstone, as well as quartzite.

The Abbottabad Formation was named by Mark and Ali (1961)[1a] for a set of predominantly dolomitic rocks with subordinate siliceous and argillaceous rocks from the Sirban Hill, Abbottabad. Ali (1962)[1b] included similar lithologies exposed in the southern Tanawal region west of Abbottabad into the Abbottabad Formation. Calkins et al. (1975)[2], however, misinterpreted these lithologies to be of Triassic age and mapped them as Kingrialli Formation, a sandstone unit exposed in the Salt Ranges

Several studies have been performed to describe the various aspects of the formation such as Stratigraphic characterization of the Abbottabad formation and correlation with NW Himalayas by Qasim et al (2014) [3]; geotechnical properties of Cambrian dolomite by Khan et al(2018)[4]. Recently in 2019, Inam ur Rahim et al [5], describe the provenance of the Abbottabad formation through macro and microfabrics characteristics. However, the broad sedimentological and lithological work of the Early Cambrian Abbottabad Formation is still missing. Therefore, the present study has been adopted to interpret the lithofacies of the Early Cambrian Formation. Moreover, many sedimentary structures are also present that can be used to interpret the environment of deposition.

2.0 Geological History

The collision of the Indo-Pakistan and Eurasian Plate has been started at the end of the cretaceous about 65 million years ago that leads to the existing location of the Hazara area (Hazara Thrust and Fold Belt [6]. At the beginning of the Cretaceous, the Indo-Pakistan subcontinent was present in Gondwana Region and located near Australia, Africa, Antarctica, and southern America. The uplifting of the Himalayas took place after World Plate kinematics resulted in the reconstruction of present-day Himalayan landmass including the Indo-Pakistan subcontinent which subsided below Eurasia. During the Journey of the Indo-Pakistan Plate from the South towards the North gave rise to the close of Pangea and trigger an island arc i.e. Kohistan Island Arc in Pakistan [7]. The Kohistan Island Arc kept its igneous activity for about 45 million years, after this magmatism back-arc basin was finally closed and Kohistan Island Arc was accreted onto Eurasia. In this way, the Andean Plate margin was emanated. Finally, Powell [8], described a speculative tectonic history of Pakistan and consociated main boundaries from north to south, which is controlled by major faults and portraying various tectonic forces and stratigraphic succession.

The area of study is located exactly between the Main Boundary Thrust (MBT) in the south and the Panjal Thrust in the north (Figure 1). The Metamorphic, meta-sedimentary, and sedimentary rocks aging from Pre-Cambrian to Miocene are exposed in the Hazara Basin. Structurally, Hazara Basin is located in a compressional tectonic regime, with many thrusts, small and large scale folds, and their overall north-east, south-west trend illustrating compressive stresses coming from northeast direction [3]. A generalized geological map elaborating major faults and tectonic regions modified from [9], is shown in figure 1.

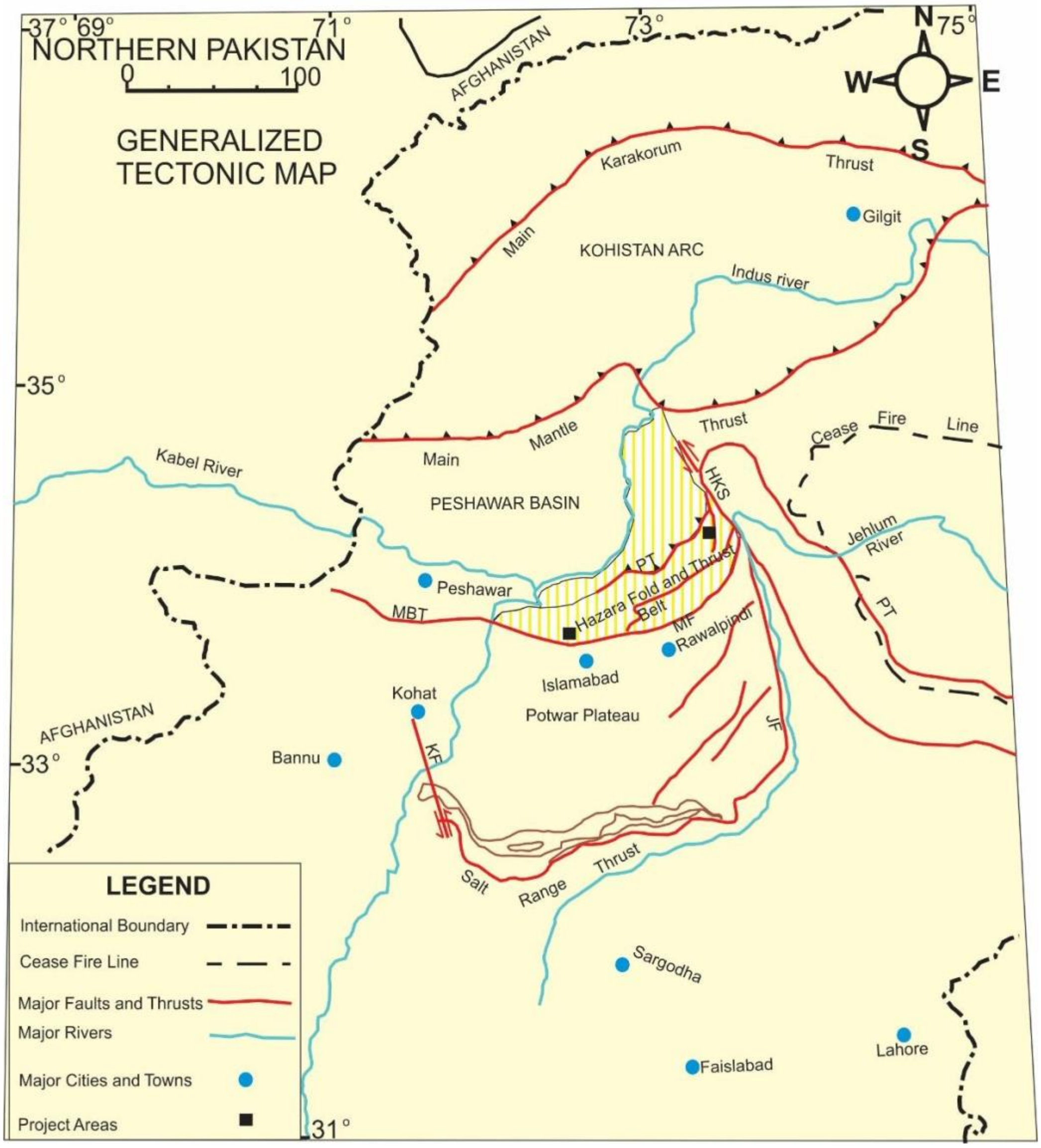

Figure 1: A generalized tectonic map showing major faults and tectonic regions along with the representation of the study area (modified from [9]).

The stratigraphic sequence exposed in the southern part of the Hazara is composed of Precambrian to Miocene age rocks separated by various unconformities during the Paleozoic time [3]. Latif [10] described several Lithostratigraphic units of southern Hazara. Latterly, Shah [11], comprehensively described the Hazara strata. The composite stratigraphic column of the Hazara Area is given in Figure 2.

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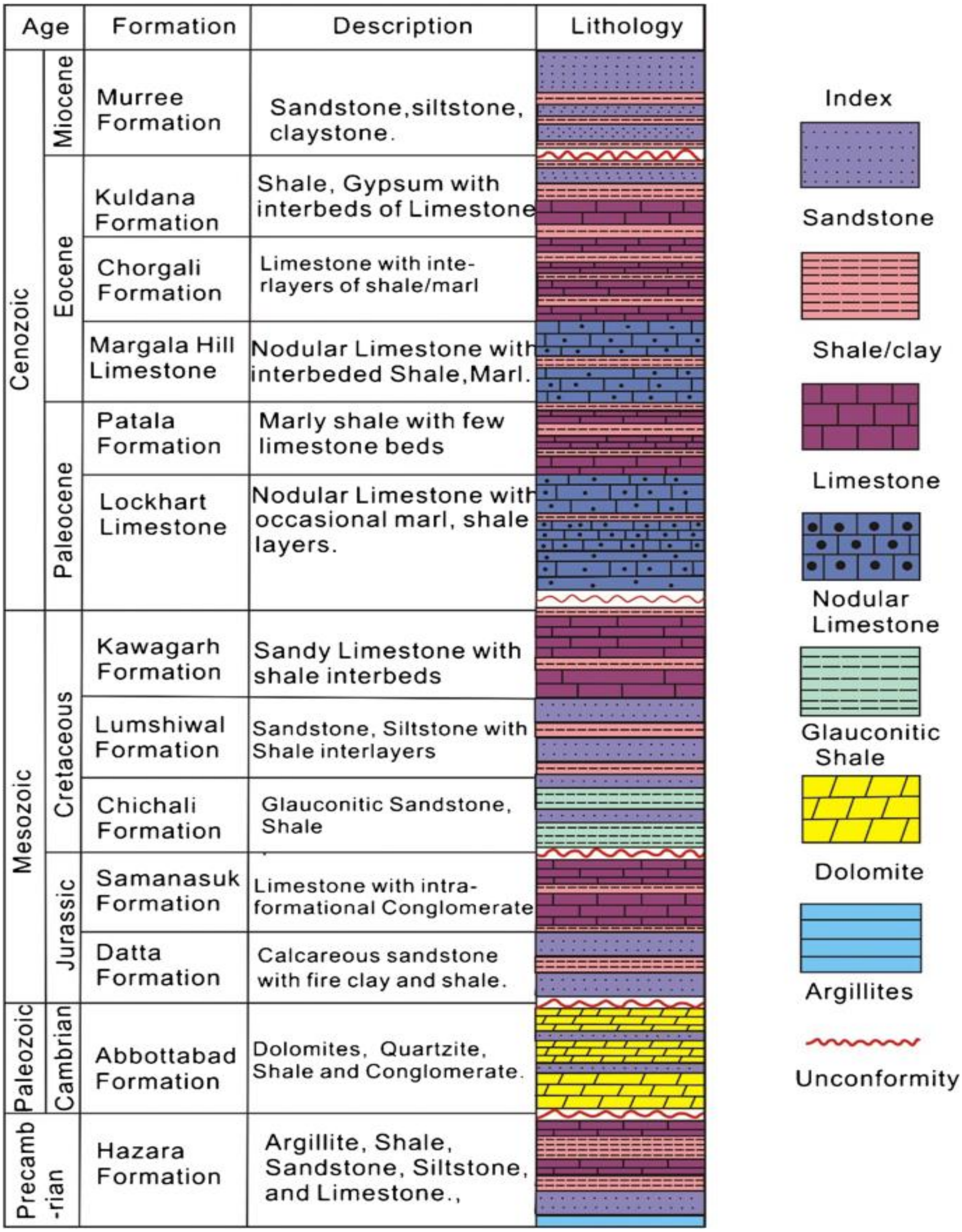

Figure 2: Composite stratigraphic column of Hazara Area, KPK

(Modified after Latif, 1970; Shah, 2009)

3.0 Methodology:

Measurement, as well as sampling, was done along the section, the thickness was 80m along which various samples were collected. The coordinates of the Abbottabad Formation in the Mera Rehmat Khan section (Thandiani), are bounded between latitude 34.13’7835°N and longitude 73.205892ºE. Sidewise different sedimentary structures were observed during the fieldwork to interpret the environment of deposition.

Standard petrographic techniques have been used to identify the mineralogical composition of sandstone, for which various samples have been taken from the formation that leads to the identification of major framework grains. The proportion of different rock components were calculated using standard methods and charts. Ternary diagrams were used for the classification of the sandstone Pettijohn [12], and provenance analysis Dickinson et al, [13], by placing framework grains in a diagram as quartz, feldspar, and lithic fragments (QFL) and monocrystalline quartz, feldspar, and lithic fragments (QmFL). The determination of grain texture and fabric was done by a visual estimate of the thin section.

4.0 Results

4.1 Microscopic Features of Lower Abbottabad Formation:

It is estimated by studying the samples collected that about 80% of this part is comprised of sandstone, the remaining portion is composed mostly of shales and siltstone. Formation includes quartz, feldspar, and lithic fragments as its major component. Quartz is the most abundant detrital grain which exists in the form of poly and monocrystalline quartz. Orthoclase which is a potassium feldspar is present in more proportion as compared to plagioclase and microcline. Plagioclase can be recognized under the microscope showing Carlsbad and albite poly-synthetic twinning. Alteration can be seen in feldspar due to its non-resistive nature to weathering. Some sedimentary lithic fragments of siltstone are also present (Figure 3). Detailed proportions of all the rock fragments calculated from 12 samples, collected from the Lower Abbottabad formation are shown in Table 1.

S No	Quartz			Feldspar			Lithics			Mus	Tmln	Matrix	Cement	Roundnes	Sorting
	Q_m	Q_p	Q_t	F_o	F_{pg}	F_m	Ign	Sed	Met						
1	70	2	72	3	1			2		1	1	10	10	Subangluar to angular	Well
2	63	2	65	6	4			9		0.5	0.5	5	10	Subangular to subrounded	Moderately well
3	Very Fine grained which are very well sorted														
4	73	1	74	5	4			6			1	4	6	Angular to subangular	Well
5	60	2	62	5	5			10			1	7	10	Angular to subangular	Moderately well
6	56	1	57	7	4			8		1	5	9	9	Angular to subrounded	Well
7	79	3	82	4	3			1		1	2	3	4	Angular to subangular	Very Well
8	80	1	81	3	2					1	2	4	7	Angular to subangular	Well
9	Very Fine grained which are very well sorted														
10	74	1	75	5	4			1		1	1	7	6	Angular to subangular	Well
11	67	1	68	4	6			8		1	1	4	8	Subangular to angular	Well
12	79	1	80	3	2			6		1	1	1	6	Angular to subangular	Well

Table 1: Proportions of all the rock fragments of the lower part of Abbottabad formation. S No 3 and 9 are very fine-grained are very well sorted.

Abbreviations	Description
Qt	Total Quartz (Monocrystalline and Polycrystalline)
Qm	Monocrystalline Quartzz
Qp	Polycrystalline Quartz
Fo	Orthoclase
Fp	Plagioclase
Fm	Microcline
Ign	Igneous Lithics
Met	Metamorphic Lithics
Sed	Sedimentary Lithics
Mus	Muscovite
Tmln	Torumaline

Table 2: Description of symbols used in table 1

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The matrix which is seen is mostly of quartz and feldspar and cementation is done mostly by silica and in some part by the ferruginous material. Texturally, grains are sub-angular to angular and sorting is moderately to well sort which indicates the physical maturity of the rocks. There exists variation in the color of sandstone, some are red, brick red, and at some places, these are grey. The change in the color of the sandstone is due to the change in the source material, type of cement, and the amount of interstitial hematite in the matrix [14].

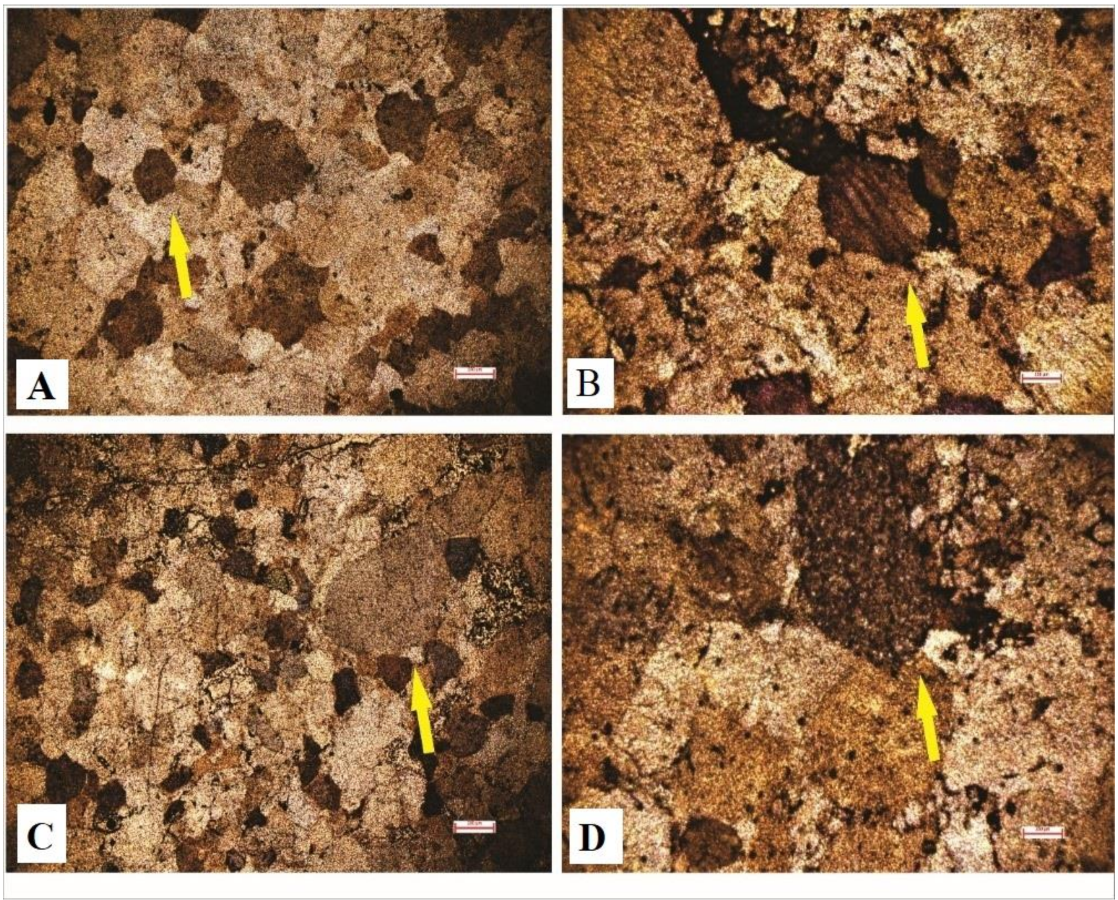

Figure 3: (A). Micro photo shows polycrystalline quartz in Sandstone. (B). Sandstone showing twinning indicates it as plagioclase (feldspar) (C). Sandstone depicting the cloudy appearance of grains (orthoclase) (D).Lithic fragment in sandstone.

4.2 Diagenesis:

Various diagenetic changes can be observed in Abbottabad formation are compaction, dissolution, replacement, cementation, alteration, and grain fracturing.

The absence of primary porosity in the sandstone gives evidence of mechanical and chemical compaction. Grains are tightly packed which is also a consequence of mechanical compaction in sandstone (Figure 4). Contacts of grains are straight, concavo-convex, and sutured, which

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are the effects of mechanical compaction can be seen till the last stages of mechanical compaction, Tucker [15].

Dissolution mostly occurs in grains of feldspar and also present in the grains of sandstone which is due to the overgrowth by the authigenic cement of SiO_2. Dissolution also forms by the ferruginous material (Figure 4).

Alteration mostly occurs in grains of feldspar because they are less resistant to weathering. Due to the presence of ferruginous material which covers the grains and alteration products, the alteration is very difficult to identify under thin section (Figure 4). They are often confused with cementing material.

Fracturing is not most commonly occurring in grains, but in some grains, it can be seen more prominent at the upper part of the section (Figure 4). These fracturings are due to the presence of stresses applied, leading to evidence of mechanical weathering.

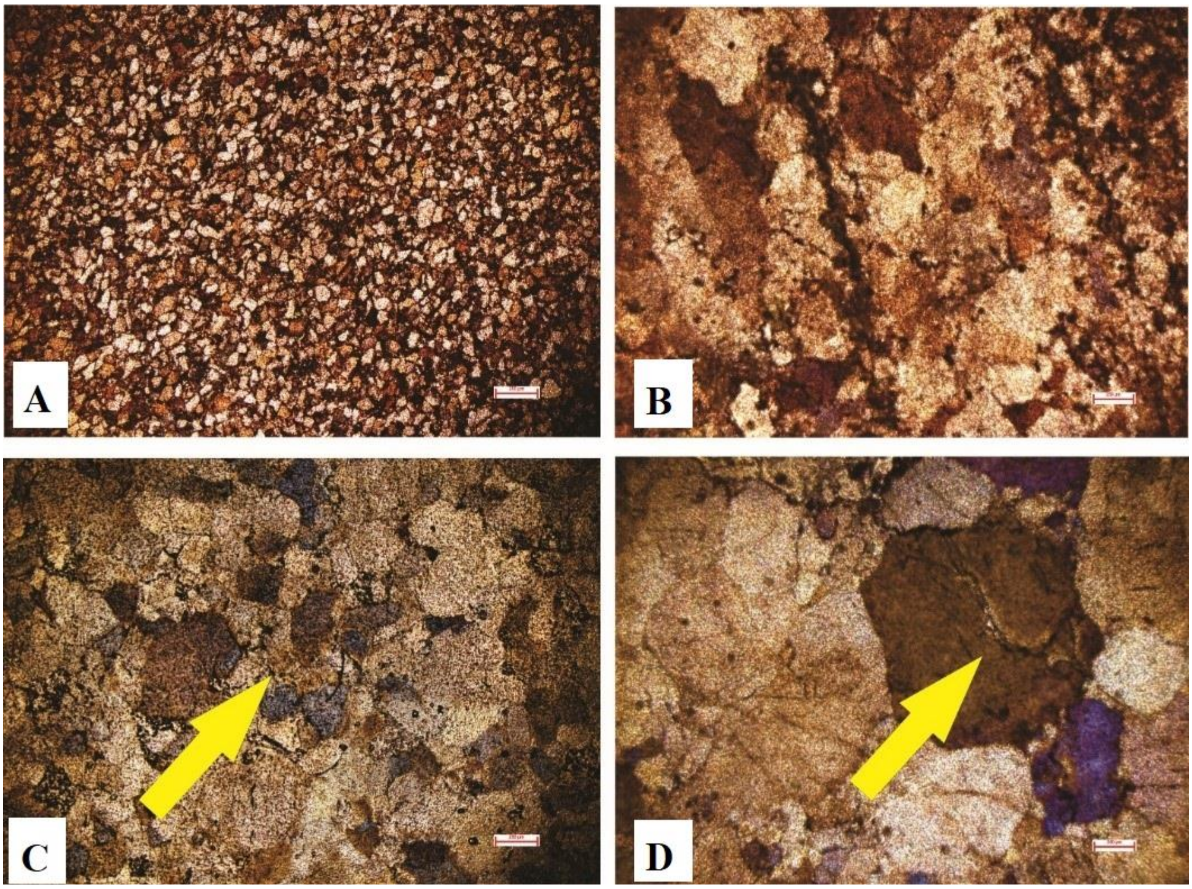

Figure 4: (A&B). Micro-photo of sandstone showing coating of ferruginous material on grains (C). Overgrowth of quartz grain (D). Fractures in grains of quartz.

4.3 Modal composition of framework grains:

Percentages of main framework grains which are quartz, feldspar, and lithic fragments are calculated to 100 and they are plotted on a ternary diagram [12], which is used for the

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classification of the sandstone [16]. Based on calculated framework grains with quartz being most abundant and presence of feldspar and lithic fragments depicted that type of sandstone is quartz arenite to subarkose (Figure 5), [16]. Percentages of detrital mineral composition calculated from the samples for classification and provenance are shown in Table 3 below.

S No	Q	F	L	Qm	F+L
1	77.4	11.9	10.7	75	25
2	92.3	5.1	2.56	89.7	11.3
3					
4	83.1	10.3	6.7	82	18
5	75.6	12.2	12.1	73.1	26.9
6	75	14.6	10.5	73.6	26.4
7	91.1	7.7	1.1	87.7	12.3
8	94.1	5.8		93	7
9					
10	88.2	10.5	1.1	87	13
11	79	11.6	9.3	78	22
12	87.9	5.5	6.6	86.8	13.2

Table 3: Percentages of detrital mineral composition for classification and provenance. For abbreviations see Table 2.

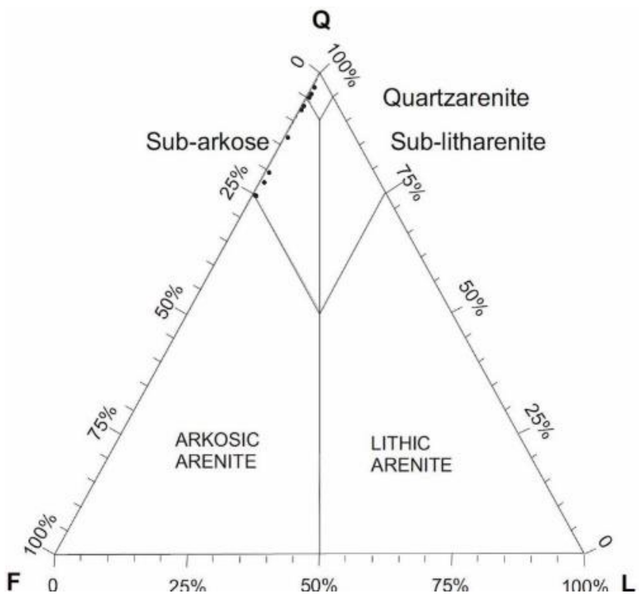

Figure 5: QFL triangular classification of sandstone samples, Pettijohn [11].

4.4 Provenance of Lower Abbottabad Formation:

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The provenance scheme is based on the schemes of Dickinson et al., [13]. For this, percentages of monocrystalline quartz, feldspar, and lithics were recalculated to a hundred and then these are plotted on ternary diagrams (Figure 6), which shows that this sandstone has been derived from craton interior and transitional continental [16].

The composition of sandstone is mainly dependent on the type of source rock, tectonic settings, and climate conditions [17]. The type of source rock could be determined based on the composition of the sandstone and the types of detrital constituents present. The presence of monocrystalline quartz having a uniform or slightly uniform extinction is considered to derive from plutonic rocks i.e., granites [18]. However, the presence of the polycrystalline and monocrystalline quartz grains having undulatory extinction, also suggests that these fragments have been derived from metamorphic sources [19]. If there exist rounded overgrowths in some quartz grains, there is an indication that these grains are derived from recycled sedimentary sources [18].

Crystalline rocks are the main source of K-feldspar i.e., granites and gneisses [15]. If there is a high ratio of K-feldspar as compared to plagioclase, it leads to evidence that these grains have been derived from mixed plutonic and metamorphic sources [15].

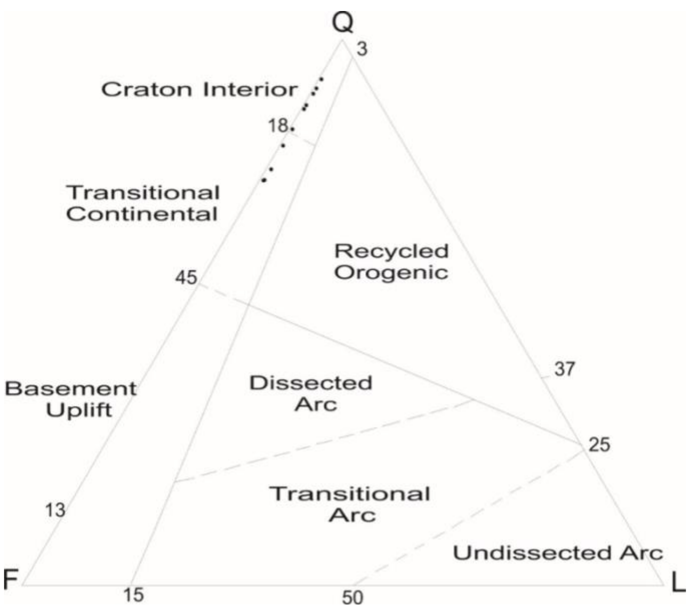

Figure 6: Interpretation of the provenance, based on schemes of Dickinson et al., [13].

5.0 Discussion

5.1 Lithofacies interpretation

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Based on detailed studies carried out in the lower part of the Abbottabad Formation at Thandiani, it was interpreted that the lower part of the Abbottabad Formation is divided into various lithofacies. Four main lithofacies are identified in our study are based on dominant lithology, textural characteristics, and bedforms, which include, horizontally laminated and bedded sandstone lithofacies, Rippled Sandstone, Coarser grained Sandstone lithofacies, Hummocky cross-stratified Sandstone.

5.1.1Horizontally Laminated and bedded sandstone lithofacies:

Description:

The horizontally laminated and bedded sandstone lithofacies is present in the lower part of the Abbottabad Formation (Figure 7). Parallel and cross laminations are rarely preserved because these have been destroyed by bioturbations. The lithofacies comprises fine-grained, well-sorted, friable sandstone and represent variable thickness (From 1m to 2m thick). The lithofacies shows a coarsening upward trend grading into rippled sandstone units. Different sedimentary features such as bioturbations, wavy beds, cross-beds, sole marks are also associated (Figure 7). Thick sandy veins and sand lenses could also be seen.

Interpretation:

The deposition of the horizontally bedded sandstone had occurred in the upper flow regime conditions in the point bar and can also be inter-bedded with small-scale cross-beds formed by the small ripples [20]. It has been reported that horizontally laminated sandstones have deposited in a range of settings i.e. fluvial [21], shelf [21], and intertidal [22]. Sole marks may be produced either by currents or by gravity. Some of these structures are generated by particles that are moved by currents or by gravity [23]. Bioturbation present in the sandstone destroys primary structures of sandstones such as parallel and cross laminations, which are only rarely preserved. The presence of bioturbation in the sandstone and its occurrence with parallel-laminated and cross-bedded sandstone suggests its origin during alternate calm intervals [24].

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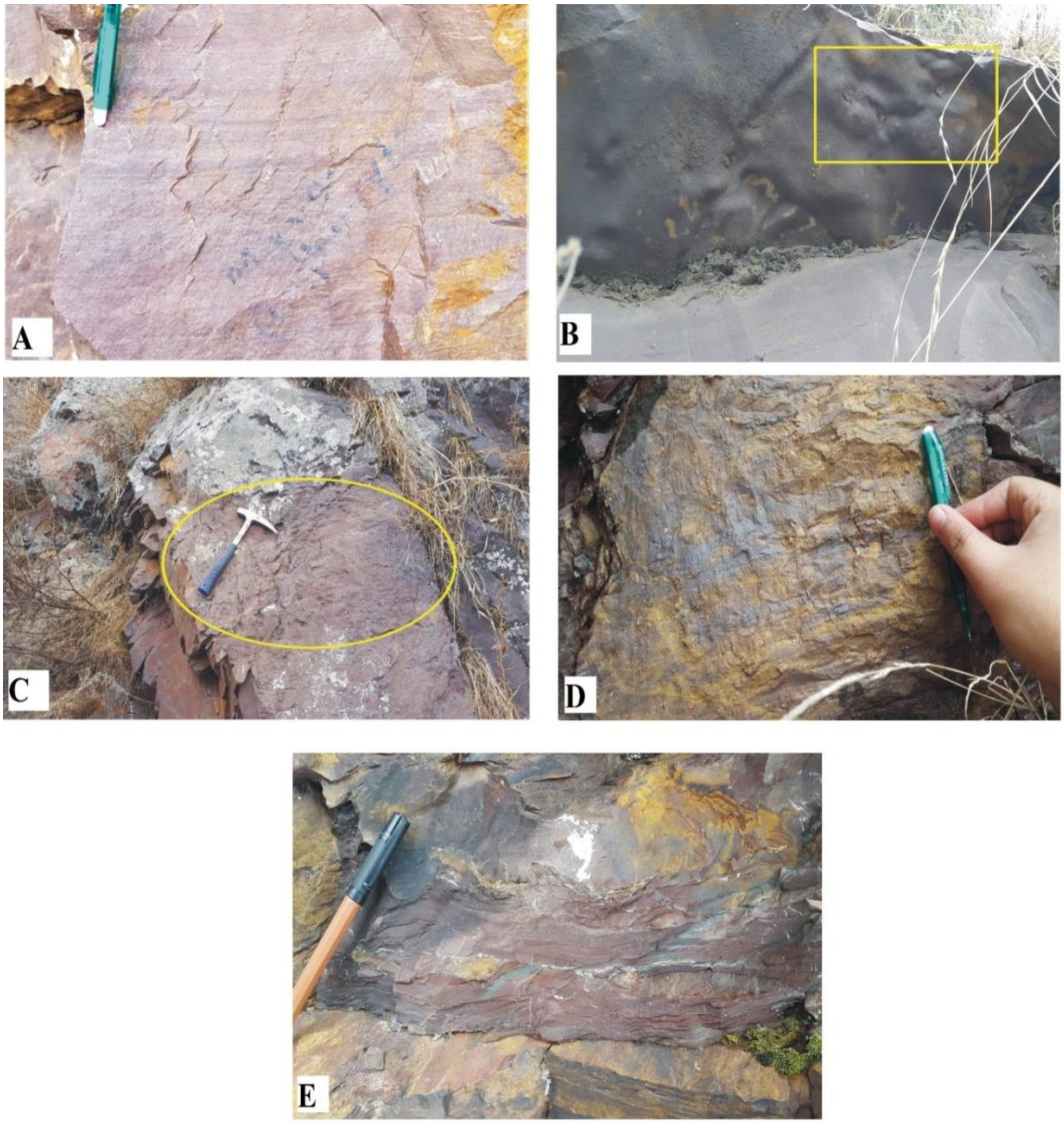

Figure 7: Photographs displaying internal sedimentary features exposed in lower Abbottabad Formation. (A) Horizontal laminations in sandstone. (B) Sole marks in fine-grained sandstone. (C) Bioturbations in sandstone.(D) Wavy bedding in sandstone. (E) cross lamination in sandstone.

5.1.2 Rippled Sandstone Lithofacies:

Description:

Rippled sandstone lithofacies is present in the studied section. The lithofacies constitutes red-colored medium to coarser-grained which is well sorted. These have a variable thickness (from 1m to 1.5m). Ripples present there are large wave ripples which can be seen as typically symmetrical or only slightly asymmetric in the field, with peaked crest and rounded troughs. These are thickly bedded sandstones which are massive at some places. Internally, these beds comprise thick sandy veins, fine sand beds, sandy lens, wavy laminations, bioturbations, and internally rippled sequence. Trough cross stratifications and low-angle cross stratifications are also present associated with these lithofacies (Figure 8). This lithofacies grades upward into coarser sandstone which shows channelized deposition.

Interpretation:

The wavy ripples are interpreted as products of intermediate turbidity energy flows and tidal currents reworking in mid to outer submarine fans setting [25]. Ripples present in the sandstone can be produced in the deeper waters by the storm velocities [26]. Sandstone is well sorted which indicates that these were deposited in high energy conditions [15]. Large-sized ripples present there is also evidence that this deposition has occurred in the deepwater [21]. Some of the massive beds have been thought of as secondary features produced by extensive bioturbation by organisms, although bioturbation commonly produces recognizable mottled structures [27]. Liquefaction of sediment by sudden shocking or other mechanisms shortly after the deposition has also been suggested as a means of destroying original stratification [27]. Deposition represented by the lithofacies is in the shoreface settings [28]. Trough cross stratifications can be caused by changes in flow rates, tidal stage, or tidal current direction [20].

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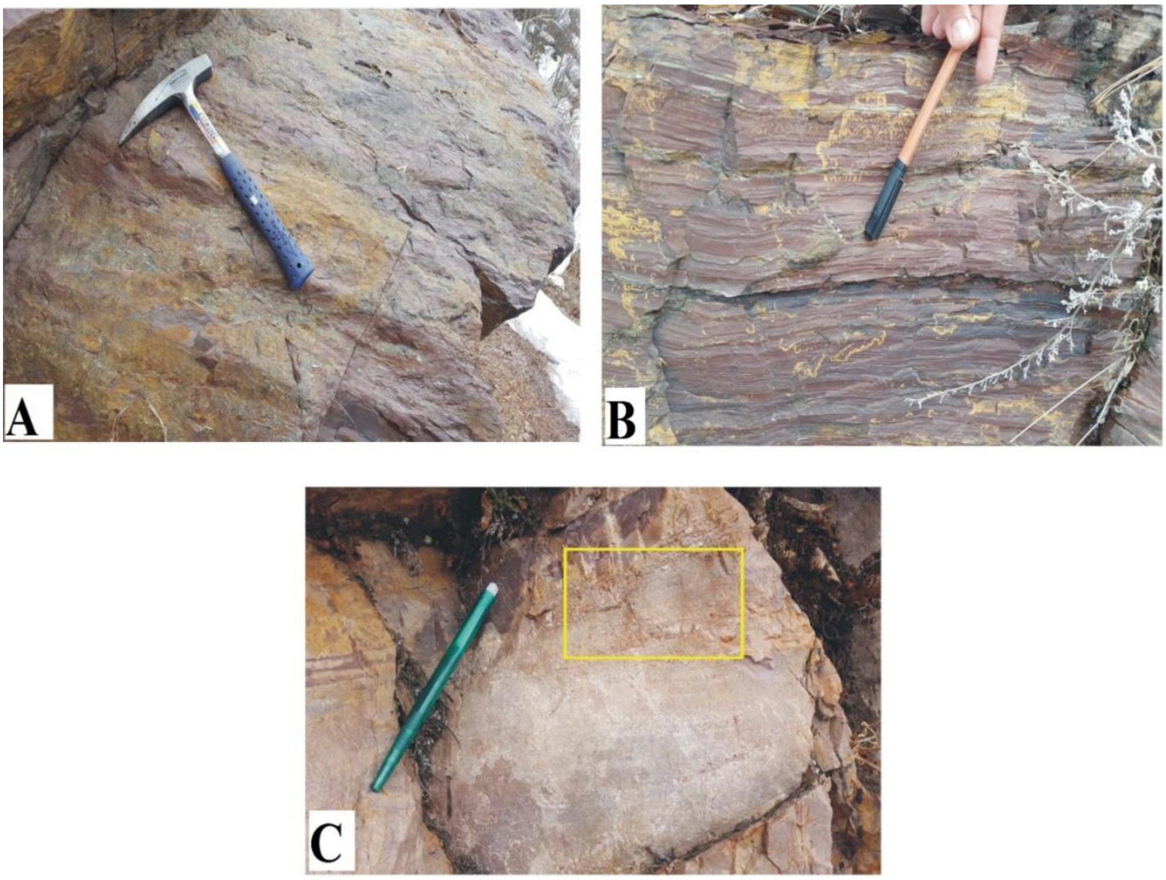

Figure 8: Photographs exhibiting internal sedimentary features exposed in lower Abbottabad Formation. (A) Asymmetrical wavy ripples in sandstone. (B) Wavy laminations in massive sandstone. (C) Through cross-stratification in sandstone

5.1.3 Coarser grained Sandstone lithofacies:

Description:

Coarser grained sandstone lithofacies is present in the lower part of the Abbottabad Formation. The lithofacies constitutes coarser grains and these are moderately well-sorted and their thickness varies from 3m to 4m. Channel sandstone is presently associated with these lithofacies. Pinching in the beds shows that these have been channelized (Figure 9). Channelization is formed by the deposition of sediments in deltas. Internally rippled laminations are also seen associated with these lithofacies.

Interpretation:

Distributary channels are the site of deposition of most of the coarsest sediment that is carried to the delta [29]. The sands also display ripple cross stratifications, scour and fill structures, and may include thin, discontinuous clay lenses [30].

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Figure 9: Photograph showing pinching of beds (channelized sandstone).

5.1.4 Hummocky cross-stratified sandstone:

Description:

The lithofacies is present at the top of this studied section. This lithofacies constitutes medium to coarser bedded sandstone which is well-sorted to moderately well-sorted. These are thick beds that are also wavy at the base with swales cross-stratification, bioturbations, and parallel laminations present at the bottom where grains are medium-sized (Fig 10).

Interpretation:

Low-angle and gently undulating cross-stratification with dips of 3 to 6 degrees has been termed as Hummocky cross-stratified [20]. Such features are presently interpreted as being generated by storm waves on the shelf environment [29]. Hummocky cross-bedding commonly occurs in the sets 15-20m thick with wavy erosional bases and rippled bioturbated tops [20]. These structures are formed from the strong waves of varied directions that are generated by relatively large storm waves [20]. There are many depositional mechanisms and settling includes for the Formation of parallel lamination out of which one includes deposition in the subtidal shelf areas, where thin sand layers that accumulate owing to storm activity may alternate with very thin mud laminae formed during periods of slow accumulations [27],[28].

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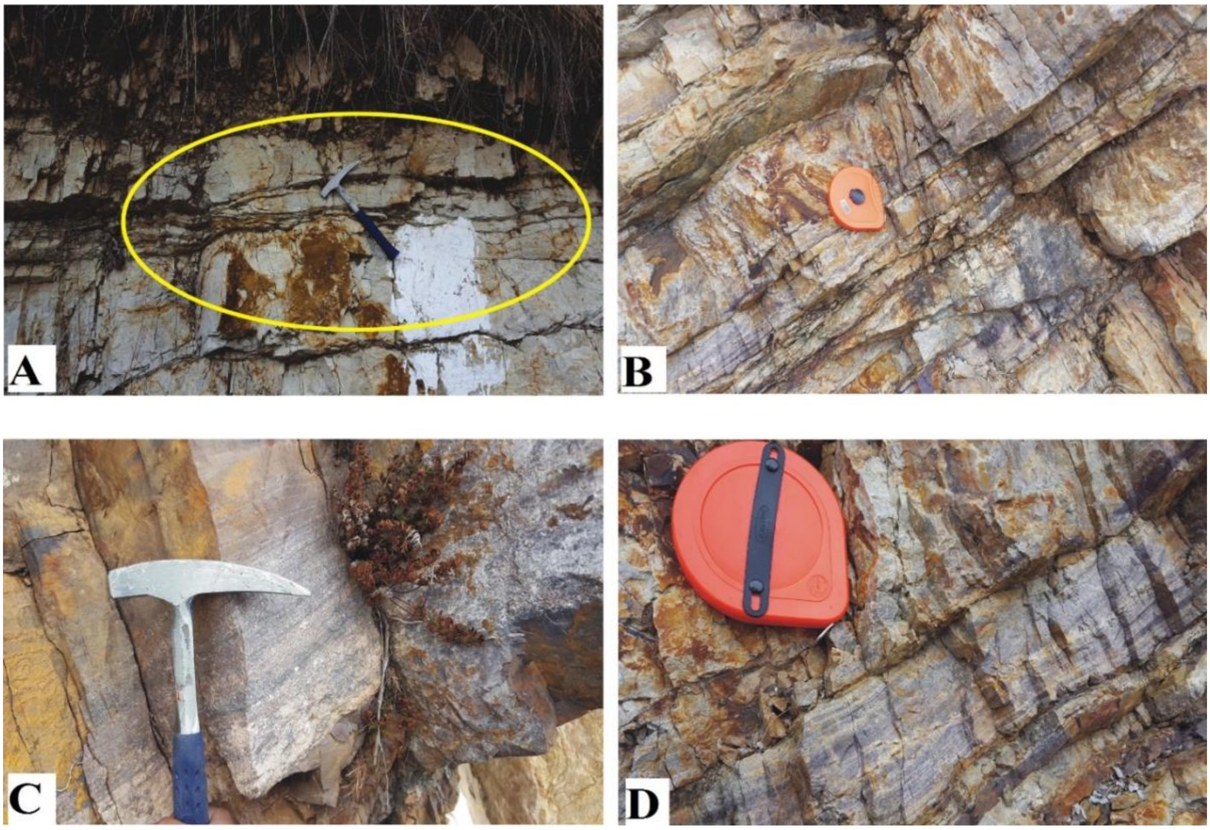

Fig 10: Photographs depicting internal sedimentary features exposed in lower Abbottabad Formation. (A) Hummocky cross-stratification in wavy sandstone. (B) Hummocky cross-stratification in low angle dipping sandstone. (C) Parallel laminations in sandstone. (D) Swanley cross-stratification in coarse-grained sandstone.

5.2 Facies Association

5.2.1 Shoreface and shelf facies associations:

Many sedimentary structures and textural trends and the presence of small cross-beds, horizontally laminated sandstones, hummocky cross stratifications, bioturbations, sole marks, parallel and cross laminations indicate their deposition in the shelf environments [21], (Fig 11). The presence of massive beds, trough cross-stratification, large size ripples show its deposition in the shoreface settings [27],[28].

5.2.2 Deltaic facies association:

Deltaic facies is comprised of coarsely grained sandstone lithofacies. Channelized sandstone which is coarser-grained indicates their deposition in the deltaic environments [29]. Vertical log showing the variation in lithology and sedimentary features (Fig 11).

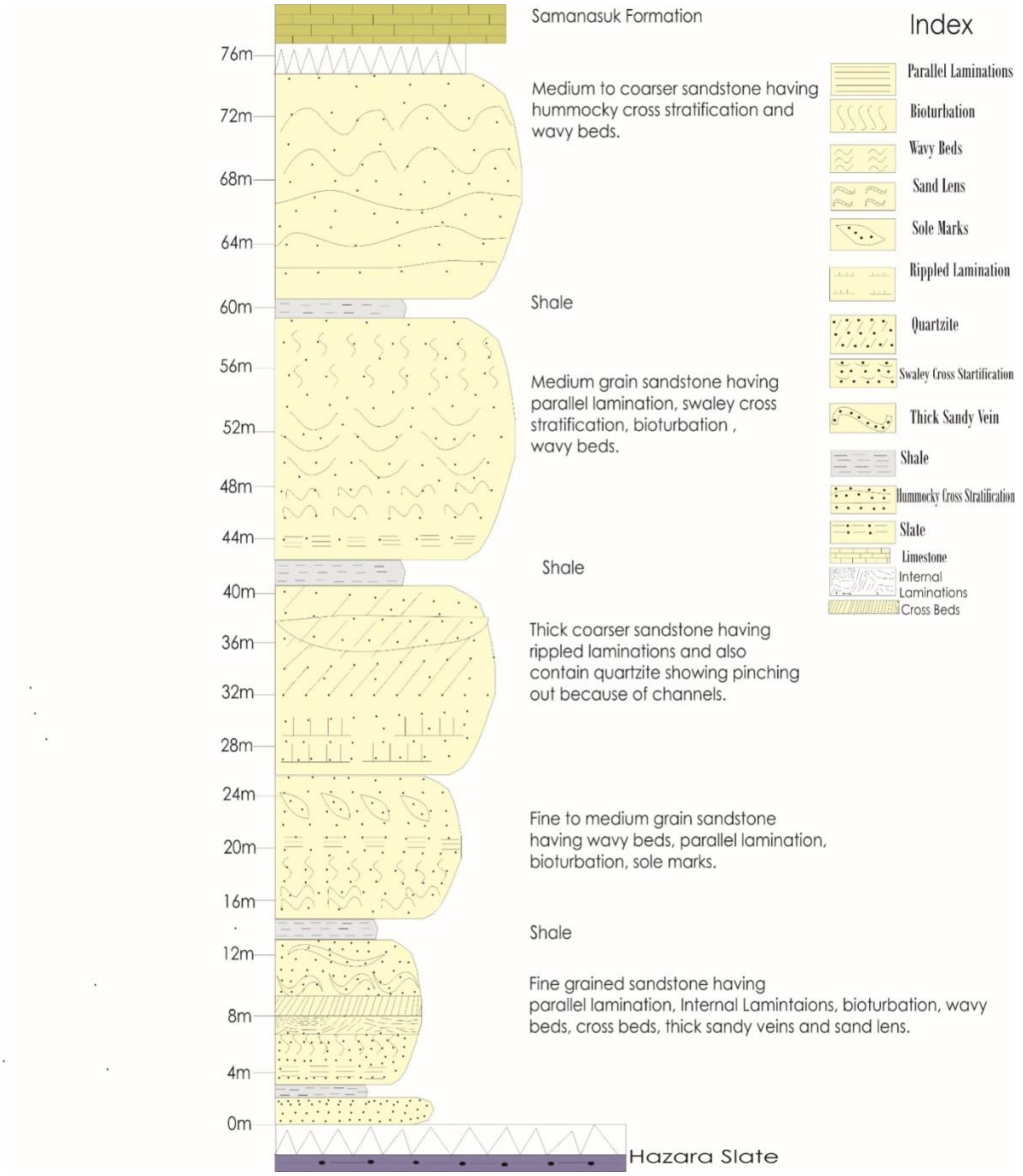

Fig 11: Vertical log showing the variation in lithology and sedimentary features.

Conclusions

The early Cambrian Abbottabad Formation is well exposed in the Mera Rehmat Khan section. Petrographic studies show that this sandstone has an abundance of quartz and feldspar while lithic fragments are less in amount. Many accessory minerals mainly tourmaline is present and heavy minerals can be identified by their opaqueness. Cement and matrix are also present. Many diagenetic features such as compaction, replacement, and dissolution, fracturing, and cementation also occur in this sandstone. When data of quartz, feldspar, and lithic fragments are plotted on Pettijohn ternary diagram, it shows that this sandstone is quartz arenite to sub-arkose. The schemes of Dickinson et al. (1983) for determining the provenance of sandstone show that sediments in the lower part of the Abbottabad Formation were derived from the craton interior and transitional continental. There exist many sedimentary features such as wavy beds, bioturbations, trough cross-stratification, rippled laminations, Hummocky cross stratifications, etc, which are used to interpret the environment of deposition. Based on these features, it can be described that these rocks were deposited in shoreface to shelf settings. Channelized sandstone represents their deposition in the delta which is formed as a result of deposition of sediments in the deltas indicating a deltaic environment.

Abstract:

Abbottabad Formation of Early Cambrian age is exposed at the Mera Rehmat Khan section Thandiani, Abbottabad, Pakistan. The dominant lithology of the Abbottabad Formation is sedimentary rocks which are 1) Dolomite; 2) Sandstone; 3) Shale; 4) Conglomerate. The lower part of Abbottabad formation is comprehensively studied during the field and lab work to interpret the lithofacies and depositional environment properly. Petrographic analysis shows that sandstone of the Lower Abbottabad Formation is predominantly composed of quartz arenite and sub-arkose. On basis of Ternary Diagrams, sandstone of the Lower Abbottabad Formation has been derived from craton interior and transitional continental. The result shows that Lower Abbottabad Formation is mainly interpreted to be deposited in shoreface and shelf settings having deltaic extensions.

Keywords: Cambrian, Lower Abbottabad Formation, lithofacies interpretation, depositional environment, Thandiani, Pakistan.

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