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Petrography of Sandstone of the Lumshiwal Formation from the Samana Range, Hangu, Northwestern Pakistan: Implications for Provenance, Diagenesis and Environments of Deposition

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Abstract

The Cretaceous Lumshiwal Formation is exposed along a road-cut in the Samana Range, situated in Hangu, northwestern Pakistan. It largely consists of sandstone with some intercalations of shale and limestone. A total of 28 samples were collected at a regular interval of 5 m from the sandstone unit of the formation for detailed petrographic studies. The studied samples of sandstone consist of abundant quartz (ranging up to 97 %), which may or may not be accompanied by accessory amounts of feldspars (averaging ~3 %) and traces of rock fragments and a variety of heavy minerals. The heavy minerals include tourmaline, monazite, zircon, muscovite, chert, rutile and goethite. Silica as quartz overgrowth is the dominant cementing material in the studied sandstone samples. A few of the samples however contain ferruginous cement. Due to very high modal abundance of quartz, all the samples classify as quartz arenite. This feature suggests that the Lumshiwal sandstone is mineralogically mature. The moderate degree of sorting and sub-angular to rounded outlines of framework constituents however point to the texturally sub-mature character of the sandstone. The mono-crystalline quartz is much more abundant than the poly-crystalline type, and the poly-crystalline quartz grains mostly consist of two to three sub-grains. Besides, the majority of the mono-crystalline quartz grains are non-undulose or only weakly undulose. These features suggest derivation of quartz from an igneous source rock. Furthermore, the presence of alkali feldspar and heavy minerals such as tourmaline, monazite, zircon, muscovite and rutile point to a source dominated by acidic plutonic igneous rocks.

Precipitation of silica as overgrowth cement in pore spaces, presence of long and sutured boundaries, absence of concavo-convex and tangential contacts and alteration of feldspar grains to clay minerals are the prominent diagenetic modifications in the studied sandstone. These changes represent the final phase (phyllomorphic) of diagenesis, deep burial, increased geothermal gradient and pressure as is also evident from quartz overgrowths, stylolitic boundaries of some of the grains and healing of intra-granular fractures in quartz and feldspar with ore minerals. The almost total absence of matrix and abundance of framework quartz suggest the falling sea level, i.e. high energy conditions. The presence of glauconite also supports shallow marine conditions for the deposition of the studied sandstone.

INTRODUCTION

Sandstone of Lumshiwal Formation is a proven reservoir in Kohat sub-basin and this paper is an attempt to provide useful information regarding its modal composition, micro-texture including grain shapes, size and degree of roundness, sorting and maturity, type and extent of diagenetic changes, nature and source of the constituent sediments and environment of their deposition The abstract of this paper has already been published (Ali et al., 2010).

In order to observe and evaluate the important features in the sandstone of the Cretaceous Lumshiwal Formation, its exposure along the Samana pass (Lat. 33° 33′ 40″ N; Long. 71° 02′ 20″ E), northwestern Pakistan was selected for the present study. Having a maximum thickness of 194 m, the Lumshiwal Formation predominantly consists of sandstone with intercalations of limestone and shale at the top and bottom, respectively. The Samana Range is a part of the Kohat Fold and Thrust Belt of the Upper Indus Basin. The Upper Indus Basin is located in northern Pakistan and is separated from the Lower Indus Basin by Sargodha Highs. Its northern and eastern boundaries coincide with the Main Boundary Thrust (MBT) the southernmost of the major Himalayan thrusts (Figure 1). The basin is further divided into Potwar sub-basin in the east and Kohat sub-basin in the west, separated by Indus River (Kadri, 1995).

The aim of the present study is to present a detailed account of the sandstone unit of the Lumshiwal Formation with special emphasis on the following:

(I) Petrographic characterization,
(ii) Evaluation of textural and mineralogical maturities,
(iii) Provenance determination,
(iv) Characterization of the type and mode of transportation,
(v) Interpretation of depositional environments
(vi) Knowing about the type and extent of diagenetic changes.

Regional Tectonic Framework

The Himalayas are the world's spectacular mountain chains, sandwiched between Eurasian plate in the north and Indian plate in the south. These mountains have north-west trend in India, which changes to east-west orientation in Pakistan and becomes more north-south along the Pakistan-Afghanistan border.

The origin of Himalayan mountain chain can be attributed to the global plate kinematics and reconstruction when a plate of the earth's crust carrying Indo-Pakistan continent get separated from the mother Gondwana about 130 Ma ago and started northwards drift (Johnson et al., 1976). As a consequence, the Neo-Tethys that was located between the Indian continent in the south and Eurasian plate in the north started shrinking. During the closure of Neo-Tethys Ocean intra-oceanic subduction generated a series of arcs, namely Kohistan-Ladakh, Nuristan and Kandhar (Searle, 1991; Treloar and Izzat, 1993). The Kohistan arc magmatism continued for a period of 40 Ma (Petterson and Windley, 1985), after which the back-arc basin was finally closed and

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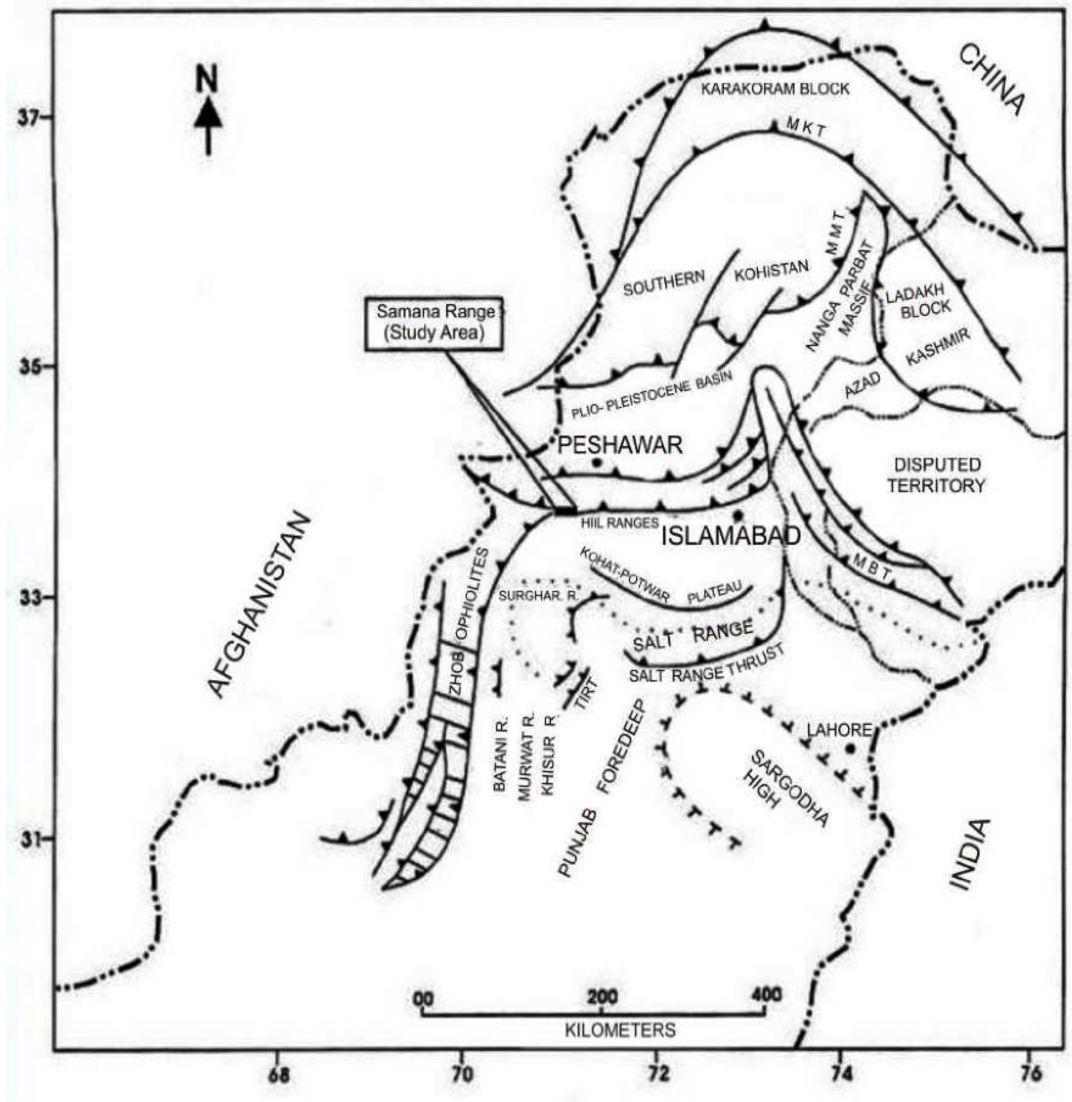

Figure 1- Map showing tectonic elements, mountain ranges (R.) (including Samana) and geomorphic features of central and northern Pakistan (after Kadri, 1995). MBT = Main Boundary Thrust; MKT = Main Karakoram Thrust; MMT = Main Mantle Thrust; TIRT = Trans-Indus Range Thrust.

the Kohistan-Ladakh arc accreted onto the Eurasian plate forming an Andean type continental margin.

The Himalayas in Pakistan can broadly be divided into five tectono-stratigraphic terrains, each separated by regional fault boundaries (Powell, 1979). From north to south this division is known as (i) Karakorum Block and Main Karakorum Thrust (MKT), (ii) Kohistan Island Arc and Main Mantle Thrust (MMT), (iii) Northern Deformed Fold and Thrust Belt and Main Boundary Thrust (MBT), (iv) Southern deformed Fold and Thrust Belt and the thrust couplet including Salt Range Thrust (SRT) and Trans Indus Ranges Thrust (TIRT), and (v) Punjab Fore-Deep (Figure 1).

The Samana Range along with Kohat Foreland Basin is located in the Lesser Himalayas of north Pakistan. The Samana Range defines an east-west trending fold-thrust belt system that separates the meta-sedimentary assemblages of Peshawar Basin in the north from the platform to Plio-Pleistocene sediments of the Kohat Fold Belt. The Samana anticline is the southern-most of the enechelon fold assemblages that characterize the Samana and Kohat Ranges. This fold is wide with a half wavelength of 05 km and a strike length of more than 20 km. The fold axis is sub-horizontal and trends east-west which is parallel to the regional structural trend of the Kohat Belt. The attitude data along this fold suggest southwards symmetry (Ahmad et al., 2004). The Samana anticline is believed to be a fault propagated fold detached at the level of Jurassic rocks (Ahmad et al., 2004). Ahmad et al. (2007) carried out a detailed fracture analysis of the Samana anticline.

General Stratigraphy of the Samana Range

The Samana Range consists of rocks that range from Jurassic to Paleocene in age, comprising of a total of eight Formations (Figure 2). The Jurassic rocks mainly include the Shinawari and Samana Suk Formations which are disconformably overlain by the Cretaceous successions of the Chichali Formation, the Lumshiwal Formation and the Kawagarh Formation. The Chichali Formation has a gradational upper contact with the Lumshiwal Formation, which in turn has a disconformable contact with the overlying Kawagarh Formation. The Cretaceous succession is disconformably overlain by the Paleocene sequence represented by the Hangu, Lockhart and Patala Formations.

Lumshiwal Formation

As pointed out above, the present study is aimed at investigating the petrographic characteristics of the sandstone representing the Samana section of the Lumshiwal Formation. Replacing the older term "Guimal sandstone" (Middlemiss, 1896; Cotter, 1933), Gee (1945) proposed the name "Lumshiwal Formation" for usage in the Salt Range. Danilchik and Shah (1967) designated a section one km north of the Lumshiwal Nala (32˚ 51' N: 71˚ 09' E) as type locality for the Lumshiwal Foramtion, while the Fort Lockhart road section in the Samana Range, was designated as one of its reference sections.

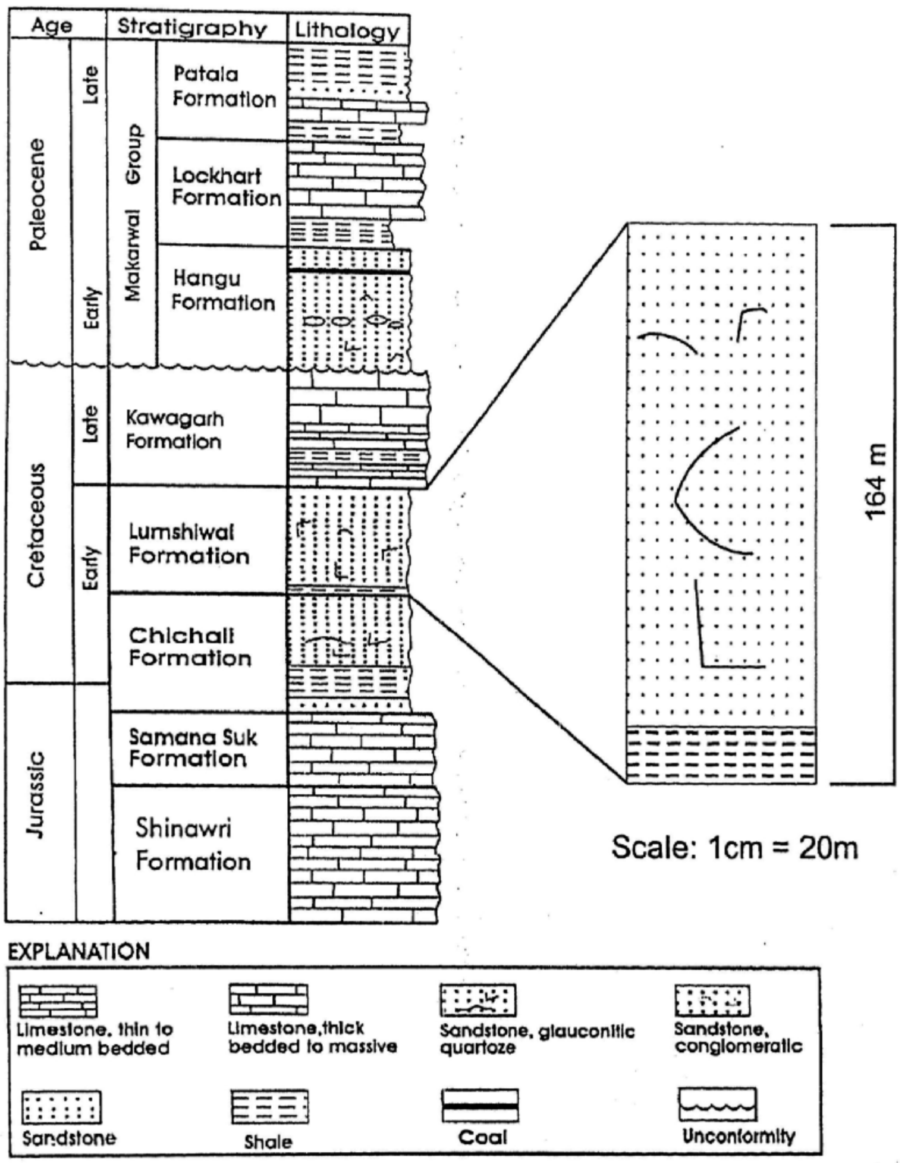

Figure 2- Generalized stratigraphy of Fort Lockhart (Samana Range), northwestern Pakistan (after Shah et al., 1993) and measured stratigraphic section of the Lumshiwal Formation.

In its type locality and in the sections in Trans Indus Ranges, the Lumshiwal Formation consists of massive, light grey, current-bedded sandstone with silty, sandy and glauconitic shale toward the base. The sandstone is feldspathic, ferruginous and contains carbonaceous material. In Samana Range, the Lumshiwal Formation has been distinguished into three parts. The lower part consists of fine to medium grained, thin to medium bedded, light grey, brown, quartzose sandstone. The middle part is massive to thick bedded, cliff forming, coarse to medium grained, light grey sandstone. The upper part contains ferruginous and glauconitic sandstone with one to two meters thick hard, calcareous, glauconitic, rusty brown and sandy limestone. The thickness is 80m to 120m in the Lumshiwal Nala but ranges up to 194m in the Samana Range. The lower contact with Chichali Formation appears transitional and the upper contact with Kawagarh Formation is disconformable in Kohat and Hazara areas.

In Samana Ranges the uppermost beds of the Lumshiwal Formation contain fossils of ammonoids, bivalves, gastropods, belemnites and echinoids. Among the ammonoids douvillecieras mammillatum is the most common specie (Fatmi, 1968; Spath, 1939). The age of the Lumshiwal Formation is Aptian to early Albian in Western Kohat and upper Neocomian to middle Albian in Nizampur, Kalachitta and Southern Hazara but Titchonian to middle Albian in Northern Hazara.

Samples and Methodology

As a result of a detailed fieldwork, 28 compact and unaltered samples of sandstone were collected at an average interval of 5 m from the sandstone unit of the Lumshiwal Formation. Besides, different stratigraphic sections were measured and lithological units identified, and contact relationship, structural features and lithological characteristics were observed and noted. All the collected rock samples were cut and made into thin sections for detailed petrographic studies using a polarizing microscope. Average modal composition of each of the samples was determined after making a number of systematic traverses within its thin section and taking readings through visual estimation in several field views.

Petrography

The sandstone from Lumshiwal Formation is very hard and compact due to the abundance and close interlocking of quartz grains. Results based on previous studies on sections in the Surghar and Kala-Chitta Ranges also show the abundance of quartz in the Lumshiwal sandstone. In addition to quartz, the sandstone from Lumshiwal Formation contains feldspars, rock fragments, glauconite, monazite, tourmaline, zircon, muscovite, chert, goethite and rarely apatite.

Major Constituents

The sandstone of Lumshiwal Formation mainly consists of quartz whose average modal abundance is 97 %. The quartz is fine to medium grained; however, larger grains of quartz also occur. The quartz grains are sub-spherical with sub-angular to rounded outlines. Rarely, however, quartz grains with angular boundaries also occur.

Most of the quartz grains are fresh and clean, while some of them are dirty and display shades of pale yellow to reddish colors due to staining from ferruginous cementing material (Figure 3a). Some of the quartz grains also contain tourmaline, mica and zircon as inclusions (Figure 3b). Most of the quartz grains show uniform extinction however, a few of them, especially the large ones display undulatory extinction due to strain induced crystallographic dislocation in lattice (Figure 3c). Some of the quartz grains show fractures, which are filled with cement or opaque material (Figure 3d). Quartz occurs both as monocrystalline and polycrystalline grains. The monocrystalline variety is much more abundant than the polycrystalline. Whereas some of the quartz grains display sutured boundaries (Figure 3e), others show straight outlines (Figure 3f). Many of the quartz have well developed overgrowths around them (Figure 3g).

Feldspars are the second most abundant and important constituent whose average abundance is 3 %. Almost all the studied samples contain appreciable amounts of feldspars. In some of them, the abundance of feldspar ranges up to about 5 %. Most of the feldspar grains are of medium size with only a minor proportion occurring as small and large grains that are randomly distributed among the medium-grained feldspars. They are mostly sub-spherical in shape and have sub-angular to rounded boundaries. The grains of feldspar are not very clean as they show alteration to clay minerals. These grains are mostly fractured and the fractures are filled with opaque minerals or cement. As compared to quartz, most of the feldspars grains display sutured boundaries. Whereas alkali feldspar is by far the most abundant type of feldspar, plagioclase (Figure 3h) and microcline (Figure 3i) also occur in some of the samples.

The grains of alkali feldspar show simple twinning and some of the alkali feldspar grains contain inclusions of tourmaline and mica. Plagioclase occurs in trace amounts and its grains show the characteristic albite polysynthetic twinning (Figure 3h). Microcline is rather rare and occurs in the form of small grains and most of the microcline grains display the diagnostic cross-hatched twinning (Figure 3i).

Accessory and Trace Constituents

These include rock fragments and a number of heavy minerals. Rock fragments are generally considered to be one of the common constituents of sandstones; however, their abundance in the studied samples of the Lumshiwal sandstone is rather low. The rock fragments occur as small grains with rounded outlines and include igneous, sedimentary and metamorphic types. The overall modal abundance of rock fragments is less than 0.5 %. The rock fragments found in the studied samples also include chert. The grains of chert are fine to medium in size, sub-spherical and have sub-angular to rounded boundaries (Figure 3j).

Trace amounts of muscovite occur as flakes in the studied samples (Figure 3k). They show bending due to deformation. The scarcity of mica in the studied samples probably reflects selective sorting of detrital grains during deposition. In addition to muscovite, glauconite also occurs (Figure 3l). However, it mostly appears to be authigenic and its abundance increases towards the top of the Formation.

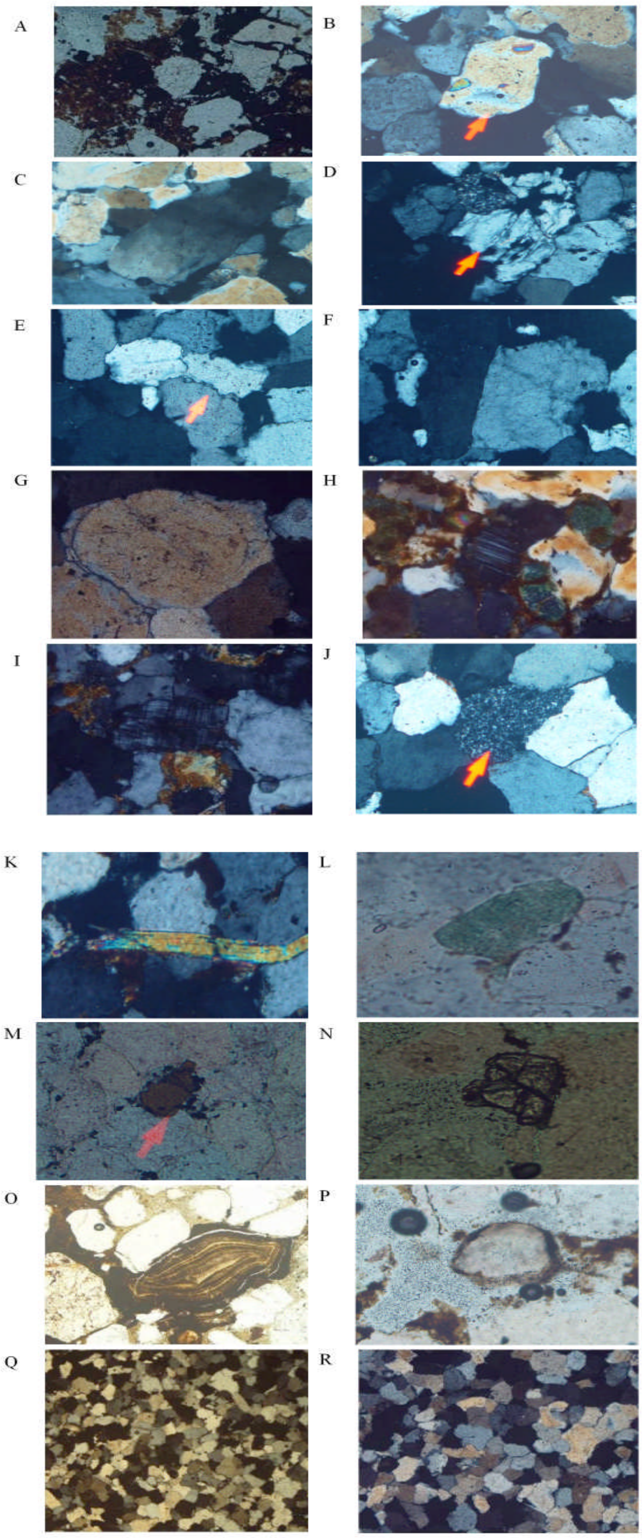

Figure 3- Photomicrographs showing (A) ferruginous cement and staining of quartz grains, (B) inclusion of tourmaline and muscovite in a grain of quartz, (C) undulose extinction by a grain of quartz, (D) fractures in a quartz grain, (E) sutured grain boundaries, (F) straight intergranular boundary, (G) quartz overgrowth, (H) a grain of plagioclase, (I) a grain of microcline, (J) chert fragment, (K) muscovite, (L) glauconite, (M) brown tourmaline, (N) monazite, (O) goethite, (P) epidote, and (Q) and (R) moderate sorting.

Trace amounts of tourmaline occur more or less commonly in the studied samples (Figure 3m). The grains of tourmaline lie randomly among those of quartz and feldspars. They are mostly small in size, have rounded outlines and display zoning. The tourmaline appears to be of several compositional types as indicated by variation in the plane light color such as green, blue and brown. All these grains with different plane light colors occur even within a single thin section.

Monazite occurs as one of the heavy minerals in the rocks under discussion. The grains of monazite are generally small and have rounded outlines. They occur in most of the samples and lie randomly among the grains of quartz and feldspar (Figure 3n).

The studied samples of sandstone from the Lumshiwal Formation contain some ore minerals, predominantly rutile having reddish brown to blood red color. Besides, the occurrence of a substantial amount of goethite (~12.61 modal %), an ore mineral of iron, has also been noticed in one of the studied thin sections (Figure 3o). A few of the samples also contain tiny grains of epidote (Figure 3p). Another heavy mineral found in the studied samples is zircon. The grains of zircon are very small in size. It is rather rare and mostly occurs in the form of inclusions in the grains of quartz and feldspar.

Discussion

Degree of sorting, Roundness and Maturity

The overall variation in grain size shows that most of the studied samples of sandstone from Lumshiwal Formation are moderately to poorly sorted (Figures 3a and b). However, samples from the upper part of the formation appear to be well sorted. The framework elements in almost all the studied samples are sub-angular to rounded and sub-prismoidal to sub-spherical (Figures 3q and r). The very high ratio of quartz to feldspar and extreme rarity of rock fragments in the studied samples indicates that the sandstone under investigation is mineralogically mature. However, the degrees of both sorting and roundness of framework constituents, mentioned above, suggest that the studied sandstone is texturally sub-mature.

Modal Composition

For classification of sandstones on the basis of their modal composition, Pettijohn et al. (1987) used the three major framework elements, i.e. quartz, feldspar and rock fragments. According to this classification, sandstones having less than 15 % matrix with a major amount of either quartz, feldspar or rock fragment are named as quartz arenite, arkosic arenite or lithic arenite, respectively. The term sub-arkose and sub-litharenite are used for transitional classes. By plotting on the triangular diagram of Pettijohn et al. (1987; modified from Dott, 1964), which consists of quartz, feldspar and rock fragment each on its three corners, all the studied samples fall in the field of “quartz arenite” (Figure 4).

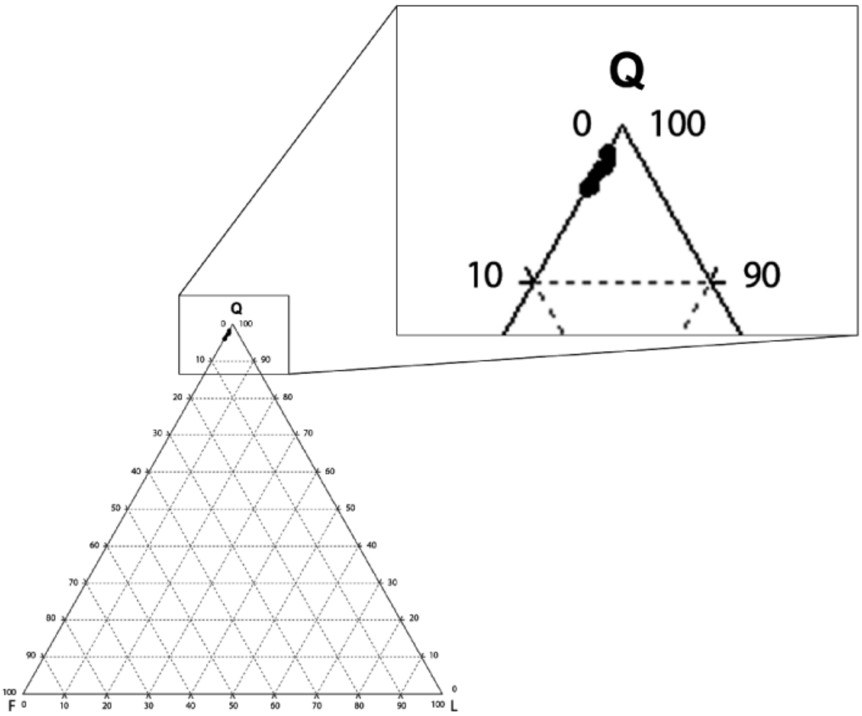

Figure 4- Modal composition of the studied samples of the Lumshiwal sandstones plotted on the Q (quartz) F (feldspar)L (lithic) triangular diagram of Pettijohn et al. (1987) (modified from Dott, 1964).

Provenance

A study of the relevant literature reveals that the type and relative abundance of four detrital components in sandstones are useful and hence more or less commonly employed for determining their provenance (Mackie, 1899; Milner, 1926; Boswell, 1933; Krynine, 1937, 1940, 1946 and 1950; Pittman, 1970; Folk, 1974 and 1980; Basu et al., 1975; Pettijohn, 1975; Young, 1976; Basu, 1985; Morton, 1985; Helmold, 1985; Pettijohn et al., 1987; Amireh, 1991). These include quartz, feldspar, lithic (rock) fragments and heavy minerals. Because of the general scarcity of feldspar and rock fragments, sandstone provenance is mostly established mainly by quartz typology and the study of heavy minerals.

Detrital quartz, because of its high mechanical and chemical stability, is the most abundant mineral in all clastic sediments derived from any common parent rock type. In multi-cycled sediments, some quartz may survive several cycles of erosion and represent some remote parent rocks. Therefore, quartz has the greatest potential of all detrital minerals for reading provenance of arenites (Basu, 1985).

Whereas continuous dislocation produces undulosity in quartz, discontinuous high density lattice dislocation imparts its poly-crystallinity. Lattice dislocation in quartz is much more common in metamorphic rocks than in igneous rocks. Statistically a higher proportion of both moderately to strongly undulose mono-crystalline quartz grains and a higher proportion of poly-crystalline quartz grains with four or more sub-grains characterize a metamorphic source (Basu, 1985). Plutonic rocks tend to produce non-undulose and weakly undulose mono-crystalline quartz grains or poly-crystalline grains with only two or three sub-grains (Basu, 1985). However, according to Folk (1974) and Basu et al. (1975), poly-crystalline grains containing more than five sub-grains with straight to slightly curved inter-crystalline boundaries also suggest a plutonic source. Krynine (1937, 1940 and 1950) worked on the extinction types, nature of sub-grains contact in poly-crystalline particles, grain and crystal shapes and inclusions in the detrital quartz with the same results as that of the above mentioned authors.

The studied samples of sandstone from Lumshiwal Formation contain a higher proportion of non-undulose to weakly undulose mono-crystalline quartz whereas the polycrystalline quartz is rare and much less abundant and predominantly consists of two or three sub-grains with straight to only slightly curved sub-grain boundaries. Hence the predominant source rock for the Lumshiwal Formation could be igneous (plutonic).

Feldspars and rock fragments make up less than 5 modal % of all the studied samples, especially the rock fragments are totally absent from many of the thin sections. The grains of feldspar, where present are mostly cloudy and show evidence of dissolution. According to Pettijohn et al (1987) and Amireh (1991), the scarcity of feldspars and rock fragments suggests that the source area for the sandstone underwent a long period of intensive chemical weathering in a warm humid climate. The feldspar from acidic plutonic rock is believed to be orthoclase or microcline and/or the perthitic alkali feldspar

(Pettijohn, 1975). Although occurring rarely, alkali feldspar is the dominant type of feldspar in the studied samples. Hence their source might have been acidic plutonic.

The heavy minerals (the minor, high density accessory detrital minerals of sandstone) have long been used as indices of provenance because certain assemblages indicate specific source rocks (Boswell, 1933; Milner, 1926). For example, an association of minerals such as apatite, biotite, hornblende, monazite, muscovite, rutile, titanite, tourmaline (pink variety) and zircon indicates an acidic igneous source (Pettijohn et al., 1987). As mentioned in the section on petrography, heavy minerals in the studied samples of sandstone from the Samana section of the Lumshiwal Formation consist most of these phases. Hence it appears that frameworks in Lumshiwal sandstone largely represent acidic igneous rocks.

Environments of Deposition

From a study of samples representing the Lumshiwal Formation at its type locality in the Surghar range, Memon and Teitze (1997) concluded that the sandstone exhibits the features typical of fluvial-dominated deltaic environment. The formation on the basis of lithology can be divided into three parts; each of them represents a particular environment. Danilchik and Shah (1987) suggested that the Lumshiwal Formation was deposited under terrestrial conditions, presumably because of the scattered coal and carbonaceous beds found in its upper part. The most probable gross environments of deposition for the Lumshiwal Formation are shallow marine in the lower part and deltaic in the upper part. This interpretation is based on (i) the predominance of sandstone in the lower part of the formation that is transitional with the underlying marine Chichali Formation, which has a clay matrix with glauconite, (ii) intense burrowing in places, (iii) generally thick-bedded character, and (iv) upward increasing grain size (Galloway and Hobday, 1983; Shah, 1980; Fatmi, 1972; Danilchik and Shah, 1987).

The matrix is almost absent from the Lumshiwal sandstone and quartz is much more abundant than feldspars and rock fragments. These features show very high energy conditions such as that prevailing in a very shallow marine environment (Pettijohn et al., 1987). The absence of matrix and abundance of quartz grains suggests falling of the sea level (Bertram et al., 1996).

Glauconite occurs in the Lumshiwal Formation, and is distributed throughout the formation from its base to top but is more abundant in the upper part. The glauconite is indicative of slightly reducing near-shore, shallow water conditions just below the sediment/ water interface and warm waters (15-20 ˚C) (Pettijohn et al., 1987; Greensmith, 1981; Odin and Matter, 1981). Glauconite is usually regarded as an indicator of marine environment, relatively shallow deposition and slow sedimentation. The mineral is often concentrated at discontinuity surfaces indicating depositional breaks (Amorosi, 1993). This hydrous potassium-iron-aluminum-silicate mineral today forms exclusively in marine environments and is found in carbonate as well as in silici-clastic sediments. In modern oceans glauconite occurs at depths between 50 and 500 m and is abundant in mid-shelf to upper slope settings at depths between 50 and 300 m (Flugil, 2004). Hence the glauconite-bearing beds of the Lumshiwal Formation might have been deposited in somewhat reducing, shallow to moderately deeper water with low sedimentation rate, at or just below sediment-water interface.

Diagenesis

The prominent diagenetic changes observed during the petrographic study of the investigated samples can be grouped into (i) cementation, (ii) compaction and (iii) mineral alteration.

Cementation: The chemically precipitated material, which forms cement, is an important constituent of sandstones (Pettijohn, 1975). Cement present in the sandstone unit of the Lumshiwal Formation from Samana is of three different types; namely silica, ferruginous and glauconitic cement. Of these, silica is the dominant type and occurs as optically continuous secondary overgrowths around the detrital grains. Where post-depositional cementation occurs, quartz is precipitated as overgrowth. The most valid source of silica for overgrowth is probably that generated by pressure dissolution of detrital quartz grains during compaction on burial (Turner, 1980) or by infiltration of silica bearing pore fluids from adjacent areas. With increase in temperature and depth of burial the solubility of silica rapidly increases. The solubility of silica also depends on PH, and the silica cements occur where acid fluids have moved through the pores (Selley, 1985). This silica crystallizes in the available pore spaces as silica cement.

Samples representing the middle part of the Lumshiwal Formation, especially those coming from the 85 m to 130 m depth interval, contain ferruginous cement, which appears to be a result of iron leaching. The precipitation of iron-oxide occurred most probably after the precipitation of silica cement as it is mainly present as enveloping or staining detrital grains, filling micro-fractures within detrital grains and as pigments.Glauconite is present both as cement and in pellet form. The glauconite cement and pellet are considered to be early diagenetic and formed mostly during deposition and very shallow burial under mildly reducing condition. Thus the major diagenetic change in the sandstone unit of Lumshiwal Formation is the precipitation of quartz as overgrowths cement. This discussion reveals that the Lumshiwal Formation was deeply buried under great pressure.

Compaction: Evidences for compaction before cementation are represented by the occurrence of interfering, sutured and corroded grains. In the Lumshiwal Formation the character of contacts between grains varies from point and planar, through interfering to sutured and corroded, depending on the degree of dissolution and compaction. The sutured boundaries appear to be a prominent and diagnostic feature of deeply buried sandstone and are also an indicator of compaction and geothermal gradient (Taylor, 1950). Grains with tangential and concavo-convex contacts rarely occur in the Lumshiwal sandstone. Some of the feldspar and quartz grains are fractured and the fractures are filled with opaque ore minerals.

Mineral Alteration: Another major diagenetic feature commonly observed in sandstone is the alteration of minerals. The minerals which are usually affected by alteration are feldspars and micas. Feldspars are transformed into clay minerals and micas are altered to other micas (chlorite and sericite), hematite and also clay minerals. In the sandstone from Lumshiwal Formation feldspar is altered to clay minerals.

Conclusions and correlation

The broad conclusions from the present investigation are compared with those drawn on the basis of similar studies on Lumshiwal sandstone from Kala-Chitta Range (Ullah and Naser, 1985) and Surghar Range (Memon and Tietze, 1997) in the following lines:

1. The Lumshiwal sandstone from Samana predominantly consists of quartz, accessory amounts of feldspar and only traces of a number of heavy minerals. More or less similar mineralogical composition has also been reported for the Lumshiwal sandstone from Kala-Chitta Range (Ullah and Naser, 1985) and Surghar Range (Memon and Tietze, 1997).
2. The sandstone of the Lumshiwal Formation exhibits mineralogical maturity. In terms of texture, however, it seems to be sub-mature. This is also more or less the case with the Lumshiwal sandstone from Surghar Range (Memon and Tietze. 1997). However, petrograpahic details have led Ullah and Naser (1985) to suggest the Lumshiwal sandstone from the Kala-Chitta Range to be well sorted and texturally mature.
3. The modal mineralogical composition, the optical properties and relative abundance of different types of quartz grains and the nature of heavy minerals all suggest derivation of the Lumshiwal sandstone at the Samana range from a source region dominated by acidic plutonic igneous rocks. However, derivation of such quartz rich sand as occur in the studied samples of sandstone from the Lumshiwal Formation directly from a weathered igneous rock seems improbable. In other words, these sands might have been derived from pre-existing sandstones, i.e. the Lumshiwal sandstone could be multi-cycled.
4. The major cementing material occurring in the Lumshiwal Formation from Samana range is silica as quartz overgrowth in sandstone (this study) and calcite in the limestone units. Similar quartz overgrowths have been observed in the sandy facies of Lumshiwal from both the Kala-Chitta (Ullah and Naser, 1985) and Surghar Ranges (Memon and Tietze, 1997).
5. Important diagenetic events noted in the Lumshiwal sandstone from Surghar Range include compaction, silica cementation, iron oxide cementation, late calcite cementation, replacement, dolomitization, dissolution and recrystallization of calcite and gypsum cementation (Memon and Tietze, 1997). Dissolution of aragonite in some bioclasts and replacement by calcite spar as inter-granular cement and replacement of calcite by dolomite are important diagenetic features observed in the Lumshiwal sandstone from the Kala-Chitta Range (Ullah and Naser, 1985). The notable diagenetic changes in the Lumshiwal sandstone from Samana range consist of precipitation of silica cement as quartz overgrowth, iron oxide cementation and alteration of feldspar to clay minerals (this study). These diagenetic modifications represent the final phase (phyllomorphic stage) of diagenesis probably resulting from deep burial, increased geothermal gradient and pressure as also evident from sutured boundaries of most of the grains and healing of fractures in quartz and feldspar with ore minerals.
6. The Lumshiwal Formation exhibits features suggestive of fluvial dominated deltaic environment at Surghar Range (Memon and Tietze, 1997), but shallow marine at both the Kala-Chitta Range (Ullah and Naser, 1985; Qureshi et al., 2006) and Samana Range (this study).

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