Reservoir Characterisation of Lower Cretaceous Clastic Succession of Nizampur Basin, Eastern Tethys; Pakistan

Faheem Ahmed[1], Muneeba Ahmad[1], Maqsood Ur Rahman[1], Muhammad Sarim[1], Muneeb Ur Rehman[2] and Muhammad Javed[3]

[1]National Centre of Excellence in Geology, University of Peshawar

[2]Department of Earth Sciences, Xi'an Shiyou University

[3]Department of Geology University of Peshawar, KP, Pakistan

Corresponding author's email: faheem.khattak95@gmail.com

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Abstract

The present integrated study is held to carry out the control of depositional and diagenetic processes on the reservoir potential of the Lower Cretaceous sequence within Nizampur Basin (Kahi Village section) and Kalachitta Range (Tora Stana section). This study was carried out in order to analyse the effect of the depositional and diagenetic processes on the reservoir potential of the studied strata. The Lower Cretaceous sequence at the western part of the Kala Chitta Ranges is mainly composed of sandy limestone and sandstone facies. Petrographic details show that the sandstone is mineralogically mature in both sections while it is texturally immature to sub-mature at Tora Stana section and sub-mature to mature at Kahi Village section. The microscopic details indicate that the sandstone at Tora Stana section is deposited in inner to middle shelf setting, while it indicates moderate to high energy condition of beach to inner shelf setting in Kahi Village section. The results of Image J software shows that the porosity of this clastic succession ranges from 2-5% at Kahi Village Section, while in the fractured and dolomitic samples the porosity exceeds up to 13.5%. The dolomites are in the form of small patches which will not add pronounced contribution to the overall porosity. At Tora Stana section the average porosity ranges from 4-7%.

Keywords: Kala Chitta Ranges; Lower Cretaceous sequence; Petrography; Reservoir characterisation.

1. Introduction

The Lower Cretaceous sequence is well exposed in the Indus Basin of Pakistan. Previously, the petrographic attributes, provenance and depositional environment of the Lumshiwal Formation pertaining to the same sequence was studied by Arif et al. (2009) in Samana Range. Qureshi et al. (2006) established lithofacies and depositional environment within the Lower Cretaceous sequence of Upper Indus Basin in Kalachitta Range. The petrophysical details of the Lumshiwal Formation in Kahi-01 well indicate few probable zones for the accumulation of hydrocarbon, however, lesser effective porosity of the same unit hinders its reservoir quality (Saddique et al., 2016). The detailed literature review shows that a proper link between the reservoir attributes, depositional environment and diagenetic fabric for the Lower Cretaceous clastic succession is still far from over. This study is therefore designed to investigate the Lower Cretaceous strata of Nizampur Basin and Kalachitta Range and to establish a possible link amongst the reservoir attributes, depositional and digenetic details of the same strata. The present study will supplement the existing knowledge on the area particularly in aspects of sedimentology and reservoir potential.

2. Geological Setting of Study Area

The Kala Chitta Range of the Hill Ranges is a narrow strip of the mountainous belt extending in E-W direction merging laterally into the Hazara Mountain in the east and Kohat and Samana Range in the west (Yeats and Lawrence, 1984). These ranges are bounded to the north by the Attock-Cherat Ranges and Peshawar Basin, to northeast by Gandghar Ranges and to the south by Main Boundary Thrust (MBT) (Burbank, 1982; Hylland, 1990). The Hissartang Thrust marks the northern boundary between the Attock-Cherat Ranges and Kala Chitta Ranges while MBT marks its southern boundary with Kohat and Potwar basins (Yeats and Hussain, 1984 and 1987). The Kala Chitta Ranges represents the Lesser Himalayan front in the northwestern Himalayas (Yeats and Hussain, 1984 and 1987).

Triassic to Eocene rocks strata are exposed in the Kalachitta Range (Fig. 1). The Lower Cretaceous strata are well exposed in two widely spaced stratigraphic sections i.e. Kahi Village Section (KVS) and Tora Stana Section (TSS) (Fig. 2). In both stratigraphic sections the main lithological units are comprised of sandstone and sandy limestone. The sandy limestone unit in both sections are bioclastic in nature and is partially dolomitized. In TSS the massive and glauconitic sandstone may corresponds to Chichali Formation of Upper Indus Basin. The typical quartzose sandstone of the Lumshiwal is not developed in TSS. In the KVS the bioclastic sandy limestone and quartzose sandstone may corresponds to the Lumshiwal Formation. The green glauconitic strata at the base of the Lumshiwal Formation corresponds to the Chichali Formation is not measured and logged. The purpose of this study is to unravel the depositional and diagenetic attributes and its effects on the reservoir quality of the Lower Cretaceous strata. In order to have better constrain on the depositional environments of the studied strata, glauconitic sandstone strata is measured and logged in TSS while the bioclastic limestone and quartzose is measured and logged in KVS.

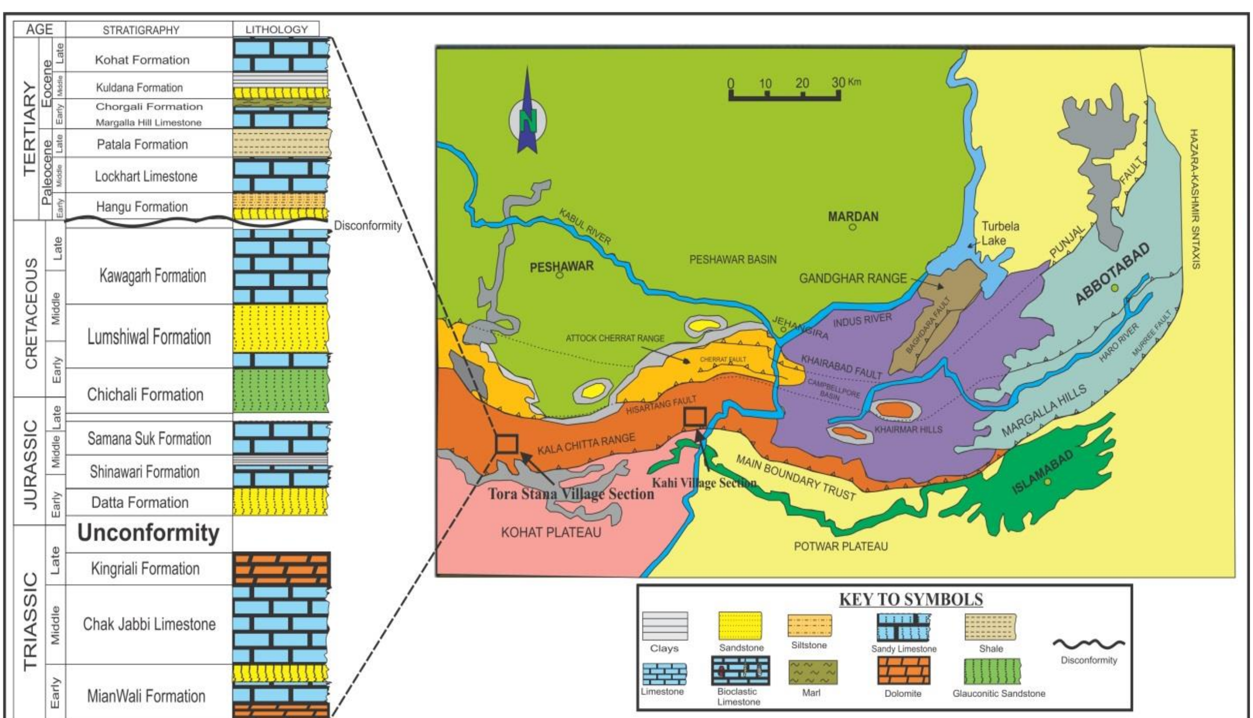

Fig. 1. Shows the tectonic setting and the stratigraphic sequence of the study area (compiled from Yeats and Hussain, 1987).

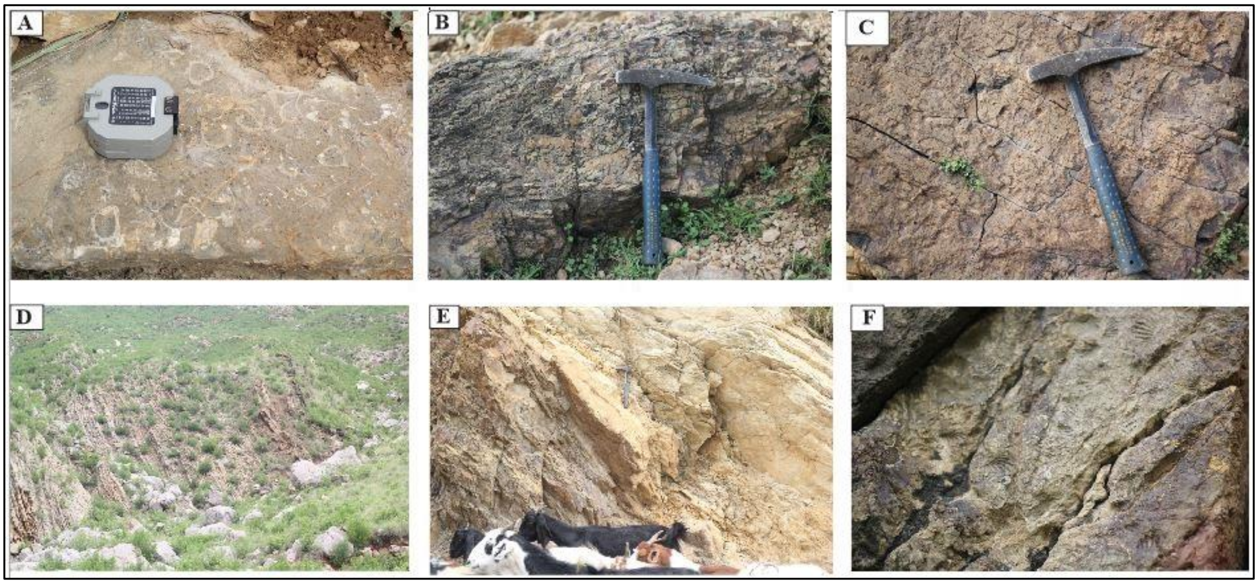

Fig. 2. Field photographs represent the field observation of the lower Cretaceous sequence in the study area. **(A)** show the bivalves in sandy limestone unit of KVS **(B)** show dolomitic effect in sandy limestone unit **(C)** show the fractured sandstone. **(D)** show the regional view of the lower cretaceous sequence at TSS **(E)** show the variation in lithological variation from sandstone to sandy limestone **(F)** show the sandy limestone unit of the TSS.

3. Methods and Materials

Two stratigraphic sections i.e. KVS and TSS were measured and logged. A total of 35 representative rock samples were collected. During field all the lithostratigraphic details are documented and photographed. Thin sections of the collected rock samples were made in rock cutting laboratory of the National Centre of Excellence in Geology (NCEG), University of Peshawar (UOP). The petrographic details were examined and photomicrographs were taken under the polarising microscope (Nikon LV100ND) at Sedimentology Laboratory of NCEG. The sandstone was classified after Dott (1964). The qualitative descriptions of various textural attributes of sandstone were inferred using the Selley (2001). The microfacies within the carbonates were established according to Dunham (1962). The Microfacies of the TSS and KVS are labelled as TSL and KVL respectively. The paragenetic sequences of both stratigraphic sections were established. The porosity of all samples is determined using the "Image j" software (see e.g. Rahman et al., 2016, 2017; Hayat et al., 2016; Haeri, 2015; Grove et al., 2011).

4. Results

4.1. Petrographic Description of the Sandstone

The petrographic details of the sandstone units in studied stratigraphic sections are as under;

Essential minerals

Quartz:

The sandstone units from both sections are mainly composed of Quartz. The overall abundance of Quartz recorded in all the samples is about 85-90%. At both sections, the quartz grains are sub-angular to sub-rounded, though the quartz of the upper part of the KVS is rounded to well rounded. The quartz grains in the TSS are fine to medium grained with rare coarse grains (Fig. 3) while in KVS, the quartz grains are medium to coarse (Fig. 4). The sphericity is low to medium at TSS while it is high in the upper part of KVS (Fig. 3, 4B, C).

Glauconite:

Glauconite is present in an appreciable amount in both sandstone and carbonates units. It is distributed throughout the TSS, while it is restricted to the lower to the middle part of the KVS. The grains of glauconite are authigenic and these replace detrital quartz at places (Fig. 3A). The majority of the grains are sub-rounded to round with moderate to high sphericity. Glauconite grains are mostly floating, however some grains with pointed contacts in TSS (Plate 3A) and planer contacts in KVS are also recorded (Fig. 4, H).

Accessory Minerals:

Heavy minerals constitute about 1–2 % of the sandstone of KVS and TSS. The heavy minerals are subrounded and fine-grained. Trace amounts of muscovite flakes and twinned plagioclase occurs in sandstones of TSS (Fig. 3F).

Sorting:

The sandstones of TSS are moderate to well-sorted (Fig. 3), while the sandstones of KVS are moderately sorted (Fig. 4A-E). However, the well-sorted sandstones occur in the upper part of the KVS (Fig. 4F).

Cement:

The brown to dark brown ferruginous cement is the major matrix type in the sandstone of TSS (Fig. 3). Leeching is common from the ferruginous cement. The cement is concentrated along fractures and stylolite seams (Fig. 3C, D). The calcite and dolomite fills the interstitial pores in the sandstones of the KVS (Fig. 4, B, E, K, and L). Quartz overgrowths are common, the probable silica source being the pressure dissolution of detrital quartz grains during compaction as evident from sutured grain contacts (Fig. 4A, E).

4.2. Mineralogical and Textural Maturity

The mineralogical maturity is determined by the crystallinity of quartz grains and its type of extinction (Carozzi, 1993). The mono-crystalline quartz grains, with uniform extinction abundance dominates over the deformed and polycrystalline quartz grains in all the sandstone samples and are mineralogically mature. The textural maturity of the sandstone is determined by the proportion of matrix, degree of roundness and sorting of their framework grains. In TSS and lower part of the KVS the relative abundance of the matrix, moderate to well sorted and subangular to sub rounded grains suggests these sandstones to be texturally immature to sub-mature. The sandstone in the upper part of the KVS are texturally mature and are well to very well sorted, sub-rounded to rounded, and contain low amount of matrix.

4.3. Modal Composition

The modal composition of the Lower Cretaceous Sandstone was determined using volume percentages of the framework grains and was plotted in the classification diagrams of the Dott (1964). In the studied sections sandstone are classified as “Quartz Arenites” at KVS and “Quartz Wackes” at TSS (Fig. 5).

4.4. Microscopic details and microfacies of TSS

a) TSL 1: Glauconitic sandstone facies

In the outcrop this facies is represented by white to pale yellowish and olive grey, fine to medium grained thick-bedded sandstone. The total thickness of this microfacies is 30 meters (Fig. 6). Petrographically, quartz constitutes about 40-45% of this sandstone, while glauconite ranges between 6-10%, while the rest are bioclasts and cementing materials. The quartz grains are sub-angular to sub-rounded and moderate to well sorted. Glauconite is present both as cement and in pellet form.

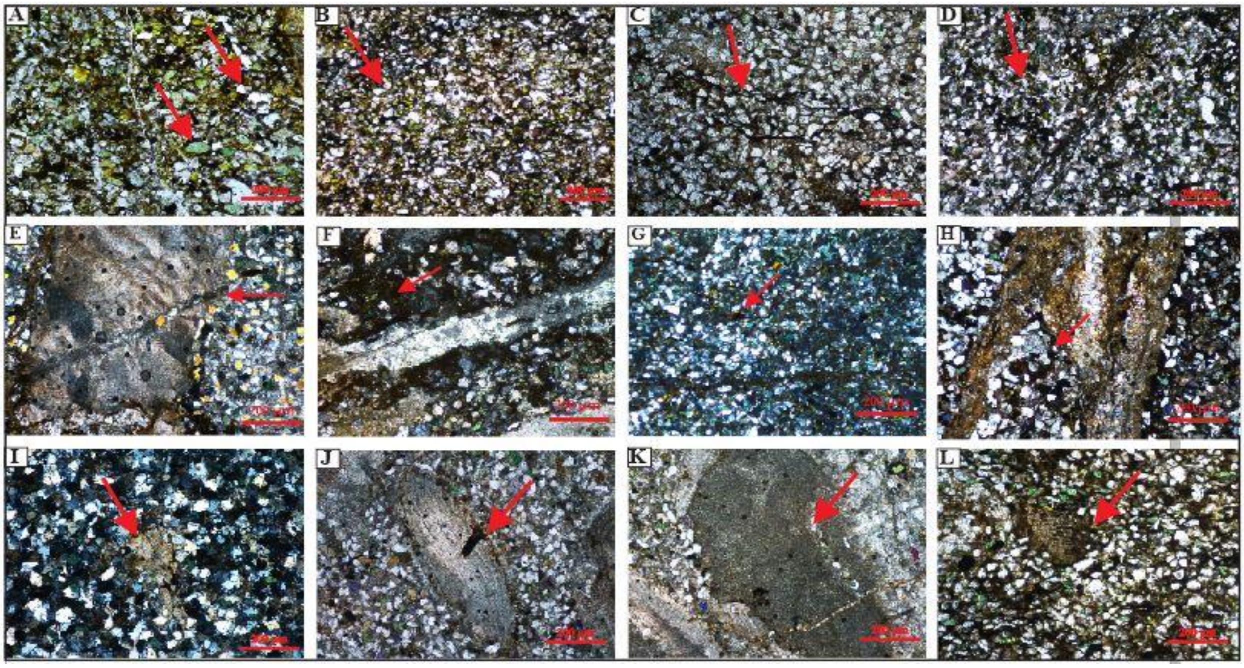

Fig. 3. Shows the photomicrographs of TSS sandstone (**A**) Glauconitic sandstone (**B**) Fine grain sandstone (**C-D**) Sandstone with ferruginous filled stylolite (**E**) Quartz Wacke; containing quartz grains along with bioclasts (**F**) Angular quartz with heavy minerals (**G**) Quartz Wacke containing fine grain quartz grains with ferruginous cementing materials (**H**) Quartz Wacke containing dolomite rhombs and bioclasts (**I**) Recrystallized bioclast (**J**) Bioclast, fine grain quartz with cementing materials (**K**) Micritized bioclast (**L**) Recrystallized bioclast (replaced by dolomitic fluid).

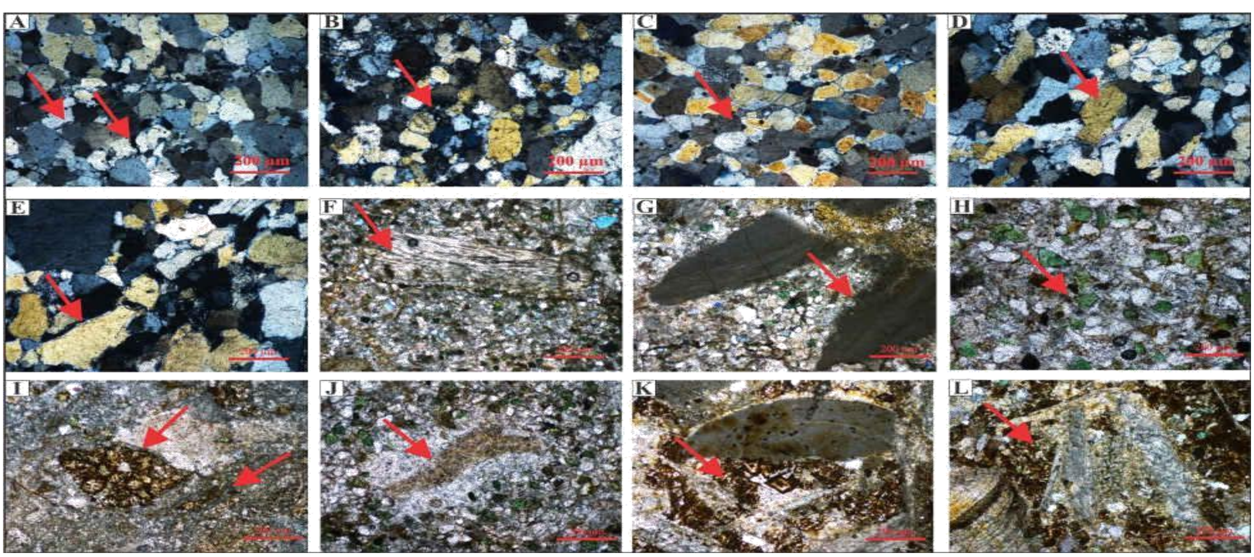

Fig. 4. Shows the KVS microphotographs. (**A**) Quartz arenite with Quartz overgrowth (**B**) Medium grain sandstone with sub-rounded shape (**C**) Medium grain sandstone with sub-rounded shape (**D**) Coarse grain angular quartz (**E**) Coarse grain angular quartz with overgrowth (**F**) Fine grain sandstone cemented by calcite cementing material; recrystallized bioclast are mentioned by red arrow (**G**) Fine grain sandstone with micritized bioclasts (**H**) Angular quartz with coarse grain glauconites (**I**) the Dolomites replace bioclasts (**J**) Dolomites replace bioclasts (**K**) Dolomitic rhombs with micritized bioclast, (**L**) Recrystallized bioclast (replaced by dolomitic fluid).

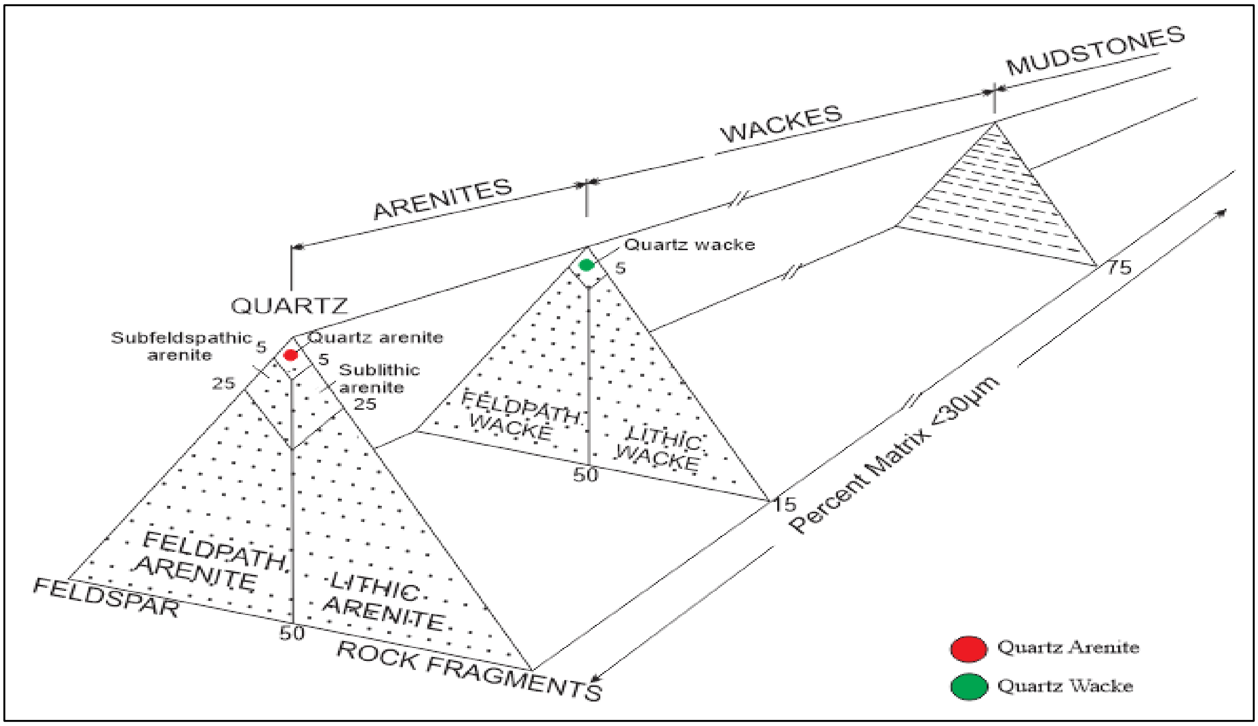

Fig. 5. Shows the model composition of the sandstone units in Lower Cretaceous sequence exposed in TSS and KSS.

The abundance of accessory minerals is 1-3% and opaque minerals is 1-3%. The grain contacts are planer and rarely sutured (Fig. 7 A, B, C and D).

b) TSL 2: Bioclastic Glauconitic Sandy Limestone

In the outcrop this unit is composed of white to pale yellowish, fine to medium grained, thick-bedded to massive sandstone. The total thickness of this unit is about 6 meter (Fig.6). The abundance of subrounded quartz grains ranges between 35-40%, glauconite varies between 5-10%, and bioclasts abundance is 5-10%; the matrix is predominantly calcareous micrite with patches of clays. Feldspar and muscovite occurs in trace amounts (Fig. 7 E, F, G and H).

4.5. Microscopic details and microfacies of KVS

a) KVL-1: Siliciclastic Bioclastic Wackestone

This microfacies is represented by medium to thick bedded, bioturbated, bioclastic sandy limestone. The unit is white to yellowish white on weathered surface and dark grey on fresh surface. This microfacies is 10 meters thick in the KVS. The bioclasts of bivalves, pelecypods, and echinoderms constitutes about 15-20% of this microfacies, quartz is 5-8%, rhombohedral dolomite about 1-3% and 50-60% micrite and coarse crystalline calcite. The micritized bioclasts are common. The grain contacts are planer to pointed and rarely sutured (Plate 7 A, B).

b) KVL-2: Glauconitic Siliciclastic Bioclastic Wackestone – Packstone

At outcrop, this microfacies is composed of thick bedded light grey fine-grained, burrowed bioclastic limestone. The storm beds of this microfacies occurs in the middle part of the Formation. The total thickness of this microfacies is 8 m (Fig.6). The bioclasts constitutes about 10-25% of this microfacies, quartz grains constitute 8-15%, glauconite 3-5%, well developed rhombohedral dolomites (10%) and micrite and spar about 15-25%. Most of the bivalves and echinoderms are completely to partially micritized (Fig. 8 C, D).

c) KVL-3: Siliciclastic Bioclastic Packstone

The microfacies characterised by the thick bedded, dark grey to black bioclastic limestone with inter-bedded shale. Its total thickness is 10 meters (Fig. 6). The microfacies contains 20-25% micritized bioclasts of bivalves and echinoderms, 3-5% quartz, 3-5% rhombohedral dolomite. The glauconite constitutes about 2-4% of the rock (Fig. 8 E, F).

d) KVL-4: Quartz Arenite

The upper part of the measures lower Cretaceous unit is composed of the quartz arenite facies. It contains 95-100% coarse-grained quartz, and silica cement as overgrowth. Quartz grains have sutured boundaries and are well to very well-sorted (Fig. 8 G, H). The total thickness of this facie is 15 meters (Fig. 6).

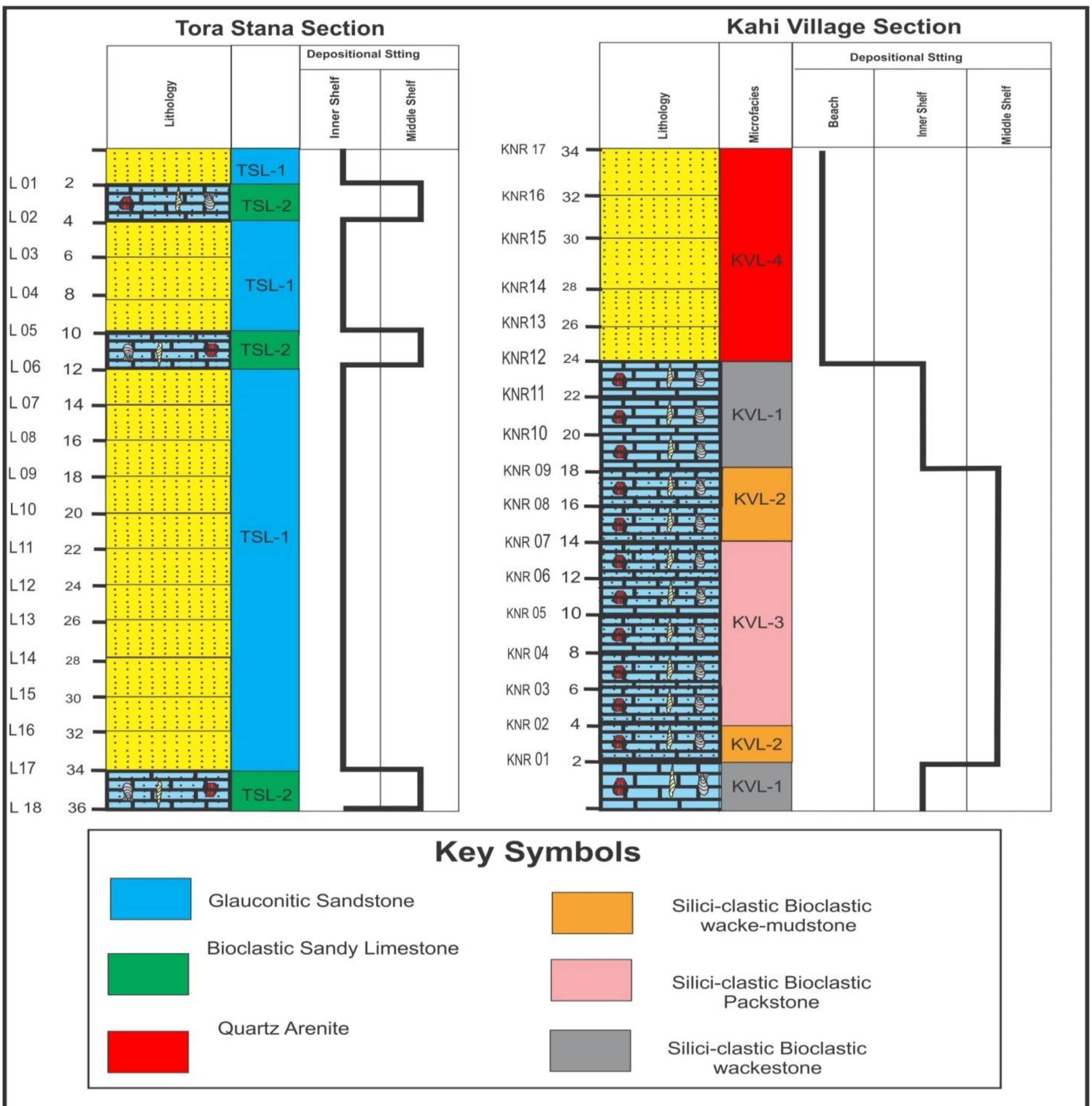

Fig. 6. Shows the microfacies column of the Lower Cretaceous sequence of TSS and KVS.

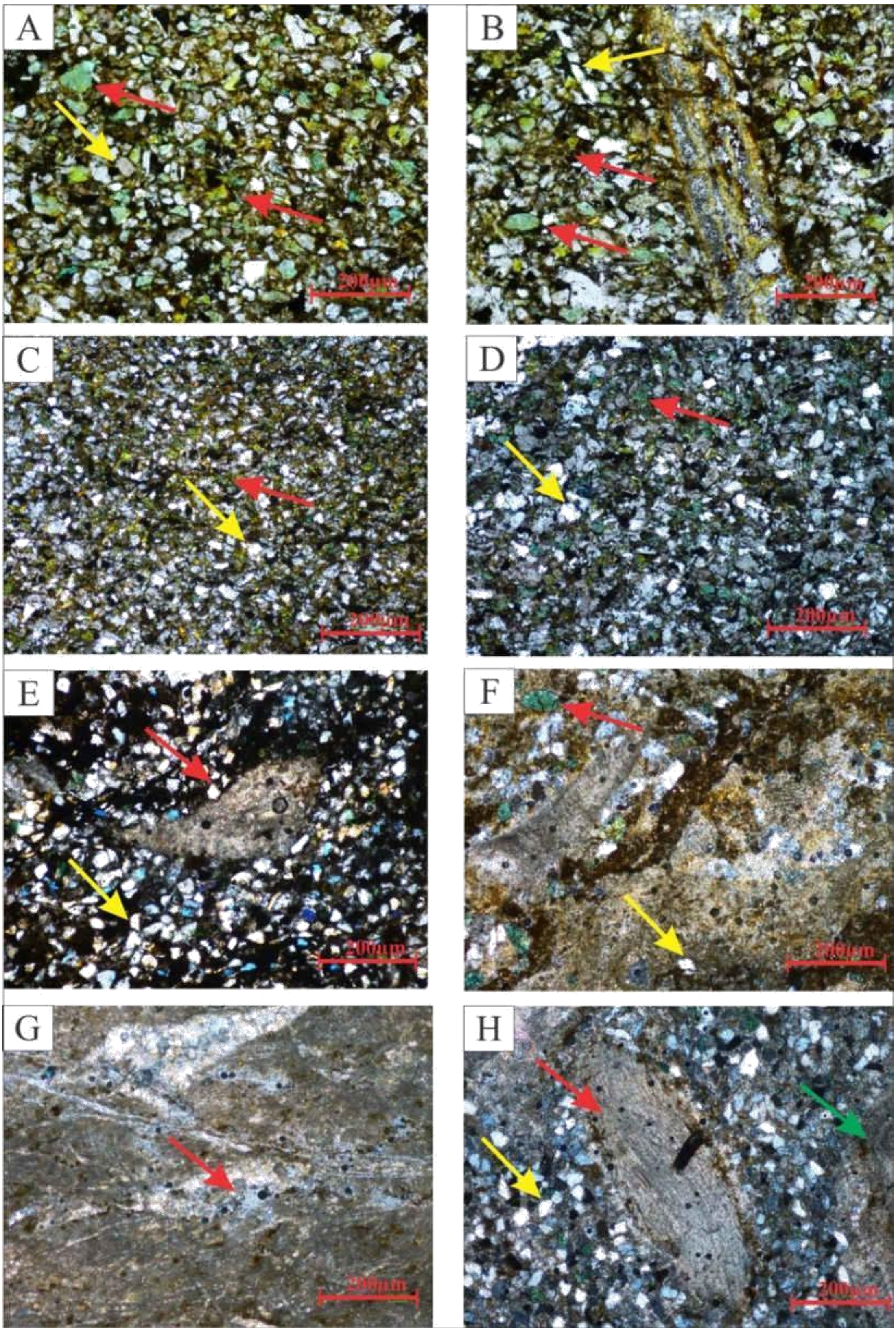

Fig. 7. Microphotographs showing the microfacies of the TSS of Lower Cretaceous sequence. Microphotographs A to D shows Glauconitic Sandstone Microfacies where in (**A**): Red arrow show Glauconite yellow arrow show quartz, (**B**): Red arrow shows Glauconite and Glauconitic cement and yellow arrow show quartz (**C**): Show the fine grain quartz with Gluconites (**D**): Fine grain angular quartz and Glauconites. Microphotographs E to H shows Bioclastic Glauconitic Sandy Limestone where (**E**): Fine grain quartz with bioclasts (**F**): Lime mudstone where bioclasts present with Gluconites and Quartz (**G**): Sandy limestone with crosscut filled veins (**H**); Fine grain quartz in bioclastic limestone.

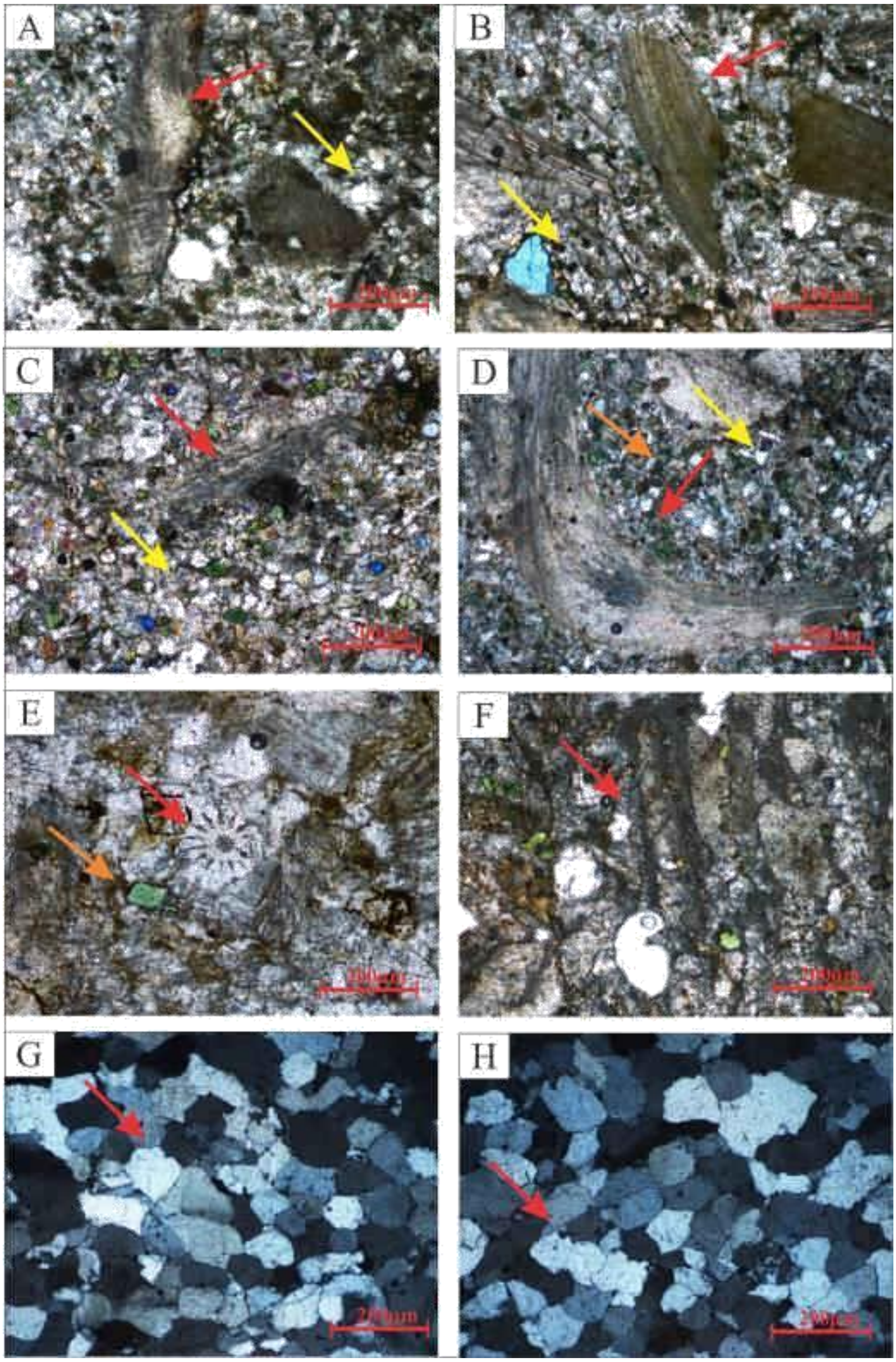

Fig. 8. Showing the microfacies of the KVS where (**A**): Shows Siliciclastic Bioclastic Wackestone Microfacies, Red arrow show micritized bioclasts and yellow arrow shows quartz (**B**): Shows Siliciclastic Bioclastic Wackestone Microfacies, the Red arrow shows bioclasts and yellow arrow shows quartz in calcite cement. (**C**) Shows glauconitic siliciclastic bioclastic Wackestone – Packstone microfacies, red arrow shows bioclasts while yellow arrow shows Quartz, Glauconites with calcite cementing materials (**D**) Shows glauconitic siliciclastic bioclastic Wackestone – Packstone microfacies, Bioclasts with Glauconites and quartz. (**E**): Siliciclastic Bioclastic Packstone, Recrystallized bioclasts with minor Glauconites and quartz (**F**) Shows KVL, recrystallized bioclasts. (**G**) Shows Quartz arenites, coarse grain quartz without cementing materials, (**H**) Showing Quartz arenites.

5. Discussion

5.1. *Microscopic details and microfacies*

The presence of abundant ferruginous clay matrix and glauconite and thick laterally extending bedding character of the TSL-1 facies indicate deposition in the distal inner to middle shelf in slightly reducing water conditions (Pettijohn et at., 1987; Greensmith, 1981; Odin and Matter, 1981). TSL-2 is composed of bioclastic glauconitic sandy limestone deposited in distal inner to middle shelf environments with periodic supply of quartz detritus from the source area (Pettijohn et al., 1987; Greensmith, 1981; Odin and Matter, 1981).

The microfacies of the KVS represents variation in depositional environments from high energy beaches to low energy middle shelf. The Siliciclastic bioclastic wackestone (KVL-1) is deposited in inner shelf setting and Glauconitic Siliciclastic bioclastic wacke-mudstone (KVL-2) and Packstone (KVL-3) have been deposited in distal to proximal middle shelf environments respectively. The matrix free Quartz arenite (KVL-4) represents deposition in high energy beach environment. The TSS lies in the south of the KVS in the context of greater Indus Basin. The microfacies of TSS shows deposition in deeper parts of the basin in contrary to comparatively shallow depositional environments of the KVS microfacies (Fig. 9), which is in contrast to the conventional northward deepening depositional trends in the Indus Basin. This contrast in depositional trend can be attributed to the active tectonics along the northwestern Indian margin in Cretaceous time.

5.2. *Diagenesis*

The various diagenetic modifications in the studied Lower Cretaceous sequence and their paragenetic sequence is discussed as under (Fig. 10).

a) Cementation

The coarse calcite, glauconitic cementation occurs in the very early stage of marine diagenesis (Fig. 11 A, B, C, D; Rahman et al., 2016a). While the silica overgrowth cement is attributed to pressure solution during deep burial diagenesis (Turner, 1980). The ferruginous cement occurs as grain envelopes, stains and as fractures filling. The dolomite cement occurs along with ferruginous cement. The precipitation of iron-oxide along with dolomite occurs most probably after the precipitation of silica cement (Arif et al, 2009).

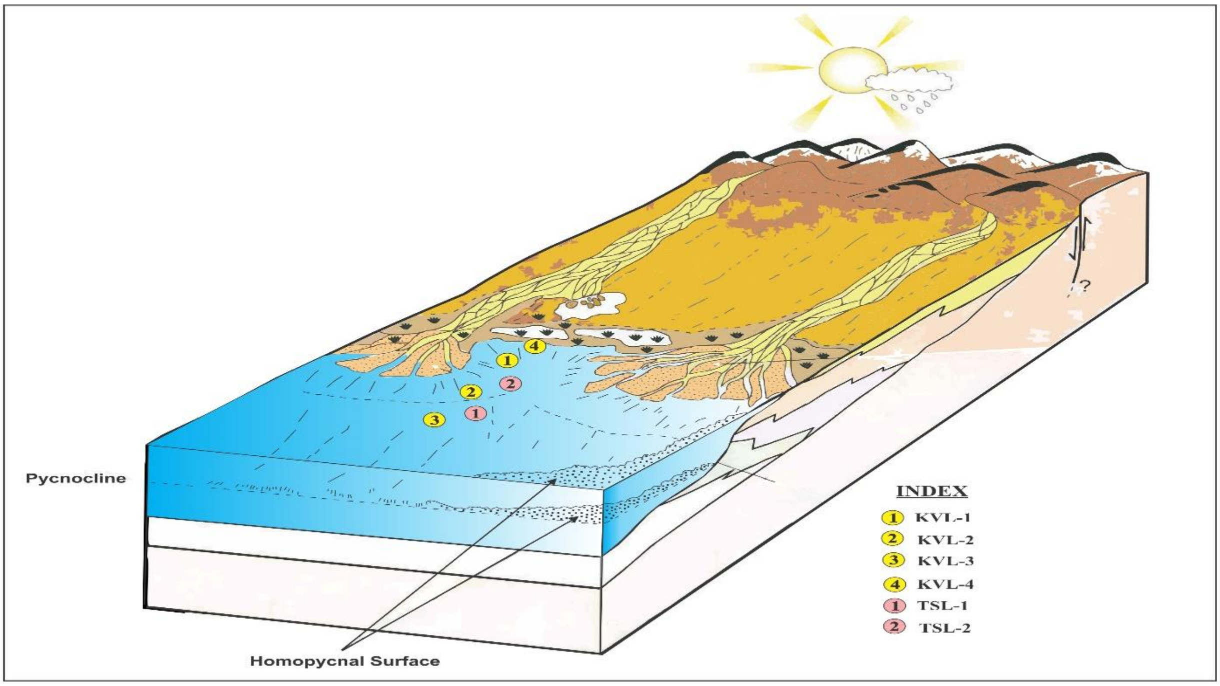

Fig. 9. Shows the depositional model of the Lower Cretaceous sequence.

In the limestone facies at both sections, the binding materials are calcite in the form of micrite envelopes and spars. The ferruginous and dolomite cement in trace amount occurs as grain replacements and fracture filling (Fig. 4I, L, 11 D J-M and G). The micritization and calcite cementation occurs in marine phreatic environments of diagenesis (Flügel, 2004).

b) Compaction

Mechanical compaction;

Sutured grain contacts, intra and intergranular fractures in samples of both TSS and KVS indicates mechanical compaction under deep burial diagenesis (Fig. 11 D, E).

Chemical Compaction;

The overburden pressure induced solutions and their reprecipitation is common in the investigated rock units. The stylolites, sutured and abraded grain contacts represent chemical dissolution of the rock material while silica overgrowth and dolomitization represents their reprecipitation along grain margins and fractures. The bioclasts at places are replaced by dolomite. Two phases of dolomitization have been identified the first phase cross cuts the stylolites while the second phase of rhombohedron dolomites cross cuts the dolomite crystals of the first phase (Fig. 11 G, J, K, L-Q). This shows that the dolomitization is the last diagenetic event these sandstones have encountered.

c) Fractures

Fracture forms in sedimentary rocks during different stages of diagenesis (Sibson, 1975). The Lower Cretaceous strata exposed in TSS and KVS is fractured at both mesoscopic and microscopic scale. The fractures are mostly filled with calcite, dolomite, ferruginous cement and some are unfilled (Fig. 11 H, J, O). Three stages of fracturing can be proposed for the rocks examined. The stage-I and II fractures are filled with calcite and dolomite respectively and have been formed during burial diagenesis. The unfilled stage-III fractures are most probably associated with tectonic uplift of the rock unit (Fig. 11 G, P).

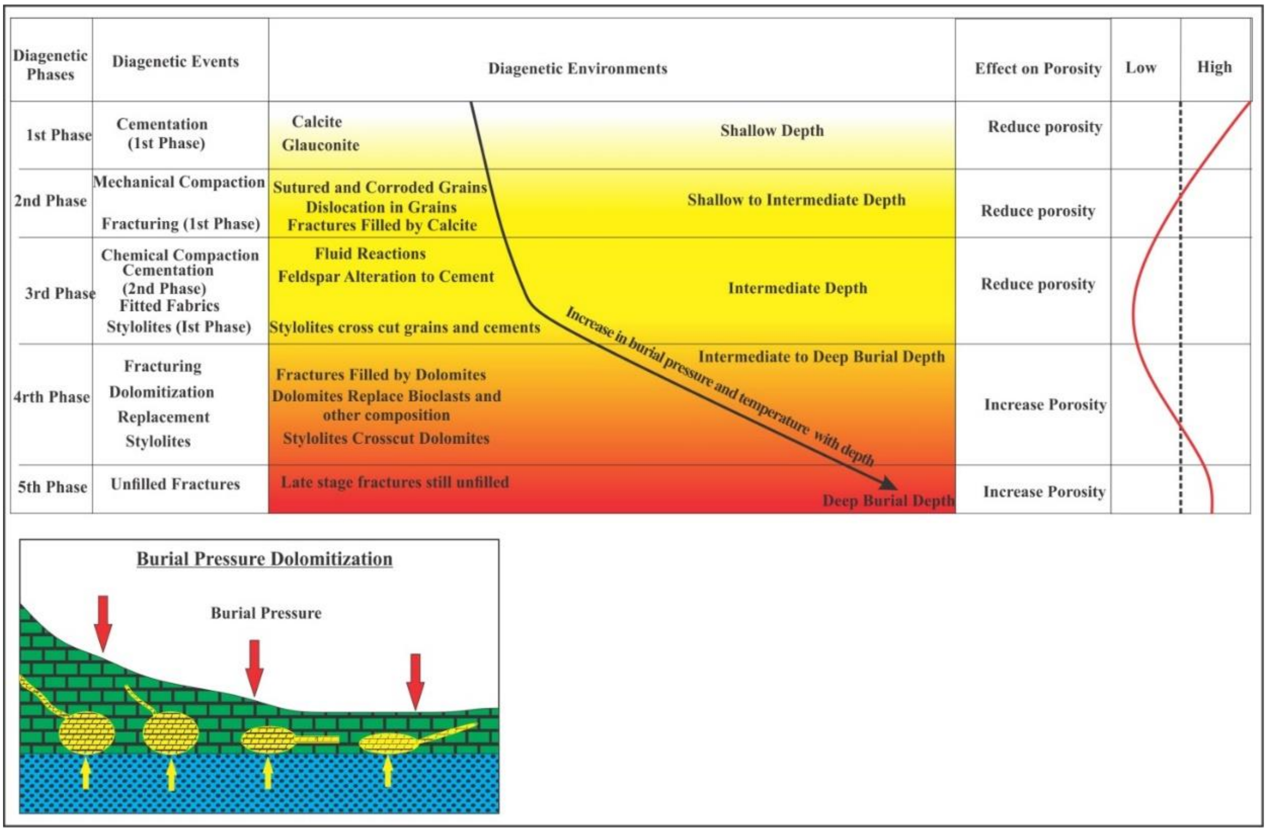

Fig. 9. Shows the diagenetic model of the Lower Cretaceous sequence.

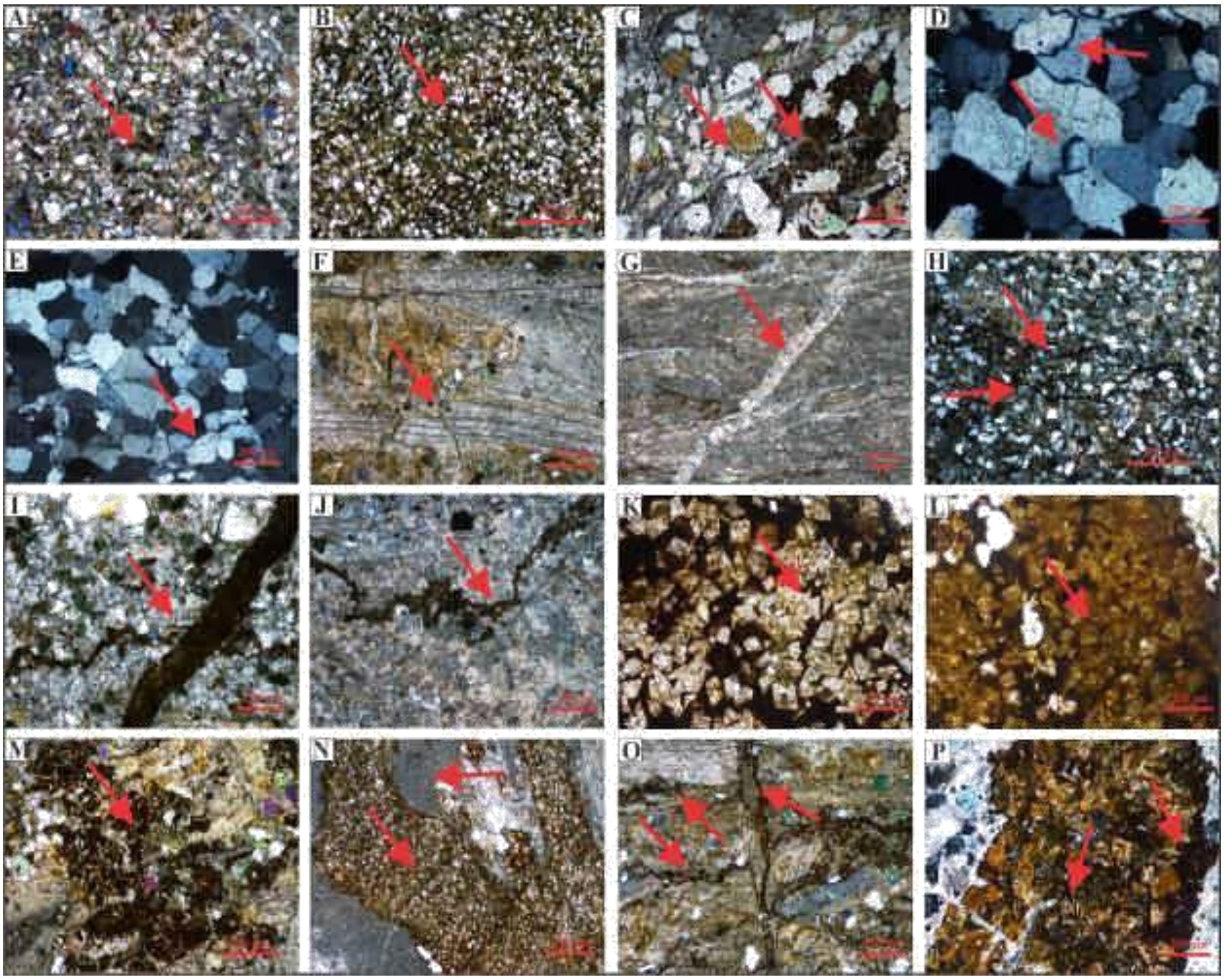

Fig. 11. Shows the diagenetic fabrics of Lower Cretaceous sequence exposed in western Kala Chitta ranges. Microphotograph shows (**A**): Calcite cementing materials, (**B**): Ferromagnesian cementing materials, (**C**): Angular quartz cemented by calcite and with dolomitic replacement, (**D**): Quartz overgrowth, (**E**): Sutured contact between quartz grains, (**F**): Recrystallized bioclasts, (**G**): Crosscut veins filled with calcite, (**H**): Stylolites in sandstone facies, (I): Stylolite cross cut filled vein, (**J**): Stylolites in limestone facies, (**K**); Well-developed dolomitic rhombs, (**L**): Dolomitic rhombs with stylolite, (**M**): Dolomitic replacement in bioclasts, (**N**): Fine grain dolomitic rhombs, (**O**): Fractures and stylolites, (**P**): Poor developed dolomitic rhombs.

5.3. Reservoir Characterization

The sandstone of the Lower Cretaceous sequence is deposited in shallow to the deep shelfal environments and are rich in carbonates. The pores in the sandstone units are mostly filled with calcite. This effects the overall porosity and permeability of these sandstones. In KVS the porosity ranges determined from image J software analysis are between 2-13.5%, with average range being 2-5% (Fig. 12). The dolomitized samples bear exceptionally high porosity values e.g. 13.5% and 12% for sample 8 and 12 respectively. The dolomites are in form of small patches which will not add pronounced contribution to overall porosity. The interconnection between the pores spaces is weak and may results in low permeability (Fig. 13). The measured lower Cretaceous unit at TSS is dominantly composed of sandstones and has fair porosity values and pores connectivity compared to the sandstone at KVS. In TSS the porosity range of the sandstone is 4-14%, averaging 6-8% (Figs.14, 15). The interconnection between the pores spaces is good (Fig. 13). The cementation and compaction occlude the reservoir potential while fracturing and dolomitization adds to the reservoir potential of the studied sandstones. The shallow sandstone facies at the TSS have high porosity values than the deeper facies of the KVS sandstone. The deep burial diagenesis and associated pressure dissolution and cementation has almost eliminated the primary porosity. The porosity in the studied sandstones is secondary in origin and is attributed to dolomitization and fracturing.

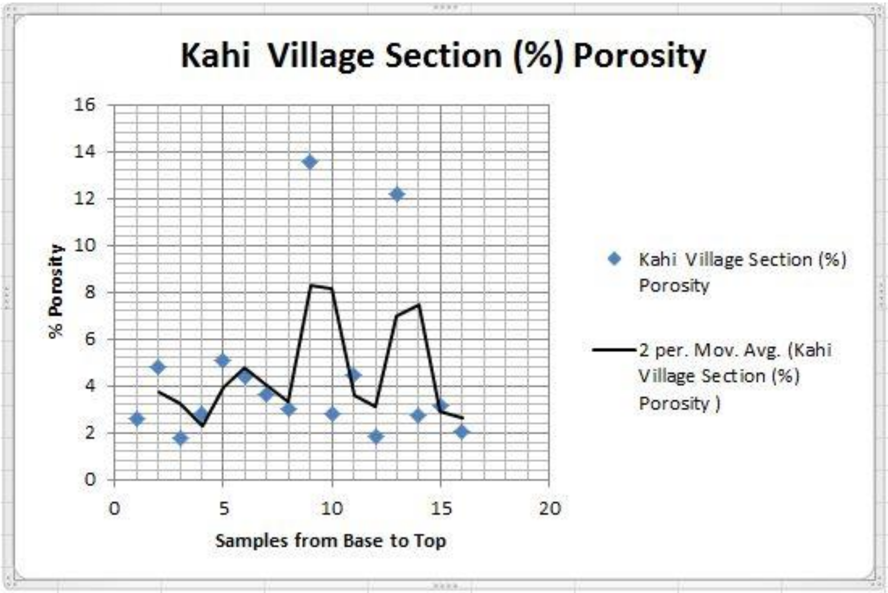

Fig. 12. Shows the porosity curve of Lower Cretaceous sequence in KVS.

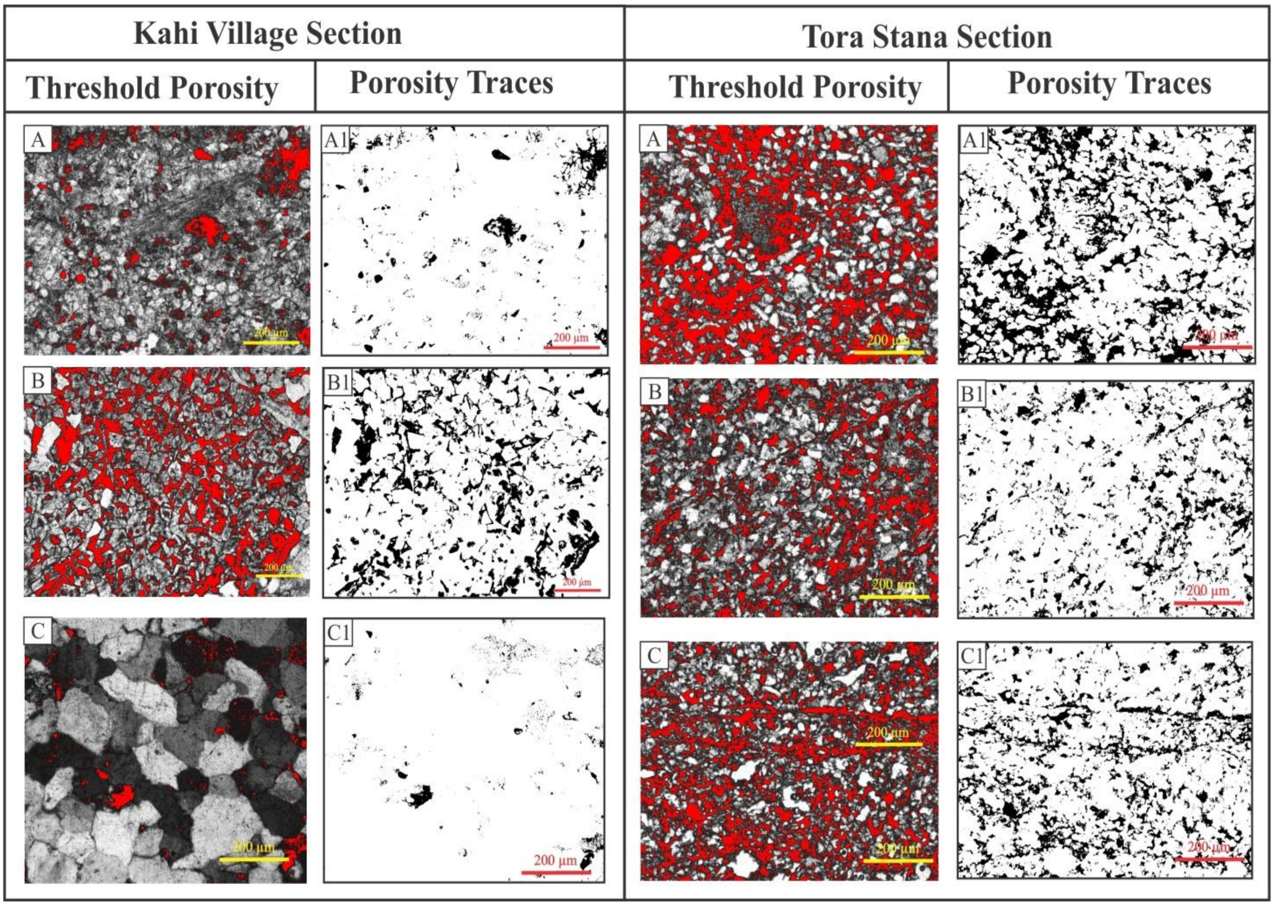

Fig. 13. Shows the threshold porosity and pores spaces traces which indicate its porosity. The microphotographs B and B1 in KVS are represented dolomites.

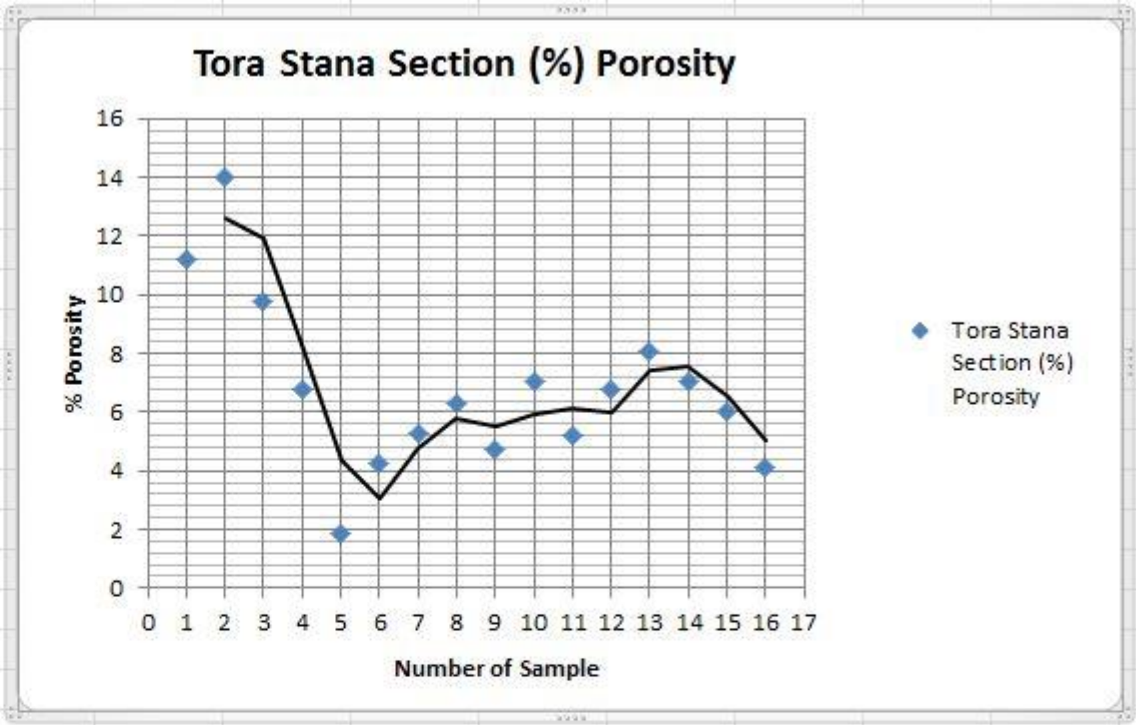

Fig. 14. Shows the porosity curve of TSS.

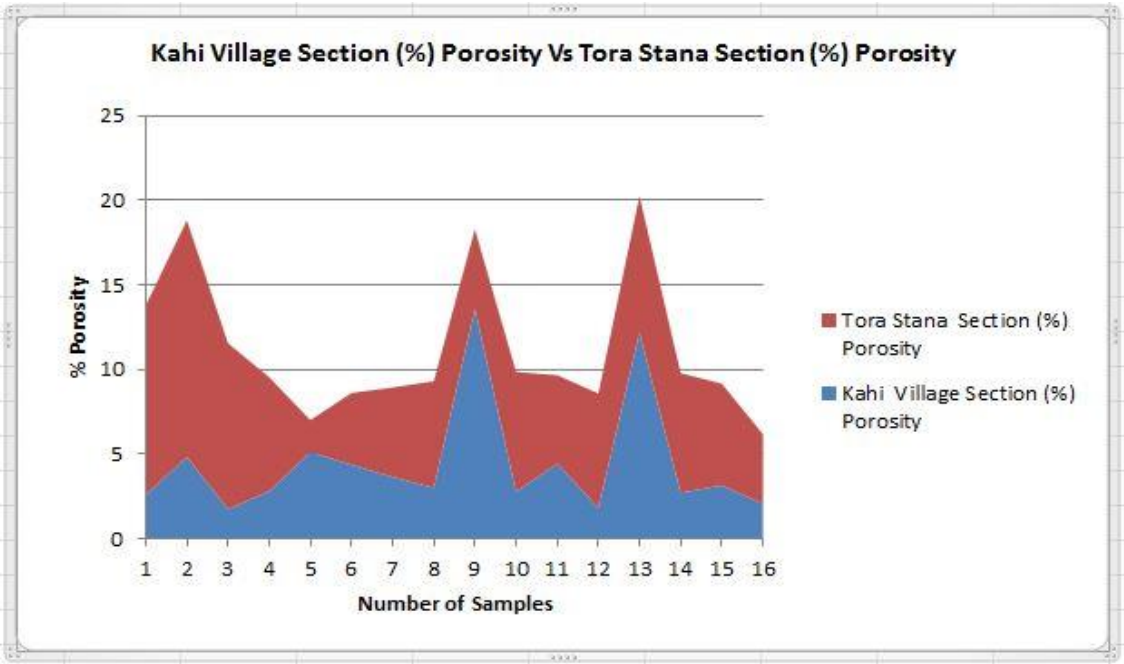

Fig. 15. Shows the comparative porosities of KVS and TSS.

6. Conclusions

- The Lower Cretaceous sequence is deposited in a shallow shelfal environment which shows a relative sea level fluctuation on vertical facies variation.
- Composition wise the Quartz arenites and Quartz Wacke are dominantly present in sandstone facies while bioclastic microfacies are dominantly present in Limestone facies.
- The present study reveals that Sandstone of Lower Cretaceous sequence in Kala Chitta Range contains fine to coarse grain

sub-angular to rounded, moderate to well sorted, mineralogically mature while texturally immature and having high to moderate sphericity.

- The notable diagenetic changes in the Lower Cretaceous sequence sandstone from Kala Chitta Range consist of precipitation of silica cement as quartz overgrowth, iron oxide cementation, stylolitization, dolomitization, Dissolution of aragonite in some bioclasts and replacement by calcite spar as inter-granular cement and at places replacement of calcite by dolomite and alteration of feldspar to clay minerals. These diagenetic modifications represent the final phase (phyllomorphic stage) of diagenesis probably resulting from deep burial, increased geothermal gradient and pressure.
- The diagenetic process disturbed the porosity; it causes reduction and increases at different stages.
- From the detailed study, it is concluded that the reservoir potential at KVS and TSS is good which is mainly controlled by depositional environment and diagenetic processes.

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Authors' Contribution

Mr. Faheem Ahmed is involved in petrography and write up of the manuscript. Muneeba Ahmad reviewed the literature and manuscript. Maqsood ur Rahman did reservoir characterization. Muhammad Sarim assisted in logs and map development. Muneeb ur Rehman did microfacies analysis and Muhammad Javed contributed in field works.

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