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Depositional, diagenetic and sequence stratigraphic controls on the reservoir potential of the Cretaceous Chichali and Lumshiwal formations, Nizampur Basin, Pakistan

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Abstract

The Early to Middle Cretaceous Chichali and overlying Lumshiwal formations from the Nizampur Basin, Pakistan have been investigated to link the reservoir quality with stratal deposition, diagenetic modifications and sequence stratigraphy. The Chichali Formation revealed laterite, glauconitic sandstone and carbonaceous green shale lithofacies, representing middle to outer ramp depositional setting. The presence of bioclastic sandy limestone, quartz arenite and glauconitic sandstone lithofacies within the overlying Lumshiwal Formation represented an inter-tidal to inner ramp depositional setting. The calcite, hematite, smectite, ferroan dolomite and glauconite occurred as cement in the coarse grained facies of the Chichali Formation, thereby reducing porosity, however, grain fracture porosity, and dolomitization, intergranular and dissolution porosity resulted in porosity increase. The overlying Lumshiwal Formation showed both physical, and chemical compaction, authigenic mineralization, cementation and late-stage dissolution. The dominant cement types in the Lumshiwal Formation are calcite, ferroan dolomite, smectite, illite and quartz-overgrowth cements. The primary intergranular porosity, and late-stage diagenetic dissolution- and dolomitization-induced secondary porosity added to the reservoir quality of the Lumshiwal Formation. The sequence stratigraphic analysis revealed that Chichali Formation is deposited during transgressive system tract of 2nd order depositional cycle. The transgression-associated glauconitic sandstone facies of the Chichali Formation acts as a good reservoir, which is bounded by carbonaceous green shale associated with maximum flooding surface. The Lumshiwal Formation is deposited in the regressive 2nd order cycle and is represented by delta plain facies. The quartz arenites represents excellent reservoir potential in the Lumshiwal Formation.

Keywords: Diagenetic and sequence stratigraphic controls, Chichali formation, Lumshiwal formation, Nizampur Basin.

1. Introduction

Sea level fluctuations control the sediment distribution patterns and hence give a clue about the deposition of source and reservoir facies along the continental margins and in the basin interiors. The study of these fluctuations is thus of essential importance in hydrocarbon exploration (Haq et al., 1987). The application of sequence stratigraphy have become increasingly important in determining the regional reservoir rocks and their properties trends and delineating the heterogeneities encountered in terrigenous reservoirs (Handford and Loucks, 1993; Grammer et al., 2004).

The role of diagenetic pattern in the evolution of the reservoir properties of rocks on the other hand has a very important role; factors that influence the diagenetic changes in sedimentary rocks include; detrital composition, burial depth, temperature and pore-water chemistry (Carrigy and Mellon, 1964; Blatt 1979; Hayes, 1979; Vavra, 1983). Diagenesis evolve through several systematic steps; starting with pore-reduction through compaction, alteration of unstable framework grains, alteration of rim cement, followed by pore-filling cement and transformation of mineral phases in deeply buried sandstone (Wilson and Pittman, 1977).

The early to middle Cretaceous succession of the Indus Basin, Pakistan, represented by Chichali and overlying Lumshiwal formations offer well-established hydrocarbon reservoir zones within various oil and gas fields in the Kohat sub-basin, Pakistan (Siddique et al., 2014; Fig. 1). These formations, though extensively exploited for upstream petroleum activities in the Kohat sub-basin have not been adequately evaluated in the Upper Indus Basin, Pakistan.

Recently, attempts have been made to understand the sedimentological characters of the Cretaceous sediments in the Indus Basin, Pakistan (Khan et al., 2002; Arif et al., 2009; Umar et al., 2011; Khan et al., 2016) however, studies pertaining to the facies variation and effects of diagenesis on the reservoir nature of these formations in the Upper Indus Basin, Pakistan are non-existent. This paper therefore, examines the variation in reservoir properties in response to sea level-controlled facies changes and diagenetic alterations of the Chichali and Lumshiwal formations in the Nizampur, Upper Indus Basin, Pakistan.

2. Methodology

To understand the variation of lithofacies from base to the top, a composite log has been constructed combining the information of three sections in the Khwari Khwar gorge and a sections along Nizampur Kahi road (Fig. 2). A comprehensive examination of sandstones and limestone samples was carried out using microscopic observations of thin sections, scanning electronic microscopy (SEM) and energy-dispersive spectroscopy (EDX). The framework grains and matrix/cement were identified, and their relative abundances were visually determined (Terry and Chilingar, 1955). SEM using JEOL JSM-5910 fitted with energy-dispersive and X-ray micro-analyzer (EDX), in the Centralized Resource Laboratory (CRL) of University of Peshawar, Pakistan was used. SEM analysis helped to generate important supplementary data on the nature of authigenic clay minerals and porosity. Attributes such as types, nature, and percentage porosities, grain size variation, amount, and nature of cement and their effects upon the reservoir qualities were observed.

3. Geological settings

The Cenozoic India and Eurasia collision resulted in the formation and uplift of the Himalayas and Tibetan Plateau (Molnar and Tapponnier, 1975; Yin, 2006). The compression associated India-Asia convergence resulted in the formation of various major thrust faults namely; Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), and Salt Range Thrust (SRT; Tahirkheli, 1979; DiPietro, 2004). The study area represents the foot and hanging wall of the Hissartang fault and Main Boundary Thrust respectively. Sandwiched between these two faults, the area has undergone severe compression (Fig. 1). The Attock-Cherat ranges bound the area to the north and includes metasedimentary rocks of the lesser Himalayas. The foreland basin strata of the Kala Chitta Range bound the area towards south (Fig. 1).

The area consists of rocks from Jurassic to Recent lacustrine sediments, including Jurassic Datta, Shinawari, Samana Suk formations; Cretaceous; Chichali, Lumshiwal, and Kawagarh formations; Palaeocene; Hangu, Lockhart, and Patala formations, and Eocene; Margalla Hill Limestone (Qureshi and Ahmad, 2001; Figs. 1-3).

4. Results and discussion

4.1. Lithofacies, and mineralogy of the Chichali and Lumshiwal Formations

The lower contact of the Chichali Formation with the Jurassic Samana Suk Formation is marked by a lateritic interval (Fig. 3B). This laterite is the result of sub-areal exposure of the carbonate platform in the Upper Indus Basin, Pakistan (Smewing et al., 2002). It is followed by a glauconitic sandstone lithofacies which is friable, fine to medium grained and occasionally carbonaceous (Fig. 4A; Table 1). The glauconite occurs throughout these facies, however, it is more abundant in the lower part and gradually decreases towards the top of this facies. The presence of glauconite indicates slightly reducing near-shore, low sedimentation, shallow water conditions, just below the sediment-water interface and warm waters (i.e. 15-20˚C; Greensmith, 1981; Odin and Matter, 1981; Pettijohn et al., 1987). The glauconite-bearing beds of the Chichali Formation showed deposition in the slightly reducing, shallow to moderately deeper marine water with low sedimentation rate, at or just below sediment-water interface in middle ramp depositional settings. The uppermost most facies of the Chichali Formation is marked by the carbonaceous green clays, containing bioclasts of belemnite and ammonite (Fig. 4B). The belemnites have been dissolved at places leaving castes. Phosphate nodules and sulphur-rich horizons are seen within this lithofacies representing further deepening of the depositional settings and reducing conditions, i.e. outer ramp depositional setting (Greensmith, 1981; Odin and Matter, 1981; Pettijohn et al., 1987).

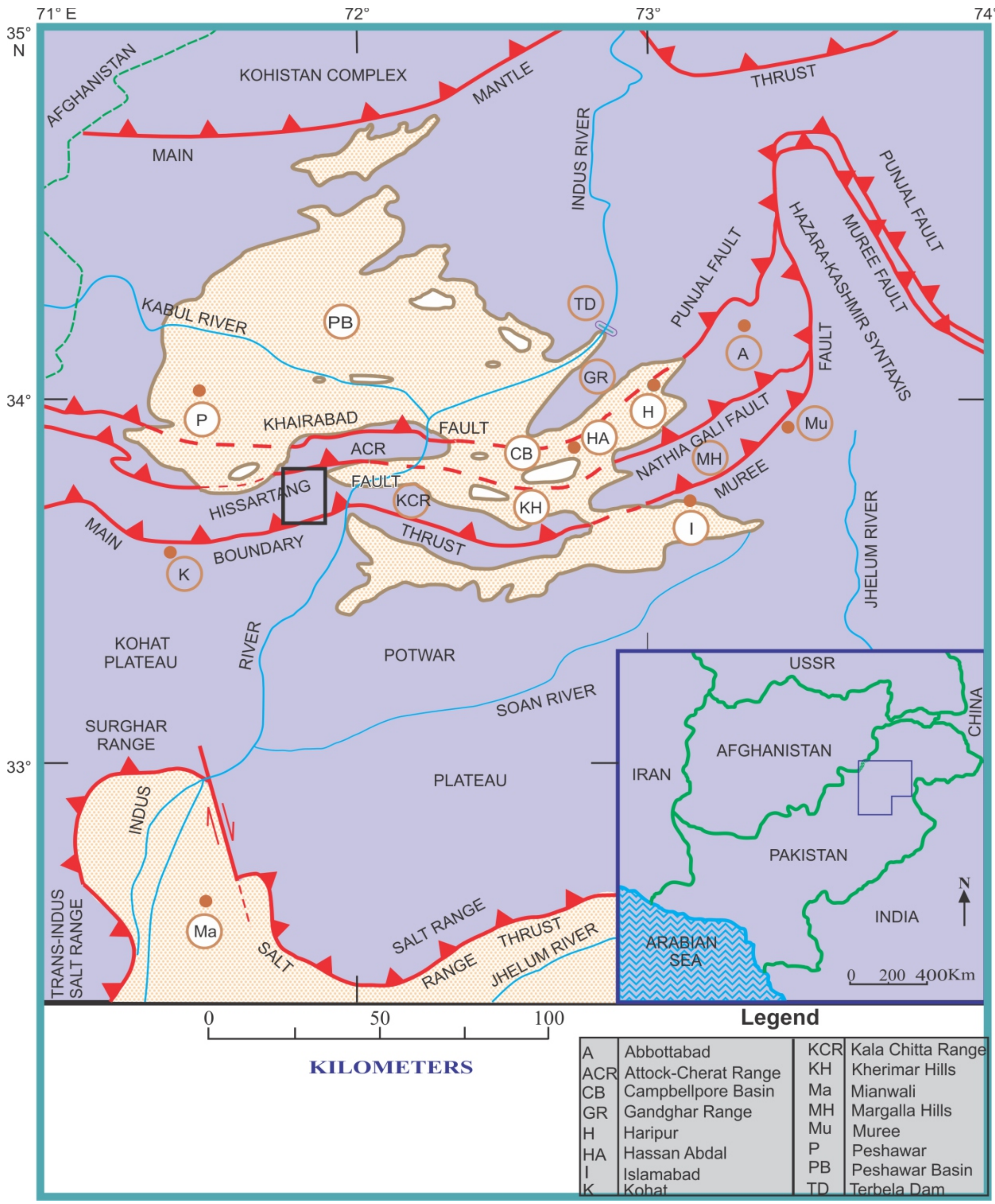


Fig. 1. Tectonic map of northern Pakistan, the black rectangle in the preset marks the location of the study area (After Hylland and Riaz, 1988).

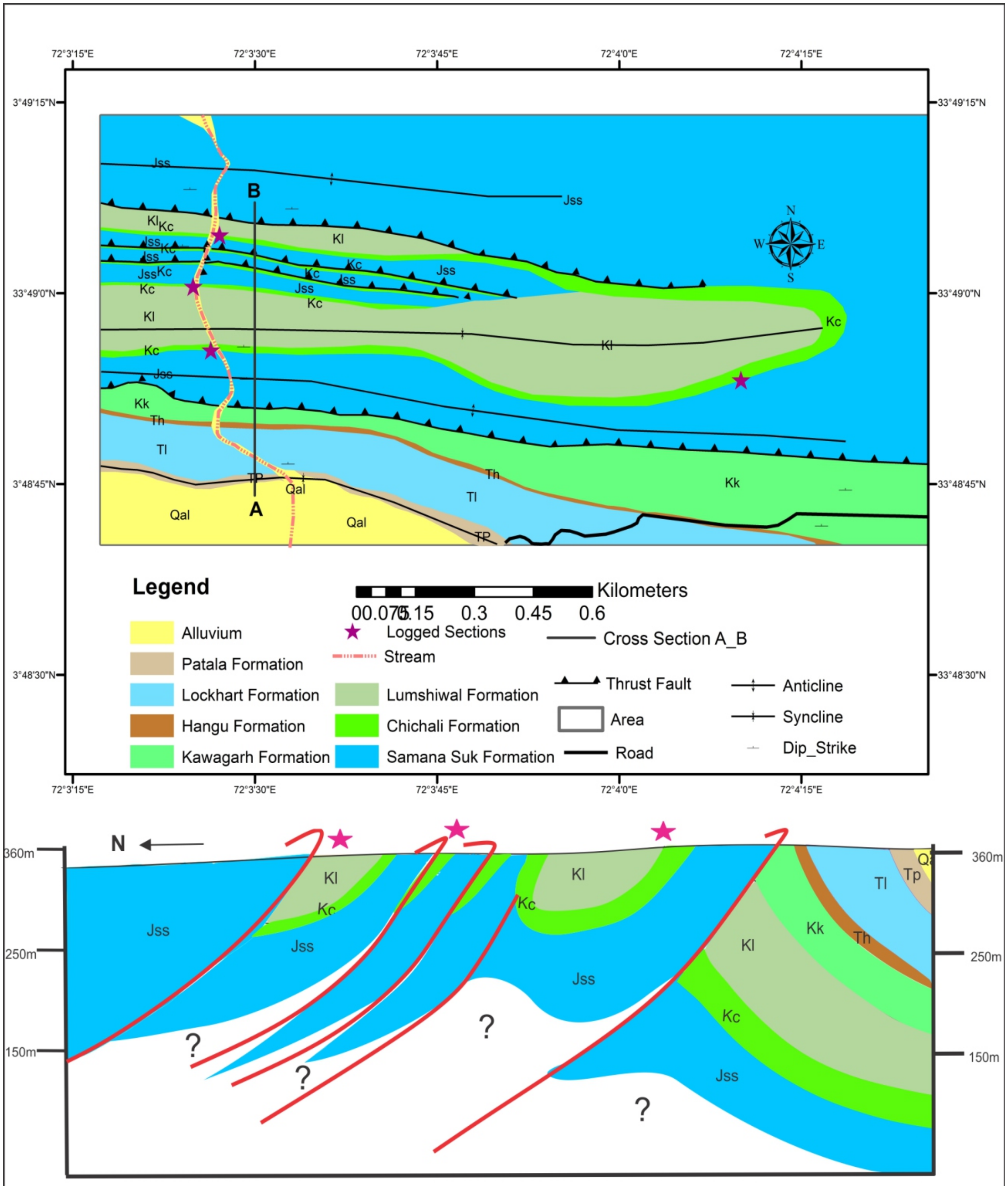


Fig. 2. Geological map and cross-section along Khwari Khwar section, Nizampur Basin Pakistan. Stars show location of the logged sections.

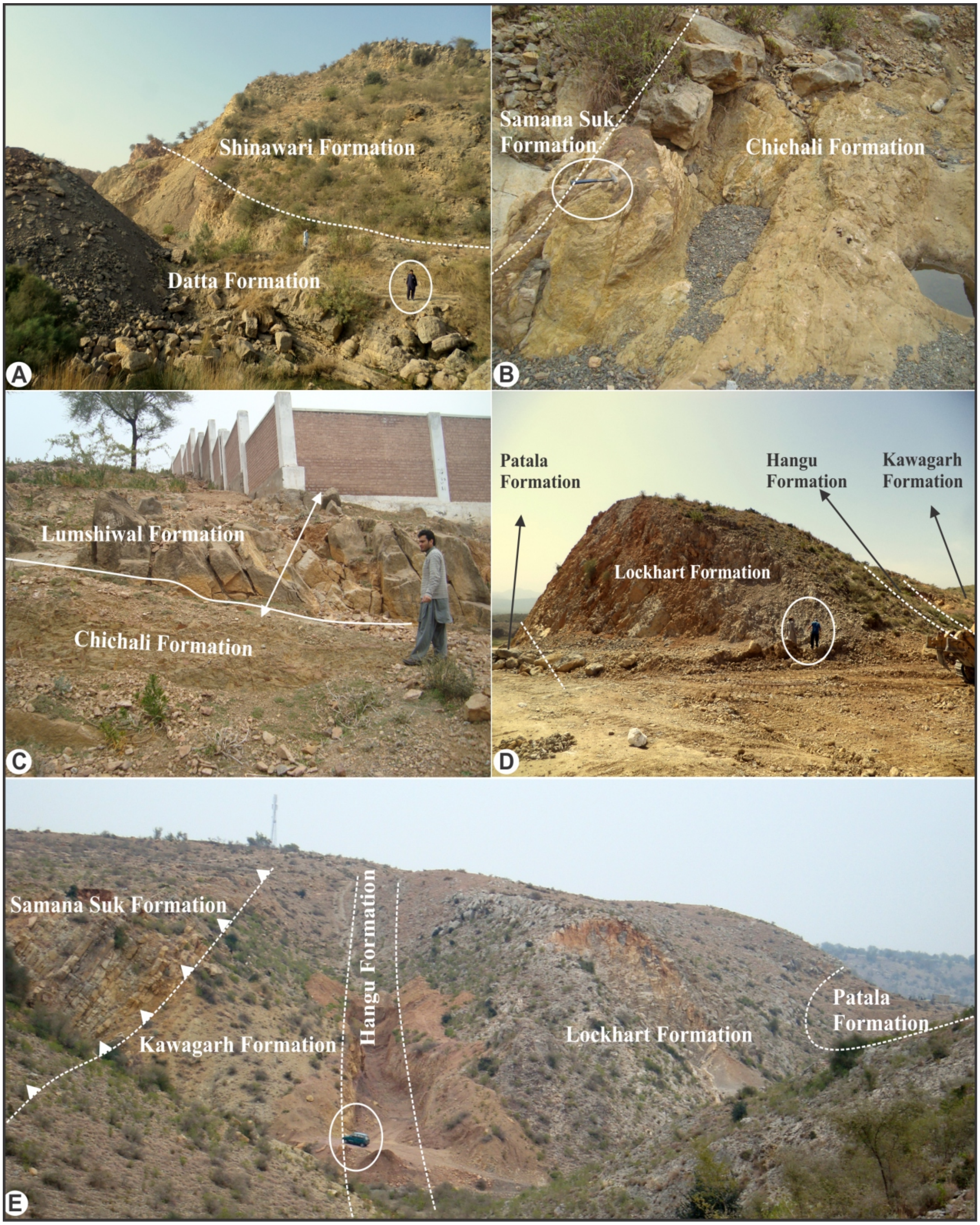


Fig. 3. Field photographs showing, (A). Contact between Datta and Shinawri formations, (B). Contact between Samana Suk and Chichali formations, (C). Contact between Chichali and Lumshiwal formations, (D). Exposure of the Kawagarh, Hangu, Lockhart and Patala formations and (E). Thrusted contact between Samana Suk and Kawagarh formations in Khwari Khwar section.

Table 1. Summary of the lithofacies and their description encountered within Chichali and overlying Lumshiwal Formations.

Lithofacies and their summarized description and interpretation within the Lumshiwal Formation				
Facies	**Description**	**Litholog position**	**Field photograph**	**Interpretations**
Interbedded limestone and marl lithofacies.	This lithofacies marks the uppermost part of the Lumshiwal Formation. The limestone is bioclastic yellowish grey on weathered surface and light grey on fresh surface. The average thickness of each limestone bed is 12 cm. The marl is carbonaceous dark and sandy with 14 cm average thickness.	Located at the upper part of the Lumshiwal Formation.	Fig. 4H.	Inner to middle ramp depositional setting.
Quartz arenite sandstone interbeded with grey clays.	Medium- to coarse-grained quartzose sandstone with ferruginous bands and liesingang rings and vertical burrows are seen at places.	Located at the middle part of the Lumshiwal Formation.	Figs. 4F and 4G.	Intertidal setting.
Carbonaceous sandy clays.	Thinly bedded, friable dark coloured sandy clays.	Located at the lower upper part of the Lumshiwal Formation.	Fig. 4E.	Middle ramp depositional setting.
Glauconitic sandstone.	Fine- to medium-grained calcareous glauconitic sandstone.	Located at the lower part of the Lumshiwal Formation.	Fig. 4D.	Middle ramp depositional setting.
Sandy bioclastic dolomitized limestone.	Thick bedded dolomitized limestone yellowish grey on weathered surface and grey on fresh surface, burrowed at places with occasional tempestite beds.	Found at the lower most part of the Lumshiwal Formation.	Fig. 4C.	Inner ramp depositional setting.
Lithofacies and their summarized description and interpretation within the Chichali Formation				
Facies	**Description**	**Litholog position**		**Interpretations**
Carbonaceous green clays.	Green soft clays carbonaceous at places and oxidized, contains clasts of belemnite.	Found at the upper part of the Chichali Formation.	Fig. 4B.	Outer ramp depositional setting.
Glauconitic sandstone.	Medium- to fine-grained sandstone, friable in nature, occasionally carbonaceous, oxidized at places and contains clasts of belemnite, phosphate and chert nodules at places.	Found at the middle part of the Chichali Formation.	Fig. 4A.	Middle ramp depositional setting.
Laterite facies.	Red coloured silty laterite, found at contact with the underlying Samana Suk Formation.	Found at the base of the Chichali Formation.	Fig. 3B.	Sub areal exposure of the platform.

The overlying Lumshiwal Formation is thick-bedded dolomitized sandy limestone. The limestone is bioclastic yellowish grey on weathered surface and grey on fresh surface, burrowed at places. Occasional tempestite beds occur in the formation and are represented by randomly oriented bivalves-rich intervals (Fig. 4C). This facies is followed by fine to medium-grained calcareous glauconitic sandstone (Fig. 4D) and carbonaceous sandy clays (Fig. 4E) which in turn is overlain by thick bedded sandstone with ash colour clay interbeds (Figs. 4F and 4G). The sandstone is light grey to brownish on weathered surface and white on fresh surface, having vertical burrows, compact, fractured and brittle at places, (Fig. 4F and 4G). The thin interbeds of limestone and marls mark the upper most facies of the Lumshiwal Formation (Fig. 4H), the limestone is bioclastic yellowish grey on weathered surface and light grey on fresh surface, the average thickness of each limestone bed is 12 cm and marl is 14 cm. Shah (1987) suggested that the Lumshiwal Formation at the Surghar Range was deposited under terrestrial conditions, based on the presence of scattered coal and carbonaceous beds within the upper part of the formation. The presence of glauconite and bioclastic limestone beds within the Lumshiwal Formation in the Nizampur Basin confirms the shallow marine inner ramp depositional environment and the presence of planer bedded quartz arenite lithofacies suggests deposition of this part of the Lumshiwal Formation in the intertidal setting (Table 1).

The petrographic investigation revealed that sandstones from the Chichali Formation is sub- angular to sub-rounded, moderate to poorly sorted and are sub-mature to mature (Fig. 5A-B) and fall in the field of “quartz arenite” (Dott, 1964; Pettijohn et al. 1987), while the sandstone of the Lumshiwal Formation, from the quartz sandstone lithofacies is sub-angular to sub-rounded, moderately sorted and are mature, (Fig. 5C-D) and fall in the field of “quartz arenite” (Dott, 1964; Pettijohn et al. 1987).

4.2. Sequence stratigraphic framework of the Chichali and Lumshiwal Formations

Sequence stratigraphy subdivides sedimentary strata into time-equivalent, genetically-related units associated with sea level changes (Catuneanu, 2006; Miall, 2010) and helps to predict the sedimentary packages, probable reservoir or source intervals, and lateral and vertical continuity of strata across a sedimentary basin (Eberli and Grammer, 2004). In this study, the outcrop information and lithofacies data were used for the sequence stratigraphic reconstruction of the early to middle Cretaceous sediments. A sequence stratigraphic interpretation presented here, is based on deepening and shallowing upward cycles and basinward shifts in diagnostic facies. The Transgressive-Regressive sequence model of Embry and Johannessen (1992) is used to address the depositional architecture of the Chichali and overlying Lumshiwal formations. The sequence stratigraphic analysis of the Kimmeridgian to Valanginian Chichali Formation (Khan, 2013) in the Upper Indus Basin revealed that Chichali Formation is deposited during transgressive system tract of 2nd order depositional cycle (i.e. ChTST; Fig. 6A). The contact between underlying Samana Suk and overlying Chichali Formation is a sequence boundary and is represented by a lateritic unit representing an unconformity and sub-areal exposure of the carbonate platform of the Upper Indus Basin, Pakistan (Fig. 6A; Table 1). The glauconitic sandstone lithofacies of middle ramp depositional setting (Table 1) represents transgressive system tract, which is followed by deposits of maximum flooding in the form of carbonaceous green clays of middle ramp depositional setting (Fig. 6A; Table 1). This transgression may be associated with the opening of the north-western margin of the Indian Plate along rift faults, before the separation of the India-Madagascar plates from the Australia-Antarctica plates (Besse and Courtillot, 1988).

The mixed siliciclastic carbonates deposits of the overlying Lumshiwal Formation represent 3rd order regressive system tract (i.e. LumRST; Fig. 6B). Based on vertical succession and depositional environments, it is suggested that the LumRST consists of three depositional cycles; the lowermost cycle (i.e. cycle 1; Fig. 6B-E) comprises of 14 meter sequence of sandy bioclastic limestone interbeded with glauconitic sandstone and sandy carbonaceous shale. This cycle is

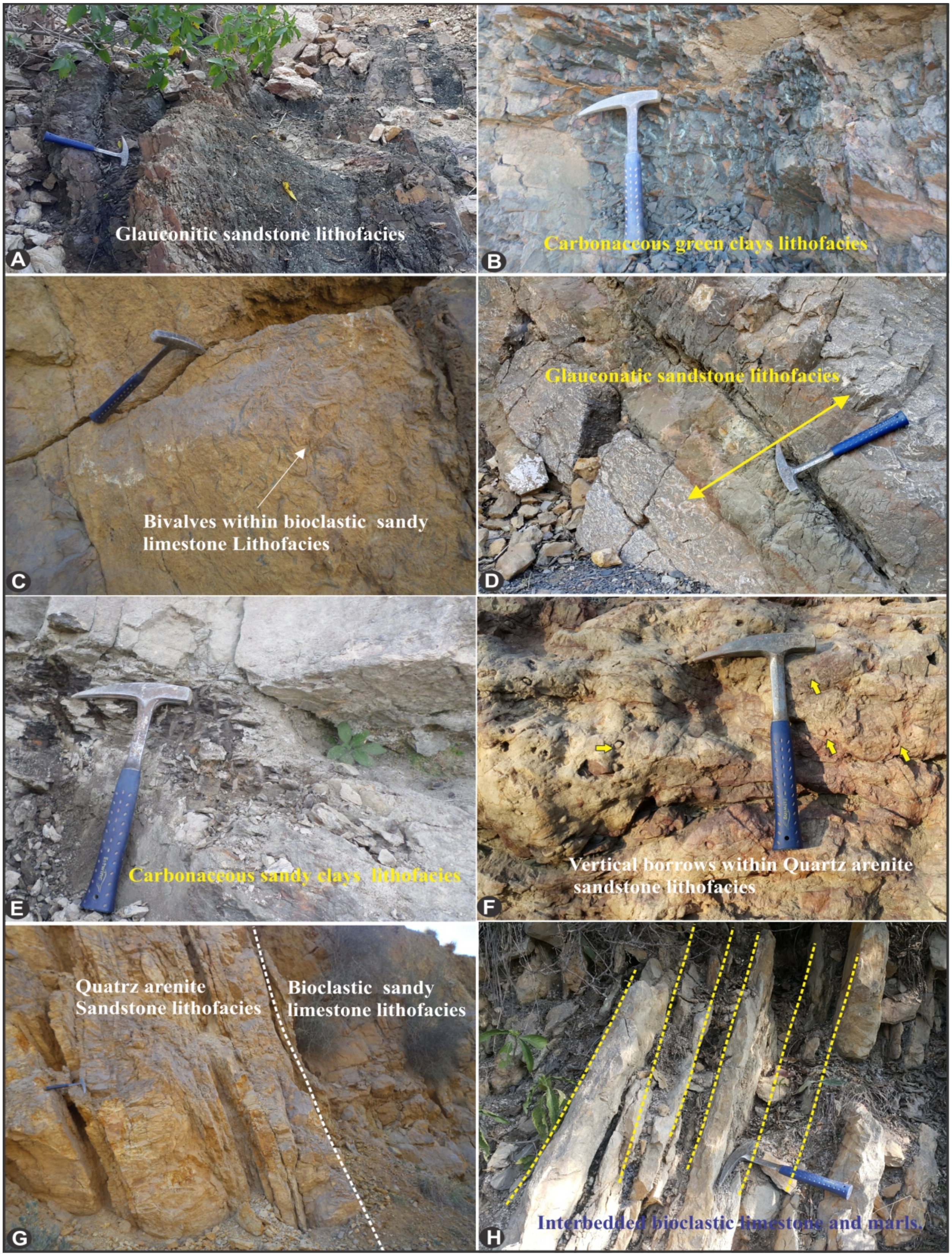


Fig. 4. Lithofacies of the Chichali and Lumshiwal formations, (A). Glauconitic sandstone lithofacies within the Chichali Formation, (B). Carbonaceous green clay lithofacies within Chichali Formation, (C). Bioclastic limestone lithofacies within the Lumshiwal Formation, (D). Glauconitic calcareous sandstone lithofacies, (E). Carbonaceous sandy shale lithofacies, (F). Vertical burrows within quartz arenite sandstone lithofacies of the Lumshiwal Formation, (G). Quartz arenite sandstone and bioclastic limestone lithofacies within the Lumshiwal Formation and (H). Interbedded bioclastic limestone and marls within the Lumshiwal Formation.

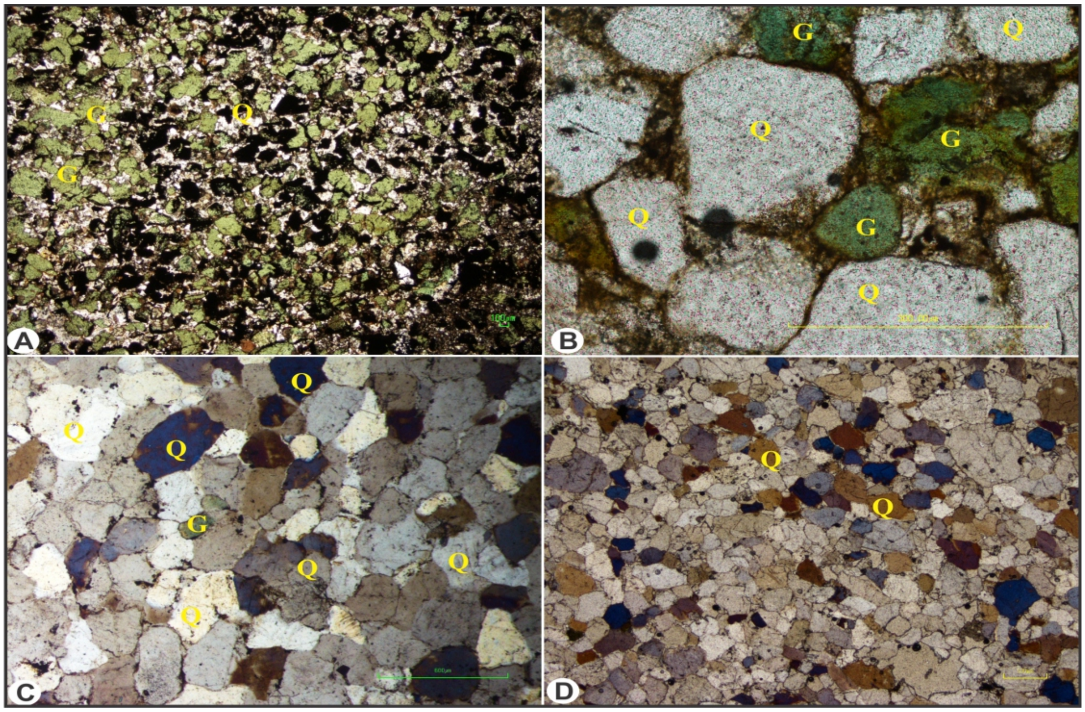


Fig. 5. Showing the lithofacies of the Chichali and Lumshiwal Formations, Fig (A-B). Glauconitic sandstone lithofacies of the Chichali Formation, Fig (C-D). Quartz arenite sandstone lithofacies of the Lumshiwal Formation

represented by six transgressions, i.e., TRT 1-6 and five regressions (RST 1-5; Figs. 6A, C, and 14, Figs. 6D, C and 14). The base of the cycle 1 is initiated by the lower most 70 cm, bioclastic sandy limestone facies. This bioclastic sandy limestone facies represents the inner ramp facies, which mark the progradation sequence after the maximum rise within topmost facies of the Chichali Formation (Fig. 14). This regression is denoted as (RST I; fig. 6B). The inner ramp facies (i.e. RST1) is followed by 6 cm glauconitic sandstone facies of the middle ramp depositional setting, which marks the TSTL I within the Lumshiwal Formation (Fig. 14). The 30 cm sandy bioclastic bed marks the RS T2. The sandy carbonaceous shale of the 30 cm marks another transgression (i.e. TSTL 2; fig. 14). The 30 cm sandy bioclastic bed marks another regression (i.e. RST 3; fig. 14). The third transgression (i.e. TSTL 3) is initiated by another 40 cm sandy carbonaceous shale. The thick bedded sandy bioclastic limestone (i.e. 6 meters) marks the 5th regression within in this cycle 1 of the Lumshiwal Formation (i.e. RST 5).

The second cycle of the Lumshiwal Formation (i.e. cycle 2; fig. 6D) is marked by 26-m intertidal sandstone and clays facies, which represent the maximum regression within the Lumshiwal Formation, denoted as RST 6 (Figs. 6D and 14).

The uppermost 10 meters cycle (i.e. cycle 3; fig. 6E), represented by lower 5-meter sandy limestone unit, marks the transgression after the maximum regression of the cycle 2. This is followed by a 14 cm sandy carbonaceous marls unit, which marks the marine flooding surface (Figs. 5E and 14). The monotonous sequence of the bioclastic limestone and marls represents intense sea le vel fluctuation in the uppermost part of the Lumshiwal Formation with ten cycles of regressions and transgressions respectively (Figs. 6E and 14).

5. Burial history

5.1. Compaction

Reservoir quality is largely affected by mechanical and chemical compactions and cementation that occur during burial (Ehrenberg, 1990, s1995; McBride et al., 1991). As a result of compaction, volume reduction and pore-water expulsion take place within the sediments. Both mechanical and chemical compactions reduce the inter-granular porosity.

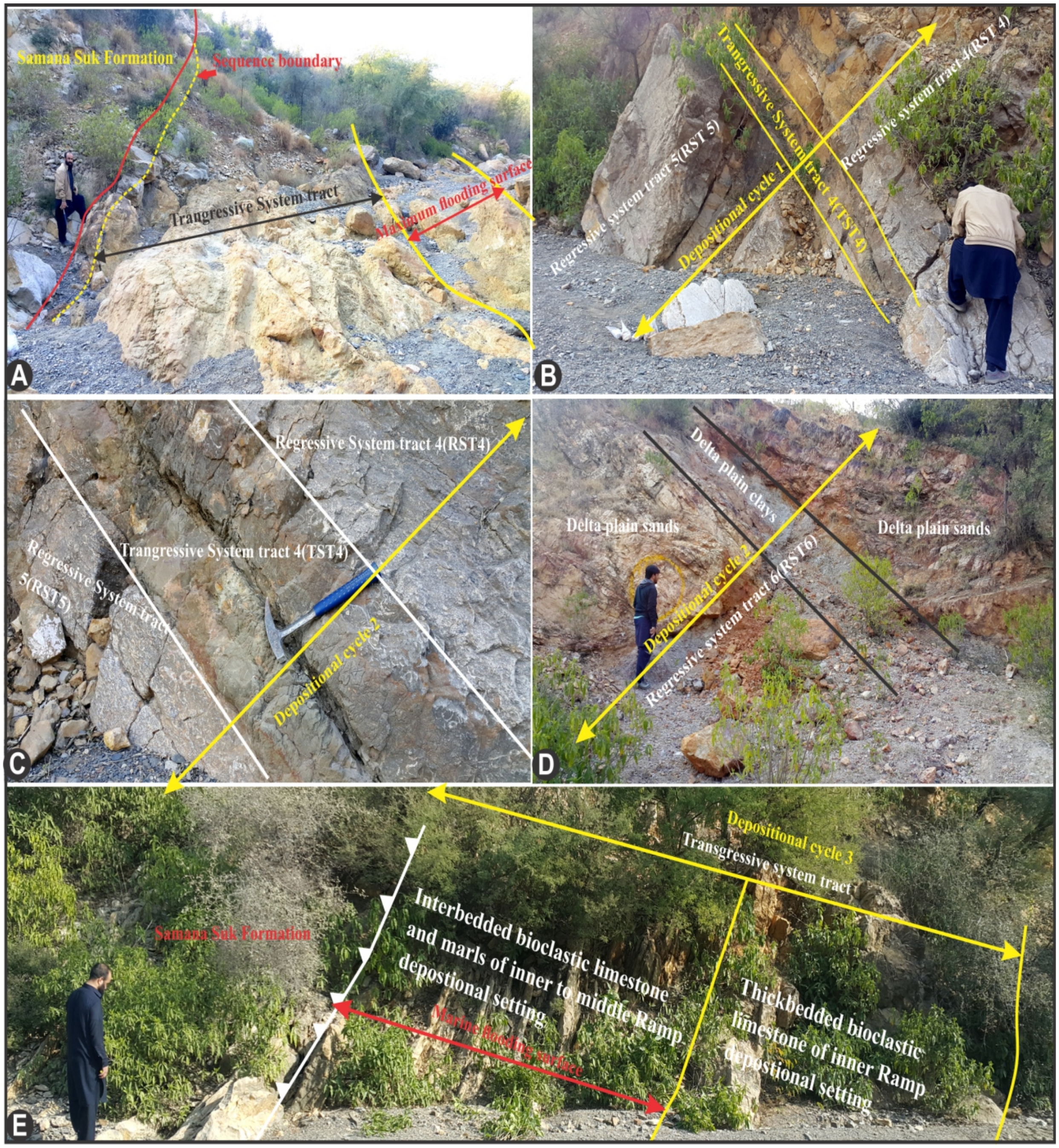


Fig. 6. Sequence stratigraphy of the Chichali and Lumshiwal formations, (A). Sequence boundary between Samana Suk and Chichali formations, deposition of glauconitic sandstone facies during transgressive system track (TST) and deposition of carbonaceous green clays during maximum flooding surface, (A). Overturned sequence of the Lumshiwal Formation, showing the deposition cycle 1; sandy bioclastic limestone during regression (RST4), glauconitic sandstone during transgression (TST4) and deposition of another sandy bioclastic limestone during regression (RST5), (C). The close-up of the cycle 1 depositional sequence, (D). Deposition cycle 2, responsible for the deposition of delta plain sandstone and clays of the Lumshiwal Formation, (E). Deposition cycle 3 within Lumshiwal Formation, responsible for the deposition of lower bioclastic limestone during transgression, and upper interddded thinly bedded limestone and marls during marine flooding surface.

Sandstones of both the formations underwent intense mechanical and chemical compactions during their continuous burial, which destroyed most of the original depositional porosity. Stylolite (Fig. 7A) within carbonates and concavo-convex (Figs. 6A), and sutured contacts (Fig. 7B) present in the studied sandstone samples are evident of intense burial induced compaction.

5.2. Cementation

Different types of cements have been recognized within Chichali and Lumshiwal formations which included calcite cement, quartz overgrowths, ferroan dolomite, iron oxide cement and glauconitic cement (Fig. 7B-F). The sandstone of the Lumshiwal Formation contains siliceous cement in the form of quartz overgrowths (Fig. 7B). The possible source for silica overgrowth is the siliceous solution generated by pressure dissolution of detrital quartz grains during deep burial compaction (Turner, 1980). The concentration of iron oxide/hydroxide cement is much more in the Chichali Formation than in the Lumshiwal Formation, and the post-uplift dissolution of this cement by surface water has caused an appreciable increase in secondary porosity. Carbonate-clay mix matrix also occurs in the Chichali Formation. All these cements lead to a significant decrease in the intergranular porosity.

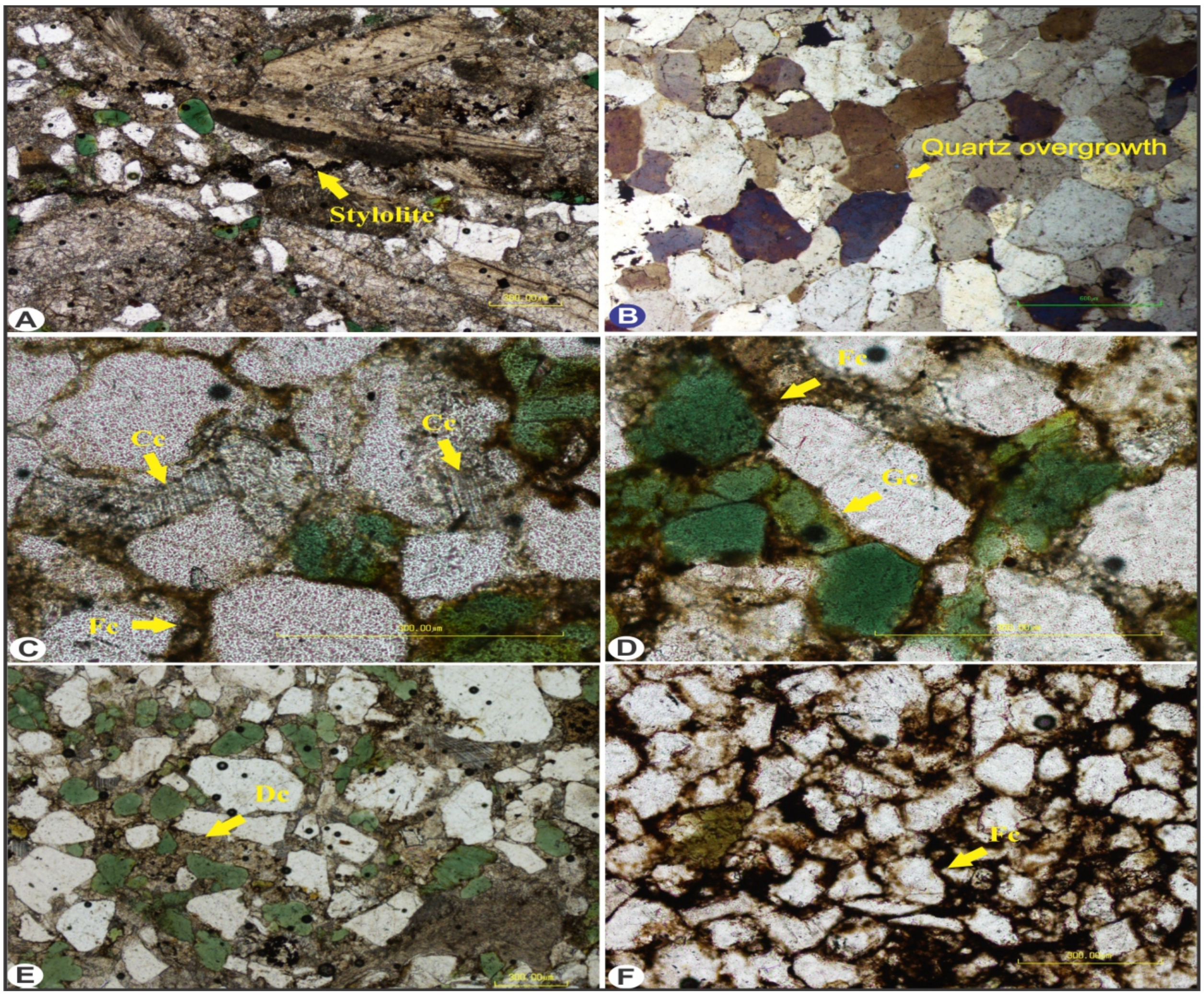
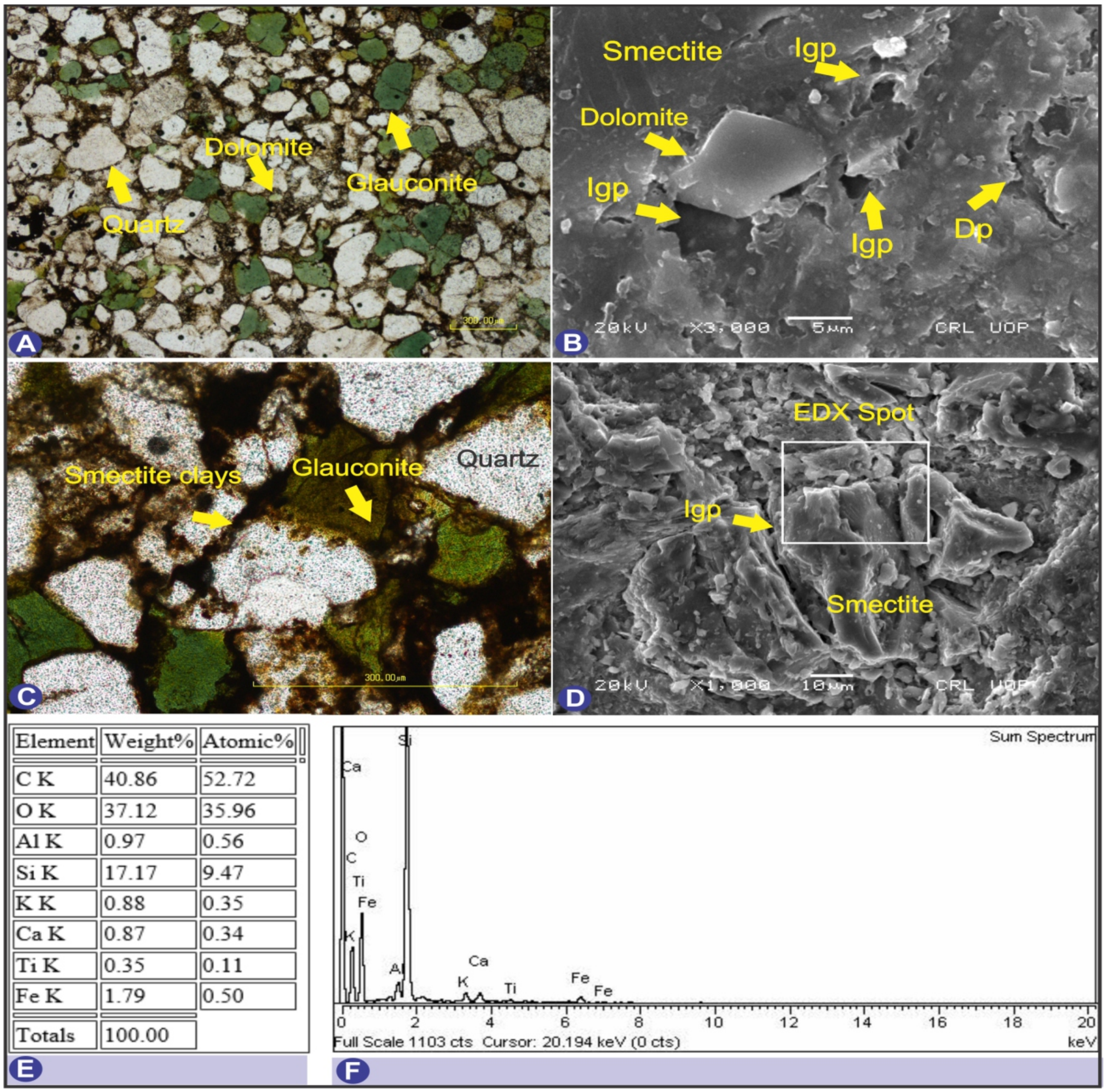


Fig. 7. Showing different types of diagenetic features, (A). Showing the stylolite, (B). Showing the sutured contact and quartz overgrowth, (C). Showing the calcite cement (Cc), filling the pore spaces in glauconitic sandstone lithofacies of the Chichali Formation, (D). Showing the glauconitic cements (Gc), filling the pore spaces in glauconitic sandstone lithofacies of the Chichali Formation, (E). Showing the dolomite cement (Dc), filling the pore spaces within bioclastic sandy limestone lithofacies of the Lumshiwal Formation, (F). Ferruginous cements (Fc) filling the pore spaces within glauconitic sandstone lithofacies of the Lumshiwal Formation.

5.3. Diagenetic history

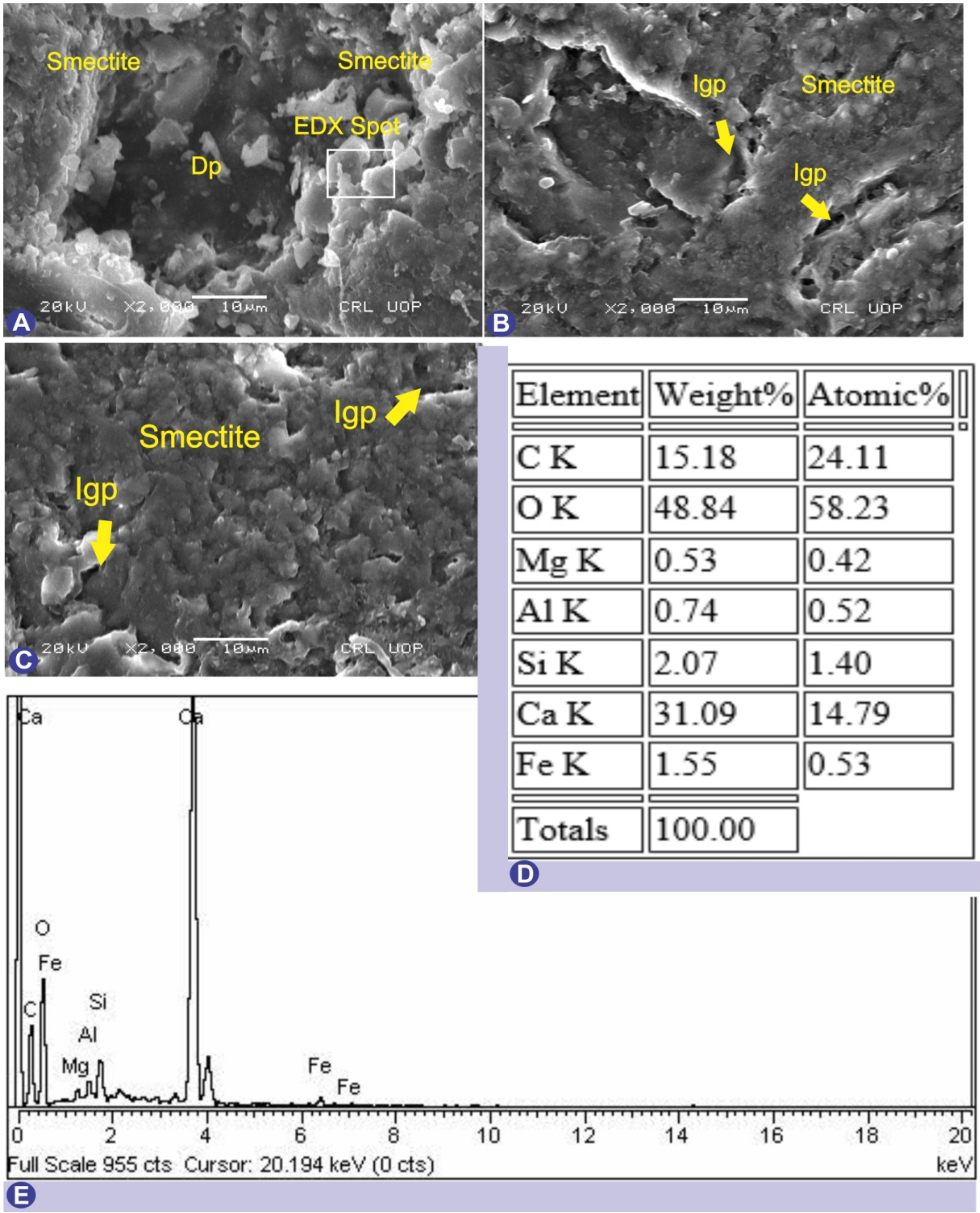
Chichali and Lumshiwal formations have undergone several stages of diagenetic events, resulting in both occlusion and, rare, enhancement of porosity. These diagenetic events and their relative timing have been interpreted by examination of the spatial relationship of cements in thin section and through the SEM or EDX analysis. The diagenetic events recognized in the Chichali and Lumshiwal formations included eogenesis, mesogenesis and teleogenesis.

During eogenesis, the Chichali and Lumshiwal formation have experienced mechanical compaction; chemical dissolution of the unstable grains, formation of smectite and illite (Figs. 8-14). The mesogenesis resulted in quartz overgrowth (Figs. 11 and 12), precipitation of drusy calcite cement (Fig. 14). The teleogenesis resulted in dissolution of iron oxide cement along fractures and precipitation of dolomite cements (Figs. 8 and 10) which may lead to an increase in the secondary porosity.



Element	Weight%	Atomic%
C K	40.86	52.72
O K	37.12	35.96
Al K	0.97	0.56
Si K	17.17	9.47
K K	0.88	0.35
Ca K	0.87	0.34
Ti K	0.35	0.11
Fe K	1.79	0.50
Totals	100.00	

Fig. 8. Glauconitic sandstone lithofacies of the Chichali Formation with dolomite cements filling pore spaces, (B). The SEM image of the same facies with intergranular (Igp) and dissolutions porosity (Dp), dolomite (D) and Smectite clays, (C). The Smectite clays, (D). The SEM image showing Smectite clays and intergranular porosity (Igp), (E and F). Composition and EDX peaks of the Smecite clays.



Element	Weight%	Atomic%
C K	15.18	24.11
O K	48.84	58.23
Mg K	0.53	0.42
Al K	0.74	0.52
Si K	2.07	1.40
Ca K	31.09	14.79
Fe K	1.55	0.53
Totals	100.00	

Fig. 9. SEM image of the glauconitic sandstone lithofacies of the Chichali Formation facies with intergranular (Igp) and dissolution porosity (Dp) and Smectite clays in A, B and C, (D and E). The EDX peak and composition of the Smecite types clays.

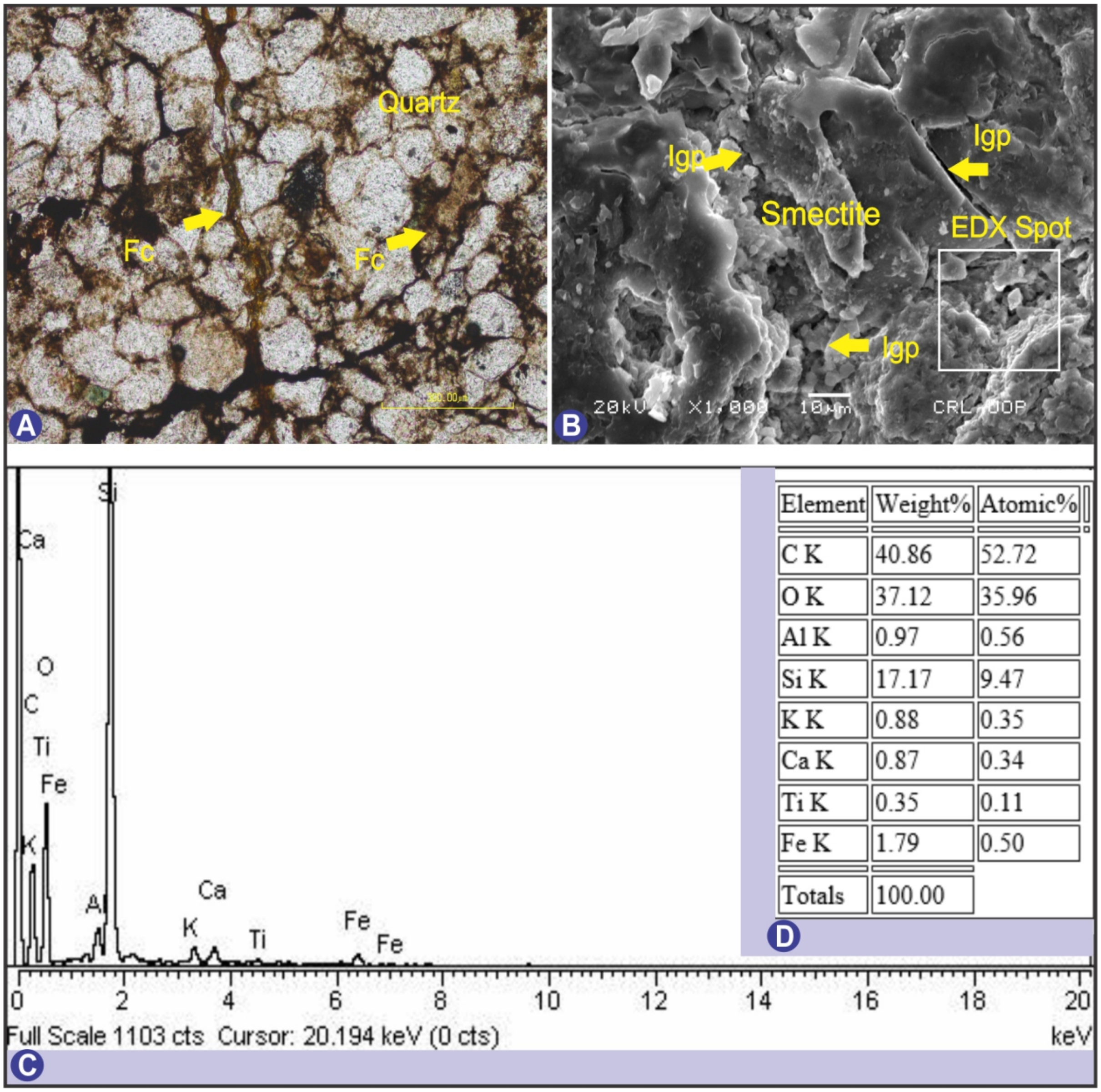
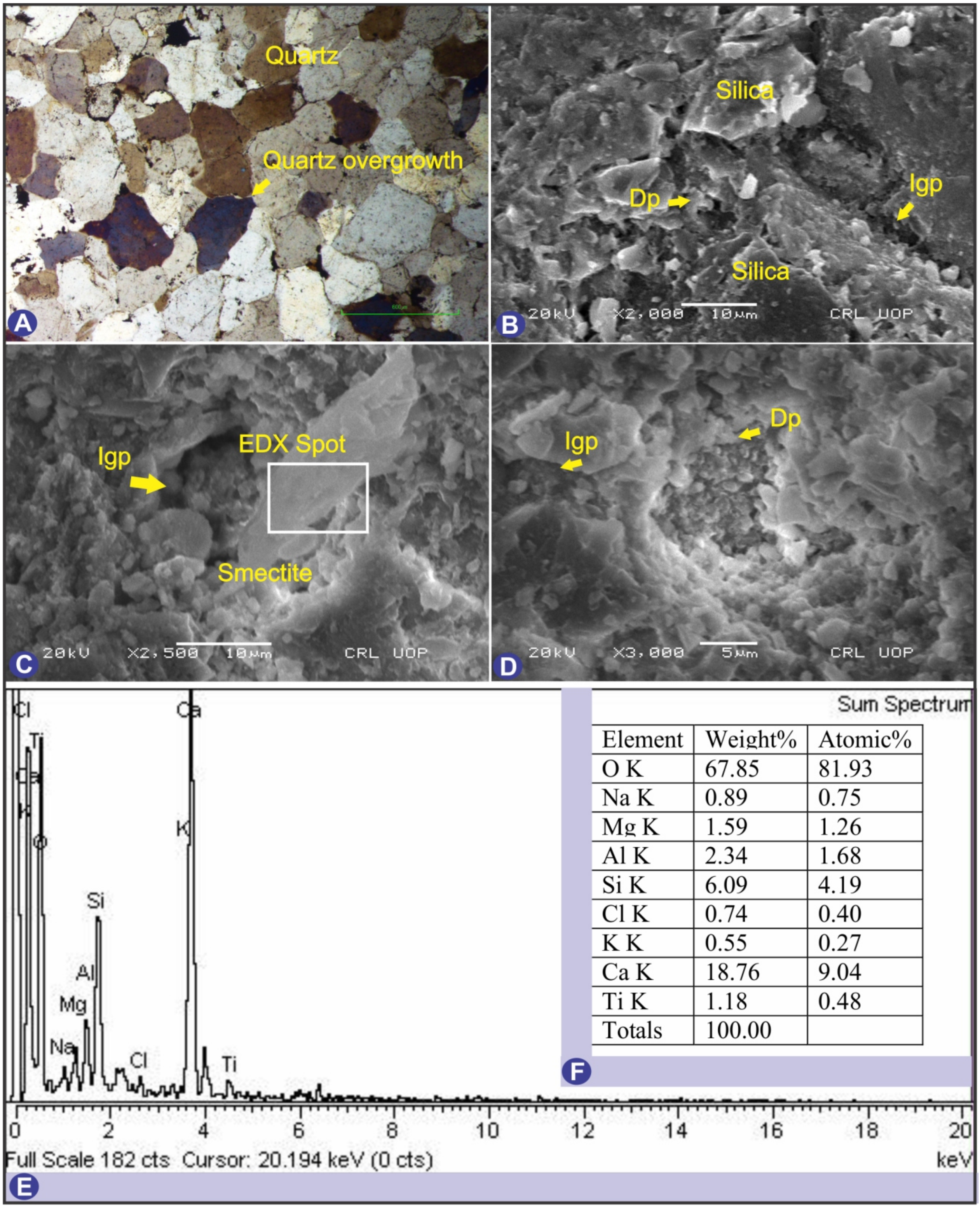
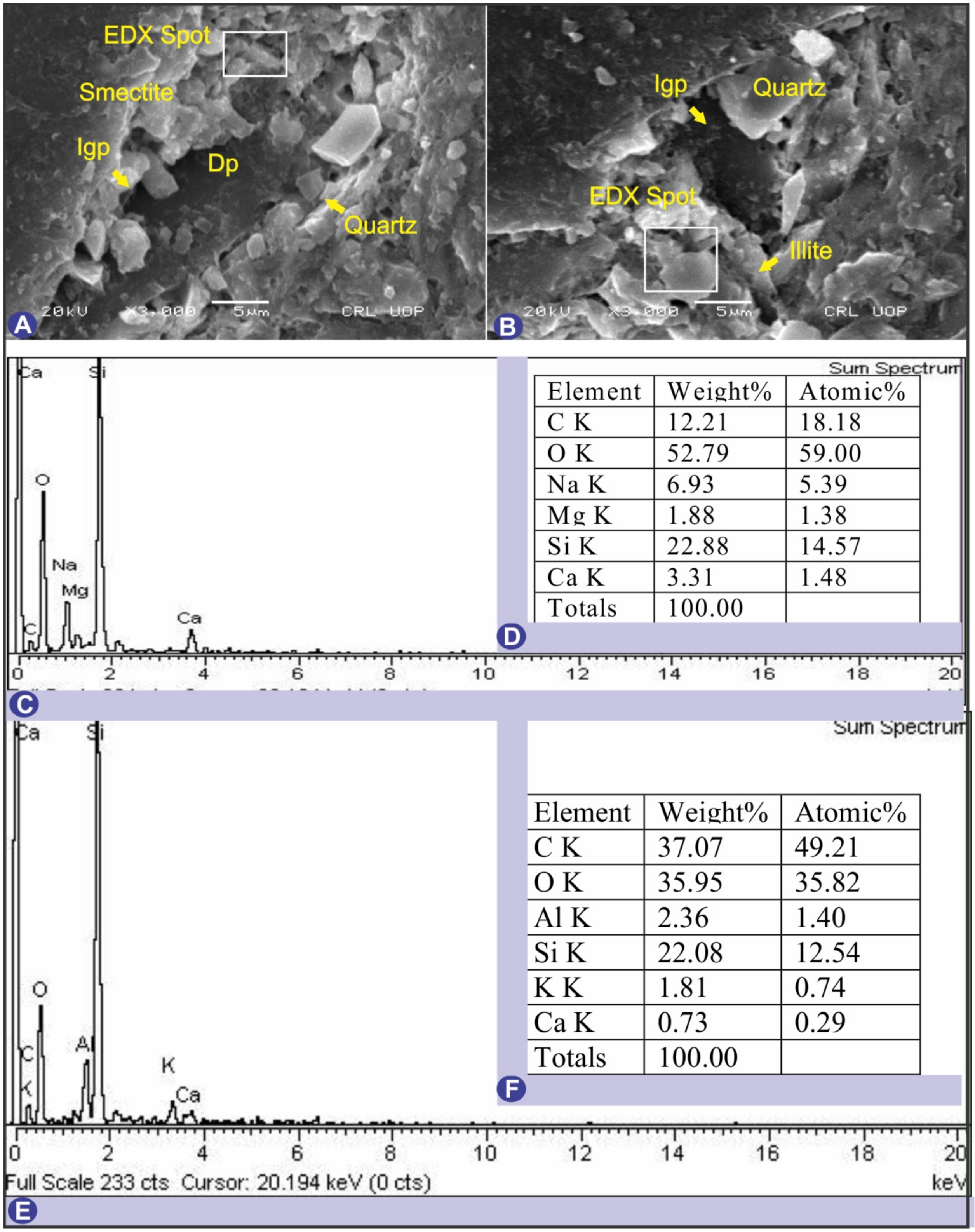


Fig. 10. (A). Photomicrographs showing ferruginous sandstone lithofacies of the Chichali Formation with ferruginous cements filling pore spaces, (B). SEM image of the same facies with intergranular (Igp) and Smectite clays within matrix of the ferruginous sandstone lithofacies, (C and D). The EDX peak and composition of the Smecite types clays.



Element	Weight%	Atomic%
O K	67.85	81.93
Na K	0.89	0.75
Mg K	1.59	1.26
Al K	2.34	1.68
Si K	6.09	4.19
Cl K	0.74	0.40
K K	0.55	0.27
Ca K	18.76	9.04
Ti K	1.18	0.48
Totals	100.00	

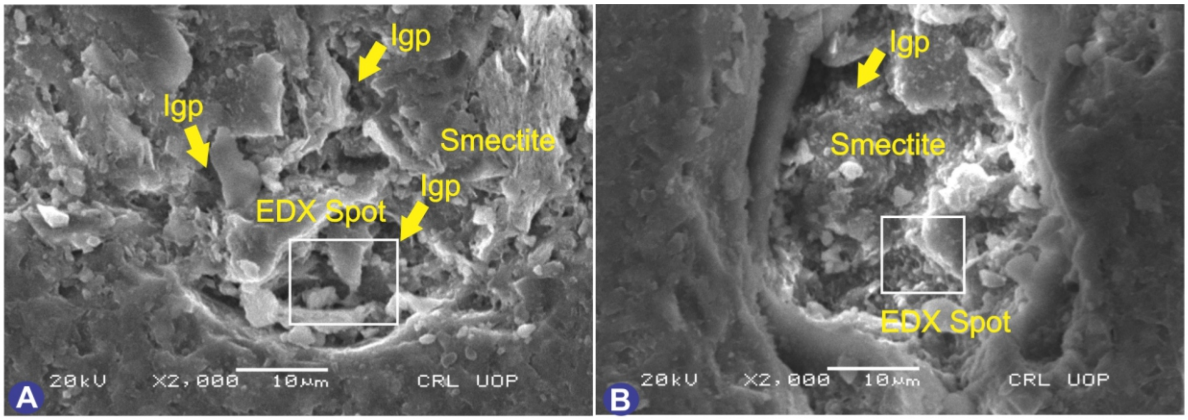
Fig. 11. Showing quartz arenite sandstone lithofacies of the Lumshiwal Formation, showing quartz overgrowth cements, (A). The SEM image of the same facies with intergranular (Igp) and dissolutions porosity (DP) in figs. B, C and D, (C). The SEM image showing Smectite clays, (F and E). Composition and EDX peaks of the Smectite clays.

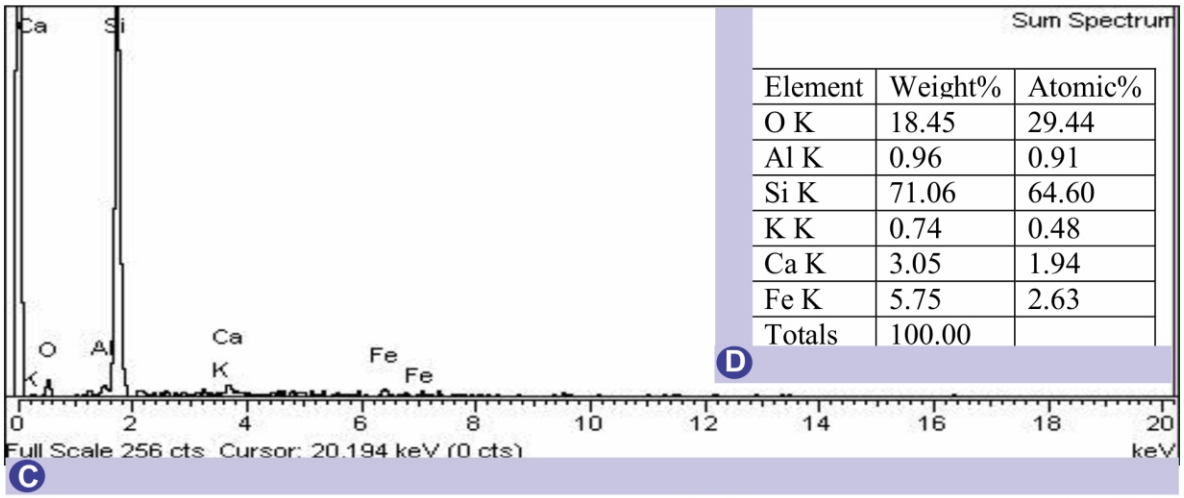


Element	Weight%	Atomic%
C K	12.21	18.18
O K	52.79	59.00
Na K	6.93	5.39
Mg K	1.88	1.38
Si K	22.88	14.57
Ca K	3.31	1.48
Totals	100.00	

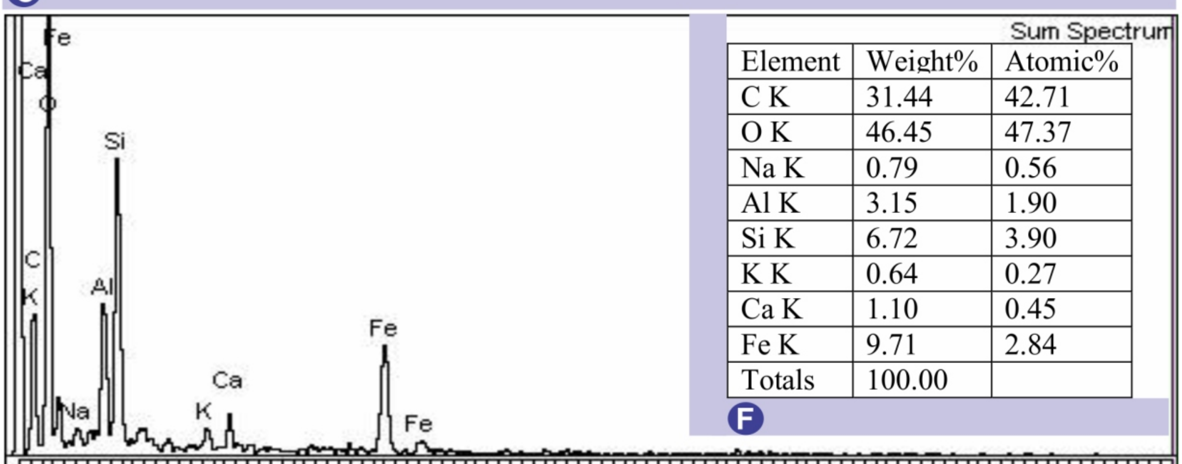
Element	Weight%	Atomic%
C K	37.07	49.21
O K	35.95	35.82
Al K	2.36	1.40
Si K	22.08	12.54
K K	1.81	0.74
Ca K	0.73	0.29
Totals	100.00	

Fig. 12. The SEM image of the same lithofacies with intergranular (Igp) and dissolutions porosity (DP) in A and B, (C and D). The composition and EDX peaks of the Smectite clays, (E and F). The composition and EDX peaks of the Illite clays.





Element	Weight%	Atomic%
O K	18.45	29.44
Al K	0.96	0.91
Si K	71.06	64.60
K K	0.74	0.48
Ca K	3.05	1.94
Fe K	5.75	2.63
Totals	100.00	



Element	Weight%	Atomic%
C K	31.44	42.71
O K	46.45	47.37
Na K	0.79	0.56
Al K	3.15	1.90
Si K	6.72	3.90
K K	0.64	0.27
Ca K	1.10	0.45
Fe K	9.71	2.84
Totals	100.00	

Fig. 13. SEM image of the same facies with intergranular (Igp) porosity in A and B, (C and D). Composition and EDX peaks of the Smectite clays, (E and F). The composition and EDX peaks of the Smectite clays of the Fig. B.

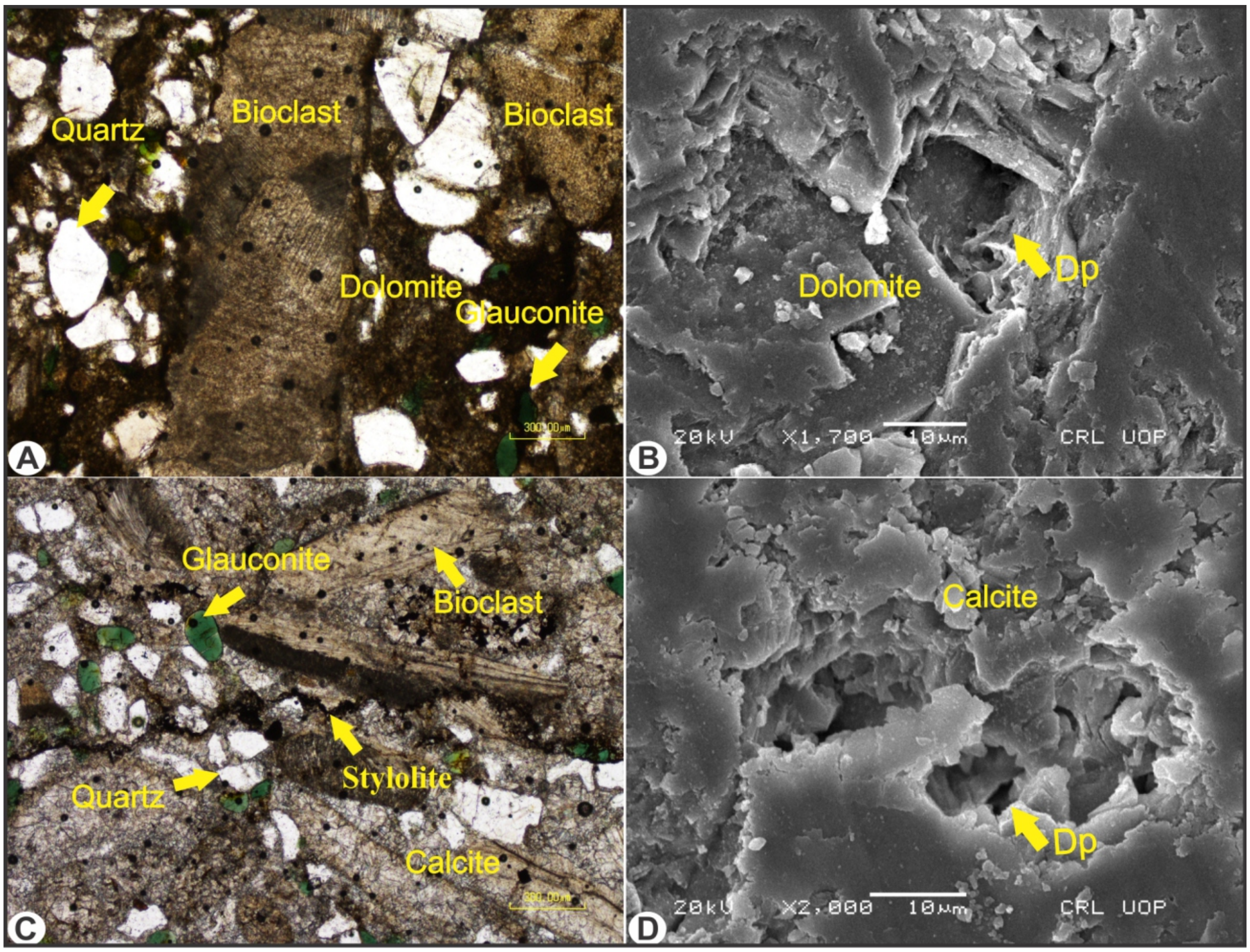


Fig. 14. Showing bioclastic sandy limestone facies of the Lumshiwal Formation, (A). Photomicrographs showing dolomitized matrix, (B). The SEM image of the same facies with dissolution porosity (DP) and dolomite, (C). Photomicrograph showing stylolites filled with ferruginous materials, (D). SEM image showing dissolution porosity within bioclastic sandy limestone.

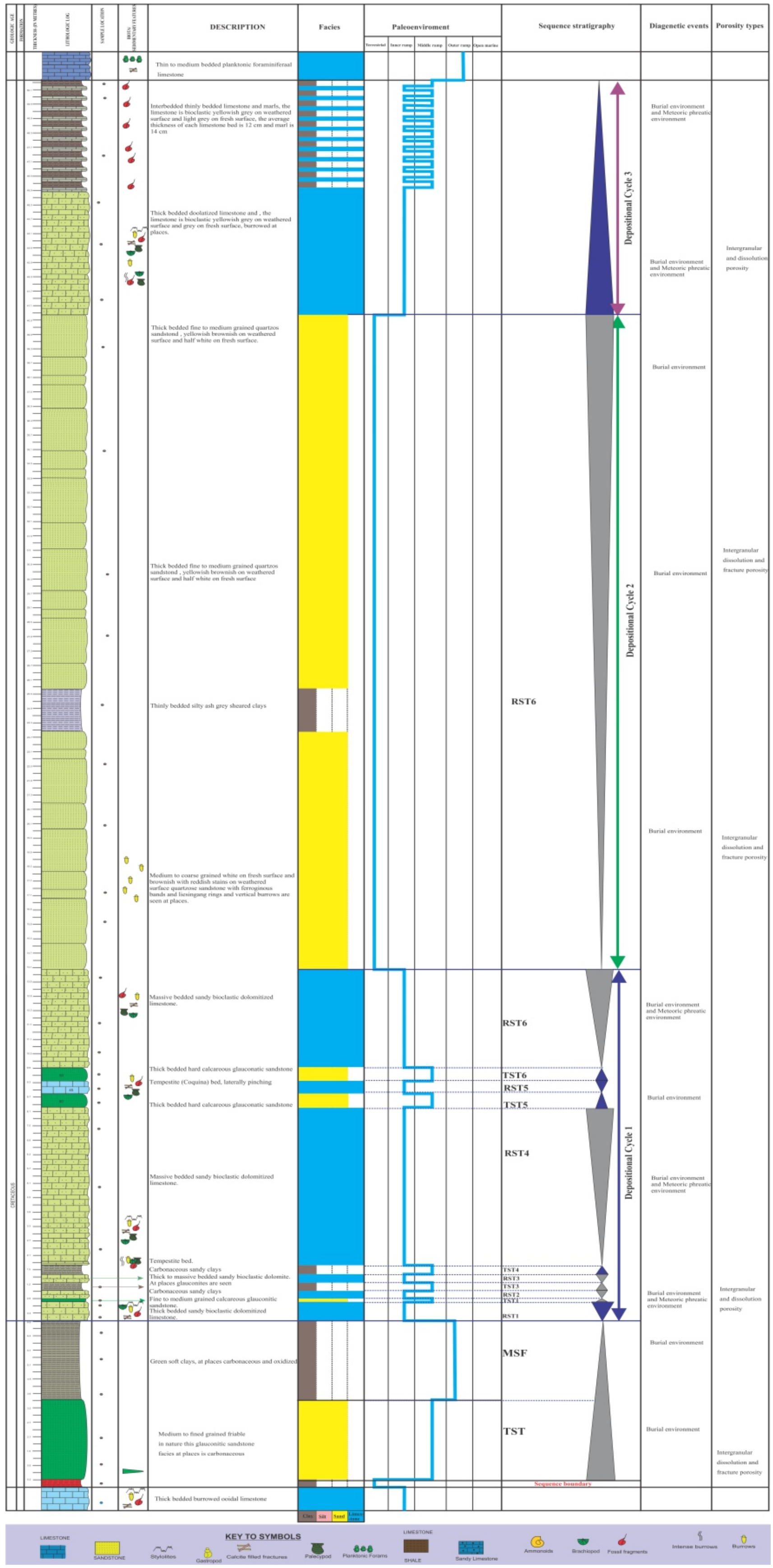


Fig. 15. Composite log showing facies distributions, sequence stratigraphy and reservoir characterization of the Chichali and Lumshiwal formations, Nizampur Basin, Pakistan.

6. Discussion

The petrographic, SEM and EDX investigations revealed that the glauconitic sandstone facies of the Chichali Formation of the early transgressions contained dissolution and intergranular porosities. The dissolution porosity may be attributed to the dissolution of unstable framework grains and pre-existing cement. The dissolution of unstable grains, probably amphibole grains (as indicated by the presence of Smectite clay) occurred during burial diagenesis (Selley, 2000). The pre-existing cement dissolution may have occurred during the subsequent epidiagenesis in RST 1 of the Lumshiwal Formation, or later, during teleogenetic stage of diagenesis. The green carbonaceous clay facies of maximum flooding surface acts as permeability barrier, resulting in the reservoir compartmentalization within the Chichali Formation to act as trapping/sealing horizons. Thus, these glauconitic sands bounded by shale facies might serve as potential reservoirs in the sub-surface.

The depositional intergranular, and diagenetic dissolution and fracture porosities are the dominant porosity types in all the stratigraphic units of the Lumshiwal Formation. The even distribution of the various porosity types in all the stratigraphic units of the Lumshiwal Formation hinders any relationship between depositional and diagenetic conditions and sea level fluctuations. The dissolution porosity may have developed during regressive episodes of deposition and subsequent burial and/or most probably during teleogenetic stage of diagenesis because of their ubiquitous distribution in all stratigraphic units.

The sandy bioclastic limestone interbeded with glauconitic sandstone in the lower most part of the Lumshiwal Formation may act as prolific reservoir intervals sealed by sandy carbonaceous shale within this unit. The lower part is overlain by a 26m-thick second depositional cycle of intertidal sandstone and thin clays of maximum regression within Lumshiwal Formation. These intertidal sandstones may act as potentially good reservoirs as these are thick-bedded arenites with good depositional and diagenetic porosities. The uppermost depositional cycle of the Lumshiwal Formation is comprised of thin bedded bioclastic sandy limestone and marls. This low energy depositional cycle may act as possible seal for the underlying quartz arenites. On average, the maximum regression associated arenites in the middle unit of the Lumshiwal Formation may act as good reservoirs in the subsurface while the transgression associated lower and uppermost units may act as permeability barriers and may form prolific stratigraphic traps in the subsurface and adjoining sedimentary basins, i.e. northwestern part of the Potwar and Kohat basins.

7. Conclusions

- The Chichali Formation in the Nizampur Basin, Pakistan consists of laterite, glauconitic sandstone and carbonaceous green shales lithofacies, representing transgression associated deposition in the middle to outer ramp depositional setting.
- The intergranular pores filling materials include calcite, hematite, smectite, ferroan dolomite and glauconitic cement in the Chichali Formation, thereby reducing the porosity of the formation. Dolomitization, intergranular and dissolutions porosity have resulted in increase in the porosity within glauconitic sandstone lithofacies of the Chichali Formation.
- The Lumshiwal Formation consists of bioclastic sandy limestone, sandy carbonaceous shale, white quatrzose sandstone, glauconitic sandstone, interbedded thin bedded bioclastic limestone and marls facies.
- On the basis of vertical succession and depositional environments, the deposition of Lumshiwal Formation took place during three depositional cycles; cycles 1-3.
- The lowermost cycle resulted the deposition of mixed carbonates and silicastic sequence with six regressions TRT 1-6 and five regressions (i.e. RST 1-5).
- The cycle 2, is responsible for the deposition of intertidal sequence of quartz arenite and clay facies.
- The uppermost cycle 3 is represented by lower sandy limestone unit and upper monotonous sequence of the bioclastic

limestone and marls.

- The middle depositional cycle 2 deposited during maximum regression may act as good reservoir with the overlying cycle 3 acting as permeability barrier.

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