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Clay Mineralogy and Petrography of Basal Sand Reservoir of Badin Block, Southern Indus Basin, Pakistan: Implications for Diagenesis and Reservoir Damage Potential Assessment

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Abstract: Lower Goru Basal sand reservoirs of Cretaceous age offer a multiple challenge such as subtle migration, microporosity and diagenesis due to its heterogeneity. Petrography, scanning electron microscopic analysis with energy dispersive spectroscopy and x-ray diffractometry analysis on selected core samples show that it contains quartz, which is a major framework detrital grain associated with authigenic kaolinite, illite and chlorite minerals. Quartz overgrowth is the major cementation phase, whereas calcareous cement also occurs occasionally, although, basal sand is classified as quartz arenite. Major diagenetic events recognized in the area include compaction, cementation, dissolution and clay authigenesis. While basal sand is clean quartz rich sand, while presence of labile clays like kaolinite, illite and chlorite may cause problem during drilling and production operations. By maintaining fluid turbulence, drilling with mud of less than 10 pH and using hydrofluoric acid instead of hydrochloric acid in acidizing may help increasing production and reducing drilling operations related problems.

Keywords: Diagenesis, kaolinite, basal sand, authigenesis, reservoir damage potential.

Introduction

The Indus basin is the most significant hydrocarbon producing province in Pakistan and extends for approximately 1600 km in a NE-SW direction and nearly 300 km in an east-west direction (Fig. 1). It is divided into upper, middle and lower Indus basins based on local variations in stratigraphy and structural style (Shah, 2009). In the lower Indus basin, a petroleum system that includes lower Cretaceous Sembar Formation (source rock) and overlying lower Goru Formation (reservoir) has been exploited for more than three decades with a high success rate (Jamil et al., 2012). The reservoir in wells drilled in Badin fields exhibits lateral facies changes from east to west, from producible sand/shale facies to entirely shale facies further to the west (Kadri, 1995). The zone of facies changes from sand to shale has been an area of major interest for oil companies, as it has hydrocarbon potential in Badin area and further northwards at least up to Khandhkot (Kadri, 1995). Hydrocarbon exploration and production from the lower Goru basal sands offer a multitude of interpretive challenges with regard to reservoir and its quality variation such as (a) multiple stack on seismic data (b) variable mineralogical and textural composition of reservoir sands (c) diagenesis (d) water sensitivity (e) micro porosity (f) fine migration (g) small hydrocarbon pools (h) variable depositional environment and (j) variation in drive mechanism. These interpretive challenges are primarily due to heterogeneous character of the lower Goru basal sand.

In order to evaluate lower Goru basal sands, two wells namely MD-1 and KD-1 in one of the Badin block fields were selected for the present study (Fig. 2). Aim of the present study is to provide a description of sandstone units of the lower Goru basal sands with special emphasis on (a) petrographic characterization (c) textural and mineralogic variation (c) identification of authigenic clays (d) interpretation of diagenetic alteration (e) assessment of extent of reservoir damage and its tentative solution.

Geological Setting

The Indus basin is located west of the Indian shield. In late Jurassic to early Cretaceous, rifting was followed by northward drifting of Indian plate (Ebdon. et al., 2004). This drifting eventually resulted in collision of Eurasian plate with Indian plate. Plate collision resulted in the formation of Himalayan ranges, characterized by compressional tectonics, in northern Pakistan and Sulaiman Kirthar Ranges to the west of lower Indus basin (Wandrey et. al., 2004). Badin area located in the lower Indus basin exhibits extensional tectonics during Cretaceous time. The area was located away from main deformation zone and hence affected only by a mild degree of deformation (Kemal et al., 1991). Badin rift system came into existence about 127 million years ago (Sahito, et al., 2013). However, major horst and graben system, that provides main entrapment mechanism formed about 100 million years ago (Sahito, et al., 2013, Ebdon. et al., 2004). Subsidence in Badin area resulted in a marine transgression represented by deposition of Chiltan limestone in late Jurassic time. Subsequent divergence and northward drifting of Indian plate throughout Cretaceous led to the deposition of drifting stage sediment represented by Sembar and lower Goru formations (Ahmed, 1988). The lower Goru Formation is primarily composed of upper sands, middle sands and basal (Fig. 3) sands separated by upper and lower shales (Sahito et al., 2013).

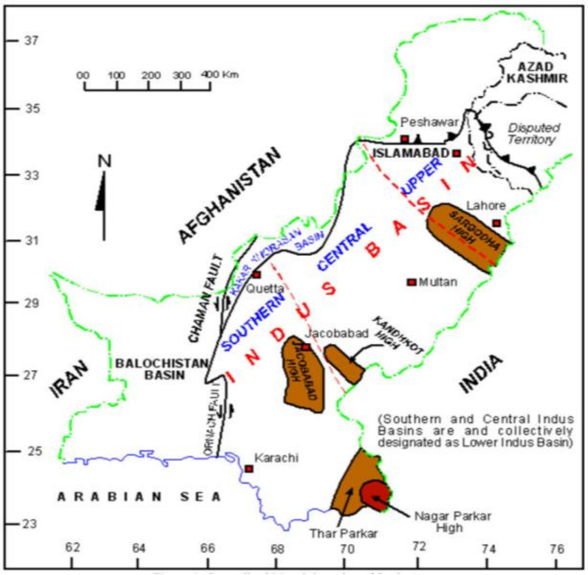

Fig. 1 Sedimentary basin of Pakistan (Farah et al., 1984).

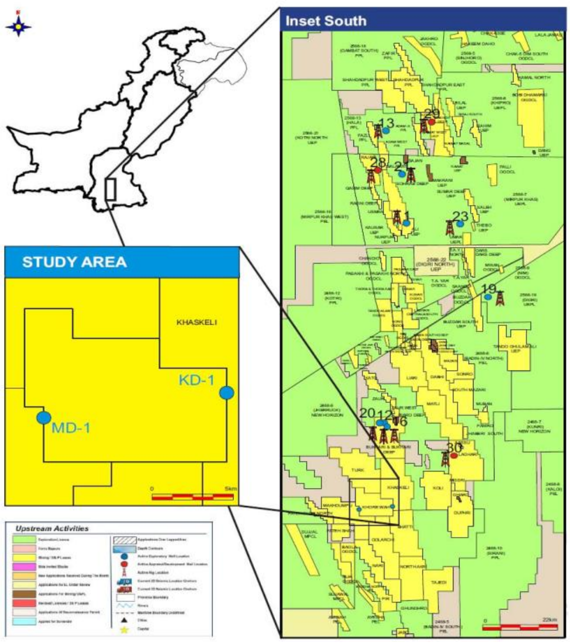

Fig. 2 Location map of study area (PPIS, 2018).

The basal sand unit, consisting of thick sand and shale interbeds, is interpreted as ranging from upper shore face tidal channel and rip-current sandstones to coarse grained deltaic distributary mouth bar sandstones (Nadeem et al., 2004). Thickness of basal sand is 35-50% of the total thickness of the lower Goru Formation. The sandstones of lower Goru Formation are capped by intra formational shales which provide both top seals for individual reservoir sand bodies and lateral seals against faults (Baig et al., 2016). The lower shale and Talhar shale are effective top seals for the upper basal and lower basal sands respectively (Baig et al., 2016). Fields originating from basal sands are Khorewah Deep, Mayun Ismail Deep, Sakhi Deep, Liari Deep Turk Deep, Makhdumpur Deep, Naimat west, Kamal North and Adam X-1 (Ali, 2000; PPIS, 2014).

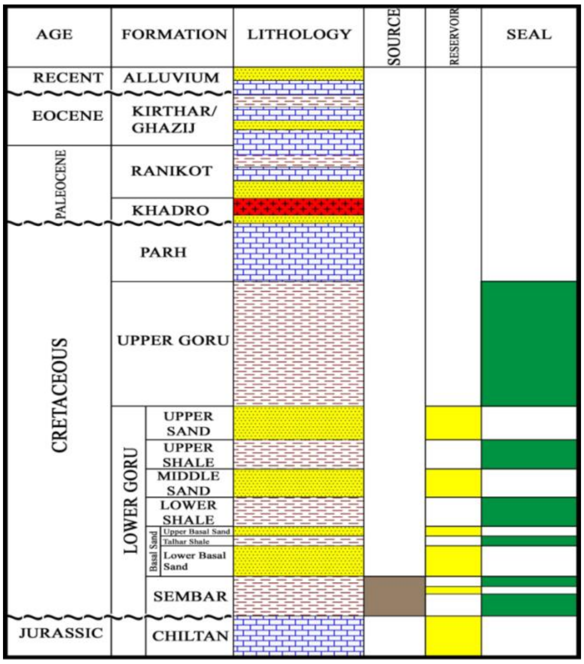

Fig. 3 Geology of study area (Mozaffar et al., 2002).

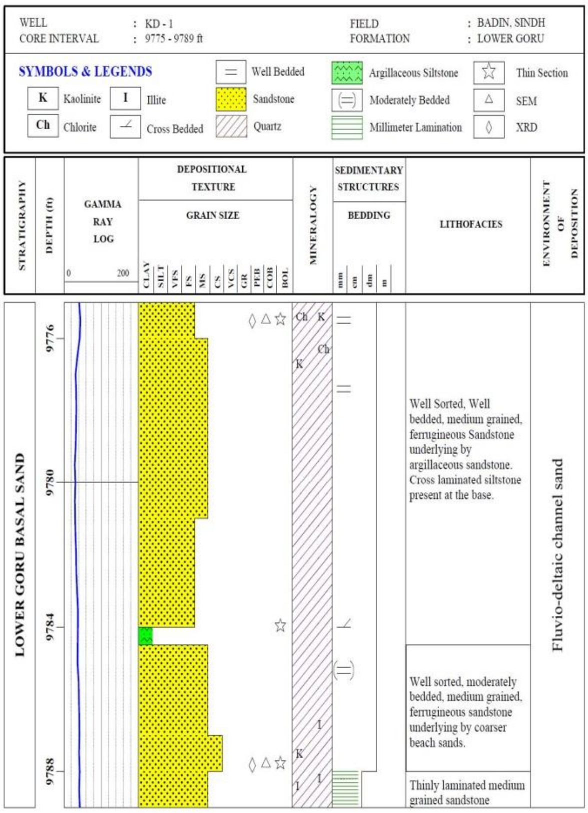

Fig. 4 Core log of lower Goru basal sand of well KD-1.

Materials and Methods

This study is based on core samples collected from wells MD-1 and KD-1 in Badin block. Analytical techniques used to carry out include petrography, scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) and x-ray diffractometry (XRD). Mineral identification in thin sections was based on scheme of Scholle (1979). Thin section petrography was used to determine whole rock mineralogy, diagenetic relationships, porosity characteristic and clay/quartz overgrowth. XRD provides a thorough assessment of crystallographic structure, grain size, morphology, mineral association and semi quantitative mineralogical determination of clay samples. SEM was carried out to characterize authigenic clays, intergranular cement and mineral alteration. This is accomplished by using SEM in conjunction with built-in EDS. Samples were prepared by dispersing dry powder on stubs and were coated up to 300°A with gold. Operative parameter for the JEOL. 6380 LA SEM is 20kv high voltage level.

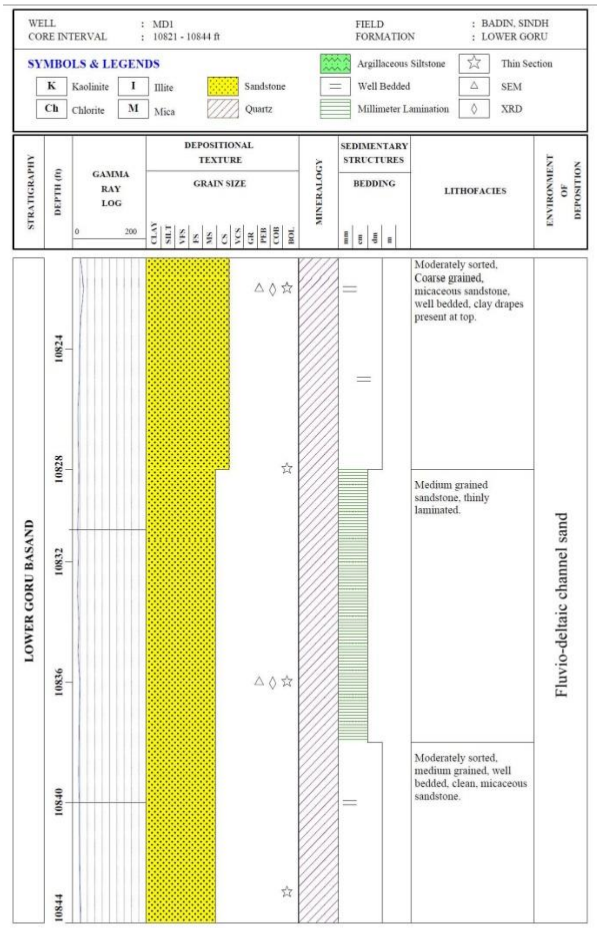

Fig. 5 Core log of lower Goru basal sand of well MD-1.

Results and Discussion

The representative core samples were taken from both wells for the evaluation. The visual core study has also been done on the entire core to observe the sedimentary structures, grain size, mineralogy, bioturbation, diagenetic effects etc. The depth of core samples and gamma ray log response, visual core studies and its depositional environment is shown in core log of both wells (Figs. 4, 5).

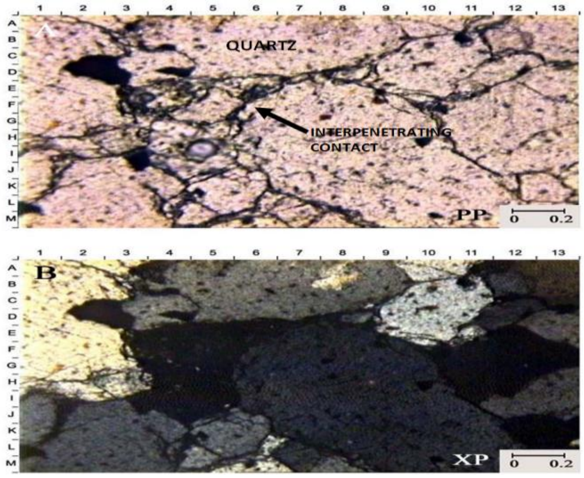

Fig.6 Thin section photomicrographs of basal sands, well MD-1 (10,828ft), detrital quartz grains surrounded by clays with interpenetrating contacts. A. PP (plane-polarized light): B. XP (cross-polarized).

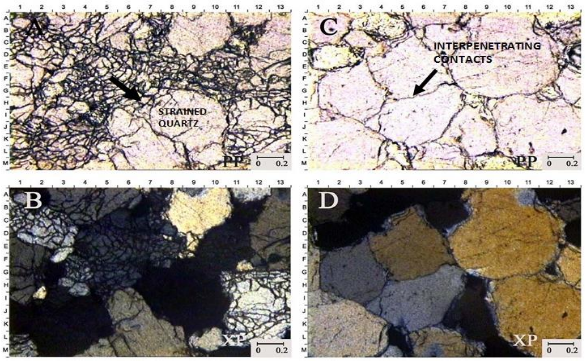

Fig. 7 Thin section photomicrographs of basal sands, well MD-1 (10822ft). A&B highly compacted quartz grains with no visible porosity. C & D concavo-convex and sutured grain contacts with quartz.

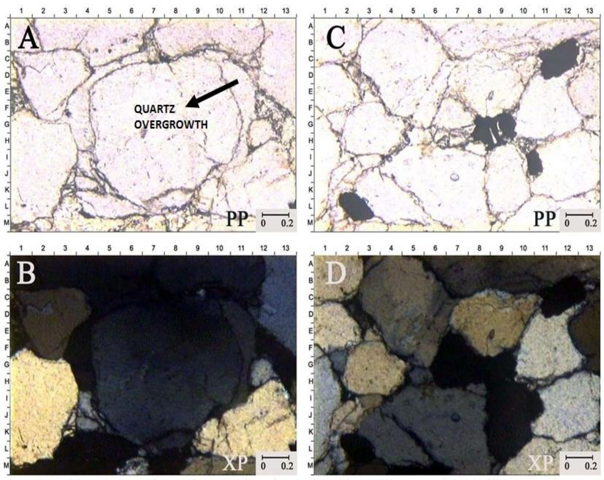

Fig. 8 Thin section photomicrographs of basal sands, well MD-1 (10836ft). A & B quartz overgrowth in quartz arenite surrounded by clays. C & D sutured grain contacts with quartz over growth.

Petrography

Thin section petrography of selected core samples of basal sand from well MD-1 shows that quartz is the main framework grain (95%). Quartz is typically medium to coarse grained, sub-rounded to sub angular, well sorted in most samples (Fig. 6). Both monocrystalline and polycrystalline quartz grains are found. Quartz overgrowth is developed, with suture and interpenetrating contacts. Grains are tightly packed with no visible porosity. Quartz grains are clear and clean but, in some samples, strained quartz is also present (Fig. 7). Cementation is primarily by quartz overgrowth, easily detected in photomicrograph because of the clear "dust rim" between detrital grain cores and the authigenic overgrowths (Fig. 8). Some interstitial clay is present but may be, in large part, authigenic. There is complete destruction of primary porosity by cementation filled interparticle porosity. According to Folk (1970), basal sand from well MD-1 is classified as quartz arenite. Overall this is texturally and mineralogically mature sandstone.

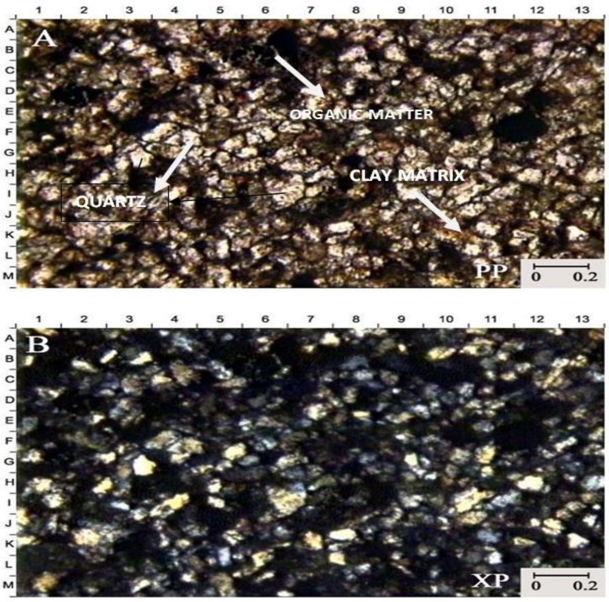

Fig. 9 Thin section Photomicrographs of basal sands, well KD-1 (9788.2 ft), fine grained quartz arenite with argillaceous matrix and organic matter. A. PP (plane-polarized light): B. XP (cross-polarized).

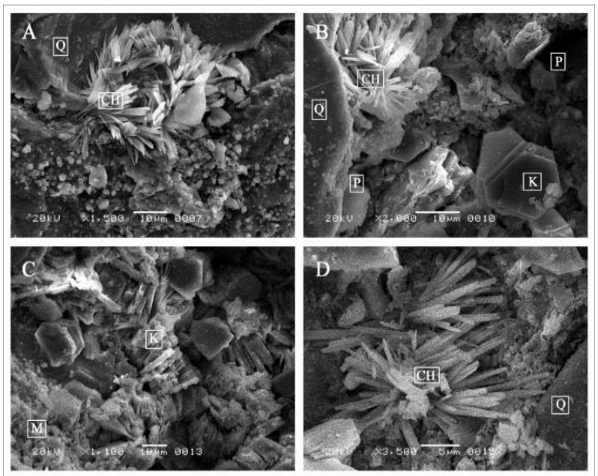

Fig. 10 SEM image of basal sands, well MD-1 (10836ft). **(A)** authigenic chlorite (CH) coating around the quartz (Q) **(B)** chlorite not completely coated quartz grain and dissolution porosity (P) present with hexagonal booklet of kaolinite (K). **(C) a**uthigenic kaolinite booklets with some mixed clay (M). **(D)** rosette shape chlorite cluster with quartz.

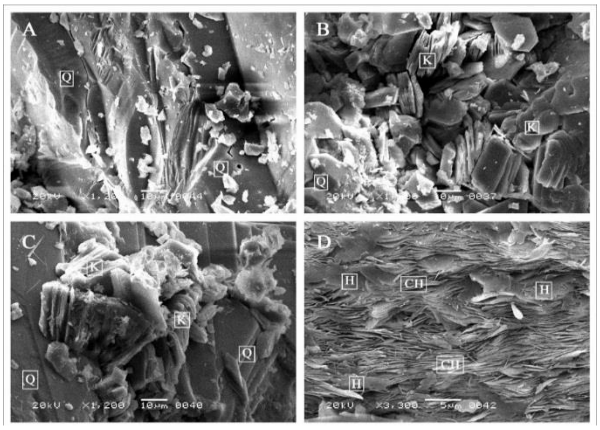

Fig. 11 SEM image of basal sands, well MD-1 (10822ft). **(A)** quartz with conchoidal fracture **(B)** kaolinite with intercrystalline porosity **(C)** kaolinite is enclosed by quartz **(D)** authigenic chlorite with hematite (H).

Petrography of selected basal sand sample from well KD-1 shows that the most dominant detrital mineral present is quartz having composition >95% (Fig. 9). Shale or clay is present as a matrix between grains and observed in the form of patches, which is clearly discriminated by brownish color. Abundant blebs of organic matter disseminated throughout field of view (Fig. 9). The sandstone is overall very fine grained and tightly packed. The grain morphology of KD-1 shows that it is made of well sorted sands in which angular grains are more dominant. The diagenetic effects can clearly be inferred by interpenetrating contact. The basal sands of KD-1 are mineralogically mature. According to Folk (1970) this basal sand from well KD-1 is classified as quartz arenite.

SEM with EDS Analyses

The SEM study of some selected samples of basal sand shows that quartz(Q) is dominant framework grain surrounded by chlorite (CH) and kaolinite (K) minerals (Figs. 10, 11). The smooth planer surface of quartz overgrowth indicates quartz overgrowth. The pseudo hexagonal vermicular stacks of authigenic kaolinite are found occluded in inter granular porosity (P). The secondary inter crystalline porosity is also developed between kaolinite. Authigenic chlorite cement is present in the form of rosette shape clusters associated with quartz grains. This growth morphology shows pore lining texture of chlorite cement. Traces of hematite (H) are also associated with chlorite cement. The EDS analysis also supports SEM data interpretation (Fig.14).

The SEM with EDS analysis of selected samples of basal sand shows that quartz is associated with kaolinite, chlorite and illite mineral (Figs. 12, 13). Quartz overgrowth is also present and shown by its smooth well-developed crystal faces. Quartz grains are surrounded by both depositional and authigenic nature of chlorite (CH) cement. Feldspars (F) which have undergone partial dissolution are also readily recognizable in images. Authigenic kaolinite pseudo hexagonal booklets also accompanied with feldspar dissolution. Authigenic Illite (I) is, characterized by sheet like flakes with wispy and fibrous termination bridging the pores, also associated with kaolinite. The EDS results also supported the SEM images interpretation (Fig. 15).

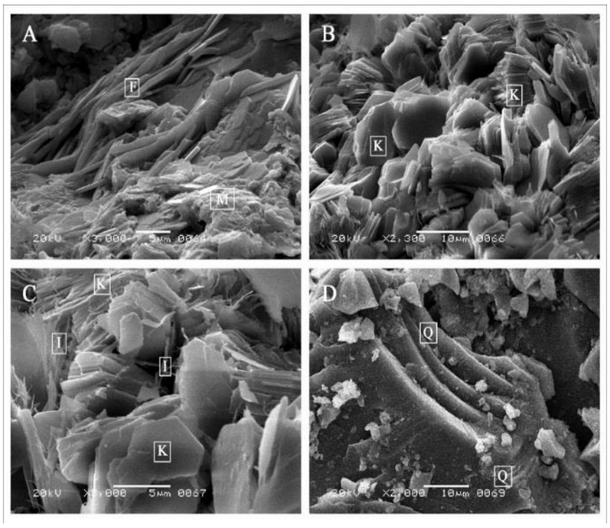

Fig. 12 SEM image of basal sands, well KD-1 (9788.2ft). **(A)** Dissolution of feldspar associated with some mixed clay mineral (M) **(B)** authigenic kaolinite **(C)** kaolinite booklets with intercrystalline porosity bridging by illite (I) **(D)** conchoidal fracture in quartz.

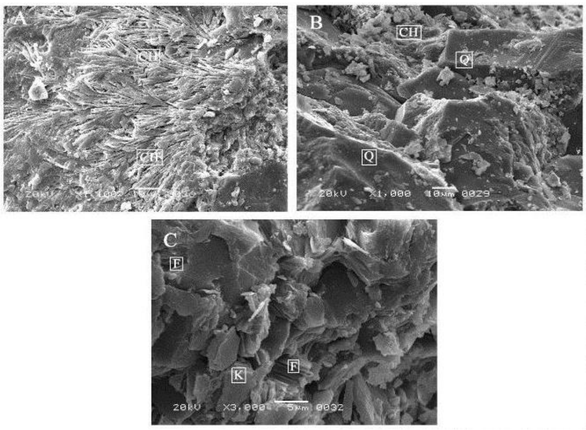

Fig. 13 SEM image of basal sands, well KD-1 (9775ft) (A) Authigenic chlorite pore filling clays. (B) quartz overgrowth. (C) kaolinite booklets with some traces of altered feldspar (F).

XRD Analysis

The mineralogical analysis of core samples from well MD-1 and KD-1 by XRD also supported thin section petrography and SEM data analysis. The XRD data of basal sand from well MD-1 shows that the sample contains quartz as the only dominant detrital mineral with subordinate clays (Fig. 16). The XRD data of basal sand from well KD-1 shows that it contains quartz as dominant mineral with kaolinite and chlorite clays (Fig.17).

Diagenesis

The main objective of sandstone diagenesis study is not only for predicting reservoir quality but also for better description of certain diagenetic (secondary/ authigenic) minerals, which can severely affect formation evaluation and reservoir damage, if improper type of fluid was used during well completion and or production (Pittman, 1982; Schaible et.al., 1986). The interpretation of diagenesis was done by integration of SEM, XRD and thin section petrography results. The main diagenetic events recognized in basal sand include cementation, compaction, dissolution, and clay authigenesis.

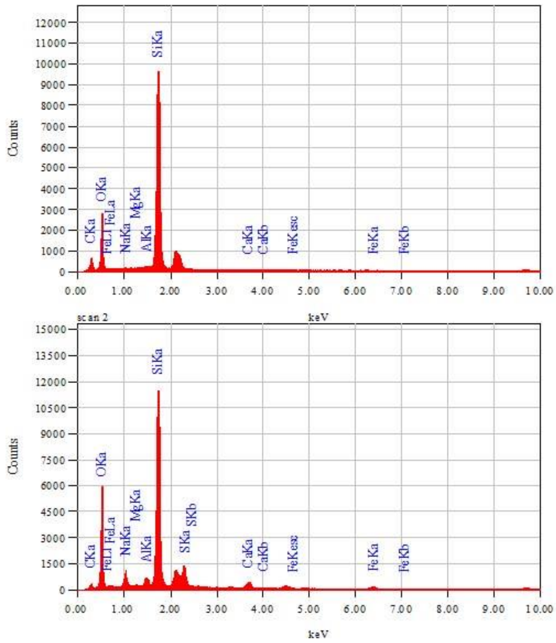

Fig. 14 Elemental analyses by EDS of basal sands, well MD-1.

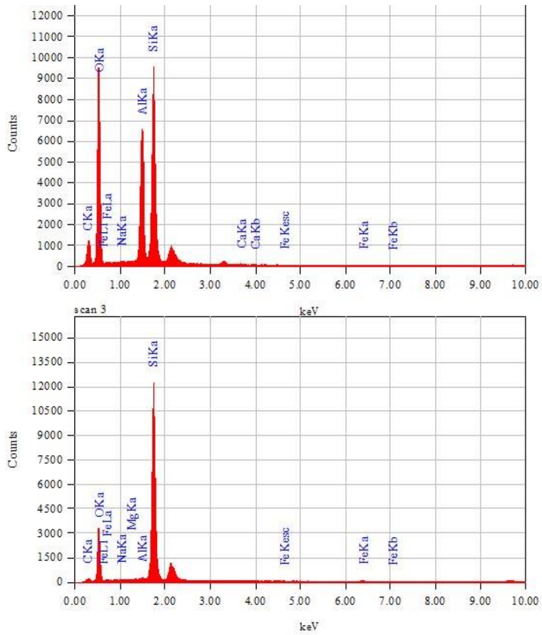

Fig. 15 Elemental analyses by EDS of basal sands, well KD-1.

Cementation

The basal sand of both wells is dominantly cemented by quartz overgrowth, which are best seen in SEM images (Figs. 11, 13); and also evident in photomicrographs (Figs. 7, 8). Authigenic quartz in basal sand shows several relationships with other authigenic phases that may help in interpretation of paragenetic sequence. Whilst, in some SEM images quartz overgrowth is clearly overlain by kaolinite and in others, authigenic kaolinite is enclosed by quartz overgrowth (Fig. 11). Typically, quartz overgrowth is nearly absent when chlorite rim is present. However, where coverage of grain is incomplete, quartz has been able to nucleate and has overgrown (Fig. 10).

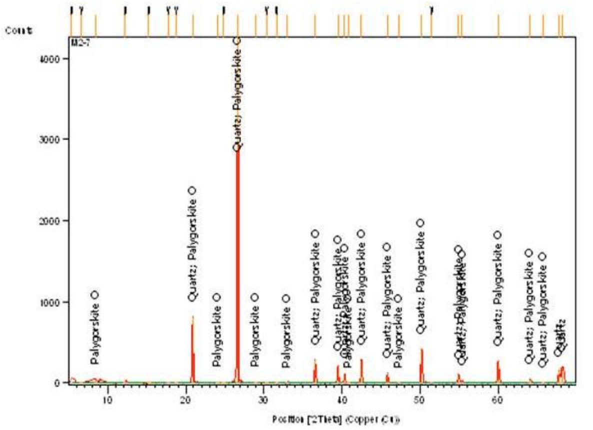

Fig. 16 X- ray diffraction analysis (XRD) of basal sand, MD-1 (10836 ft) shows quartz mineral associated with clays.

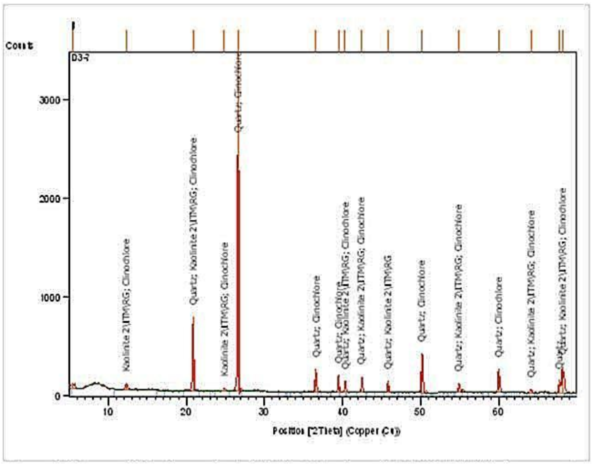

Fig. 17 X- ray diffraction analysis (XRD) of basal sand, KD-1 (9788.2ft) shows quartz mineral associated with kaolinite and clinochlore (chlorite) clays.

Authigenic Clays

Authigenic kaolinite occurs in basal sand as pore filling mineral. According to the Hurst and Nadeau, (1995) delicate euhedral booklets, vermicular texture, high intercrystalline porosity within patches of pore filling kaolinite indicate an in-situ diagenetic origin of kaolinite. The SEM images of basal sand show that the euhedral booklets of kaolinite in pseudo hexagonal crystal morphology mineral with intercrystalline porosity are evident of its diagenetic origin (Figs. 11, 12). The presence of kaolinite is evidence of open system in which meteoric water is dominant. Illite also occurs in basal sand characterized by hair like fibrous and elongate crystals. The SEM data show that at a depth of 9788 feet in well KD-1 the kaolinite is altered into illite and occurs as pore bridging clay mineral within intercrystalline porosity of kaolinite (Fig. 12). Illite is rarely present in well MD- 1. The presence of illite in KD-1 well is evident of a closed system in which kaolinite alters into illite. Chlorite grain coats prevent nucleation of quartz cements, as was noted by Berger et al. (2009) for the upper sand in the lower Goru Formation in the lower Indus basin. Same phenomenon has been reported in many sandstones elsewhere (e.g. Dutton et al., 2013; Anjos et al., 2003; Echikh, 1998; Bloch et al., 2002). Chlorite is present in almost all the core samples of basal sands (Figs. 10, 11 & 13). The authigenic or diagenetic chlorite occurs as grain coatings. Since the silica overgrowth is inhibited by chlorite coatings, quartz overgrowth must predate chlorite formation. Chlorite precipitates by alteration (Anjos et al., 2003), dissolution of volcanic fragments and alteration of kaolinite (Klass et al., 1981).

Compaction and Dissolution

The basal sands were subjected to intense mechanical and chemical compaction. This is evident by inter penetrating and sutured contacts (Figs. 6, 7). The stylolite also observed in visual core study of well MD-1 is evident of pressure solution. Overall, basal sand are tightly packed and compacted sands with no visible well-defined porosity. The dissolution of feldspar is clearly distinguished in SEM images of basal sand. It is an important process of diagenesis responsible for clay and silica overgrowth formation. Although clay formation reduces the porosity in basal sand, but dissolution of feldspar may create secondary dissolution porosity. The removal of feldspar with increasing burial depth results in enhancement of quartz arenitic nature of basal sands (Figs. 12,13).

Paragenetic Sequence

The paragenetic sequence established by integration of all the data present in this study is given in Figure 18. Compaction starts soon after deposition. The mechanical and chemical compaction in basal sand starts during early stages of diagenesis and continues till late stages. Mechanical compaction is dominant in siliceous sediments to a burial depth of about 2 km (6562feet) (>70-80°C) (Bjorlykke, 1999a, 1999b) because of low silica mineral reaction at low temperatures. The first authigenic mineral formed in basal sand during early stage is chlorite that occurs as grain coating rosette shape morphology. This chlorite coating is not successful to cover the entire grains. Dissolution of feldspar starts during early stage of diagenesis. At burial depth of >2km (>6562feet) (>70-80°C) quartz precipitation around detrital quartz grains produces a framework of quartz overgrowth which prevents further mechanical compaction (Bjorlykke, 2014). The possible sources of silica for quartz overgrowth are pressure solution and dissolution of feldspar. The quartz overgrowth formed afterwards nucleates the quartz grains, as chlorite formed earlier had not entirely covered quartz grains. The dissolution of feldspar results in kaolinization that occurs as pore filling clays. Authigenic illite occurs as pore bridging clays. The authigenic illite is formed after kaolinite as it fills the intercrystalline porosity within kaolinite. When sandstone is buried to greater depths of 3.5-4.0 km (9843 to 13,123feet), > 130°C) kaolinite will dissolve and react with any K-feldspar or other sources of potassium present, resulting in precipitation of illite and quartz (Bjorlykke, 2014). The presence of illite in SEM images of well KD-1 and its present depth of basal sand shown in core log are evident of illitization by alteration of kaolinite in the presence of K-feldspar (Fig. 12). The second phase of chlorite is also observed where it occurs as pore filling clays (Figs. 11, 13).

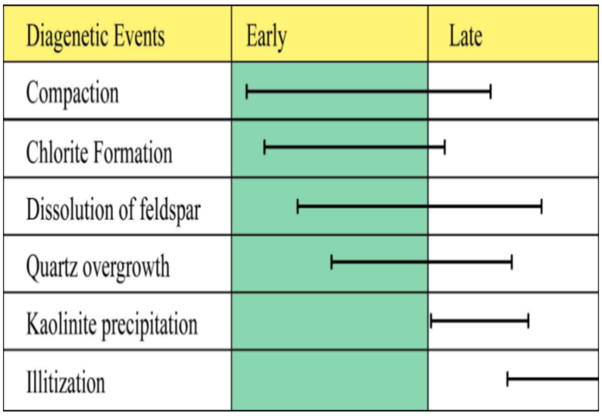

Fig. 18 Paragenetic sequence of lower Goru basal sand as established by integration of all analytical data of present study.

Implication for Reservoir Quality

The reservoir quality assessment of lower Goru basal sand has been made by comparing petrographic data obtained by thin section, SEM and XRD techniques. Overall, basal sand encountered in both wells are quartz arenite and hence mineralogically mature sandstone. The petrographic data show that compaction is the most dominant process reducing porosity in basal sand. Quartz overgrowth is also significant phenomenon, which strongly affected the reservoir quality by reduction in porosity. The presence of chlorite coating around the detrital quartz helps to restore primary porosity and permeability by inhibiting the development of quartz overgrowth (Worden and Morad, 2003). The authigenic kaolinite occurs as pore filling clay reducing the interparticle porosity but on the other hand due its platy crystal morphology, it also helps to introduce intercrystalline porosity in basal sand. Dissolution of feldspar also helps to increase the reservoir quality by adding secondary dissolution porosity. The presence of illite in well KD-1 is not good as it is occluding the intercrystalline and interparticle pore spaces and hence damages the reservoir quality of basal sand.

Reservoir Damage Potential and Tentative Solution

The petrography of core sample of MD-1 and KD-1 shows certain minerals that may cause production problems. Kaolinite is found present in almost all core samples, which occurs as hexagonal plates that are generally loosely bound to pore walls. Kaolinite clay crystals are easily dislodged and migrated under certain conditions such as high fluid turbulence, if put in contact with fresh water based fluid or high pH (>10) fluids. High fluid turbulence resulted from high well/ formation pressure may be minimized using low under balanced differential pressure (not exceeding above 2000 psi). The use of KCL, $CaCl_2$ and NaCl as completion fluid and the pH of drilling mud below 10 are recommended (Musu and Prasetyo, 2001). Illite and chlorite should also be considered attentively during enhanced recovery operations. During acidizing for the removal of calcite cement, 15% HCL should probably be avoided as it reacts with these iron clays and forms gelatinous mass (ferric hydroxide) which will occlude pores and pore throat. In this case Hydrofluoric (HFL) acid is preferable (Musu and Prasetyo, 2001).

Conclusion

The sandstone of MD-1 and KD-1 are classified as quartz arenite. The thin section studies show that the only dominant detrital mineral present in both boreholes are quartz. This shows that it possesses good reservoir quality. The mechanical compaction in basal sand is very intense, therefore it loses its primary porosity. The dissolution of feldspar introduces dissolution porosity as well as intercrystalline secondary porosity between kaolinite. The authigenic clays include kaolinite, illite and chlorite. The presence of illite in KD-1 is the evidence of its deep burial of diagenesis. The basal sand is mainly cemented by quartz overgrowth but occasionally has calcareous cement. The major diagenetic events in studied wells include compaction, cementation, dissolution and clay growth. The presence of kaolinite, chlorite and illite may cause challenges during enhanced recovery operations. By maintaining fluid turbulence, drilling mud of less than 10 pH during drilling and using HFL instead of HCL in acidizing may be helpful in enhancing the production operations.

Acknowledgements

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