The impact of diagenesis on the reservoir quality of the early Cretaceous Lower Goru sandstones in the Lower Indus Basin, Pakistan

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Abstract

The sandstone units of the Early Cretaceous Lower Goru Formation are significant reservoir for gas, oil, and condensates in the Lower Indus Basin of Pakistan. Even though these sandstones are significant reservoir rocks for hydrocarbon exploration, the diagenetic controls on the reservoir properties of the sandstones are poorly documented. For effective exploration, production, and appraisal of a promising reservoir, the diagenesis and reservoir properties must be comprehensively analyzed first. For this study, core samples from depths of more than 3100 m from the KD-01 well within the central division of the basin have been studied. These sandstones were analyzed using petrographic, X-ray diffraction, and scanning electron microscopic analyses to unravel diagenetic impacts on reservoir properties of the sandstone. Medium to coarse-grained and well-sorted sandstone have been identified during petrographic study. The sandstone are categorized as arkose and lithic arkose. Principal diagenetic events which have resulted in changing the primary characters of the sandstones are compaction, cementation, dissolution, and mineral replacement. The observed diagenetic processes can be grouped into early, burial, and late diagenesis. Chlorite is the dominant diagenetic constituent that occurs as rims, coatings, and replacing grains. The early phase of coating of authigenic chlorite has preserved the primary porosity. The recrystallization of chlorite into chamosite has massively reduced the original pore space because of its bridging structure. The current study reveals that diagenetic processes have altered the original rock properties and reservoir characteristics of the Lower Goru sandstone. These preliminary outcomes of this study have great potential to improve the understanding of diagenetic process and their impact on reservoir properties of the Lower Goru sandstone in the Lower Indus Basin and adjoining areas.

Keywords Diagenesis · Indus Basin · Lower Goru · Porosity · Reservoir quality · Sandstone

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Introduction

The effect of diagenesis and depositional environment on reservoir properties is significant in petroleum exploration (Morad et al. 2010) because it will advocate the economic appraisals Ashraf et al. 2016. The heterogeneity of sedimentary rocks and reservoir quality generally depends upon primary depositional elements and secondary diagenetic alterations (Bjørlykke 2012; Makeen et al. 2016; Ali et al. 2021). Reservoir characteristics of the sandstone such as geometry, mineralogical composition, pore characteristics, porosity, permeability, textural framework, and maturity are evaluated by depositional settings of the sandstones, whereas the diagenesis may affect the reservoir porosity by post-depositional processes (Bjørlykke 2014; Cantarero et al. 2020; Mangi et al. 2020). Reservoir quality is the main factor controlling the prospectivity during the exploration and production of hydrocarbon (Zhang et al. 2020). Lower Goru sandstone reservoirs in the Lower Indus basin have been studied with the help of core cuttings of well KD-01 well from the sandstone intervals. Integrated petrographic studies, scanning electron microscope (SEM) and X-ray diffraction (XRD) investigations, as well as porosity and permeability measurements, have been studied to figure out diagenetic impacts on the reservoir characteristics of oil and gas producing units of the Cretaceous Lower Goru Formation.

The Lower Goru Formation in the Lower Indus Basin and Middle Indus Basin of Pakistan is among the hydrocarbon producing reservoir (Ashraf et al. 2020b; Ali et al. 2020). Over the past few decades, the Lower Goru reservoir has attracted huge attention from researchers because of its hydrocarbon potentiality and depositional settings but vast hydrocarbon potential remained unexplored (Ashraf et al. 2020a; Ali et al. 2020). A productive petroleum system of both the source and reservoir Early Cretaceous Sembar and overlying Lower Goru Formation, respectively, have been used for hydrocarbon production for more than twenty years with good success and production rate (Jamil et al. 2012).

Among different authors work the most significant contribution has been made by (Kadri 1995; Robison et al. 1999; Zaigham and Mallick 2000; Ahmad et al. 2004, 2010; Baig et al., 2016; Yasin et al. 2019; Ashraf, et al. 2019; Ashraf, et al. 2021; Qadri 2019) to study the petroleum prospect stratigraphy and regional tectonic setting of the basin. To date, there are only a few research studies on the diagenetic impacts controlling reservoir characters of the sandstones. The most significant work has been done by Berger et al. 2009 on the C sand of the Lower Goru Formation in which they investigated that presence of chlorite coats is the substantial mechanism for preserving porosity.

Baig et al. (2016) investigated the Basal and Massive sand of the Lower Goru Formation and assess the diagenetic control on the reservoir properties of the sandstone they concluded that existence of abundant chlorite coats and low quartz cement are the main diagenetic reasons for the occurrence of high porosity in the massive and basal sands. This study examines that the same process operates in the reservoir encountered in the KD-01 area.

Hence, a gap still exists between the reservoir characteristics and associated impacts on reservoir quality of the other sand units of the Lower Goru Formation because of the diagenesis of the Early Cretaceous Lower Goru sandstone reservoir in the area. This research was carried out to undertake a comprehensive diagenetic analysis of the reservoir, to figure out the diagenetic history and effects on reservoir properties, to investigate how the composition and depositional environment has an effect on the reservoir characters of the sandstone. This study will improve understanding of the pore types, cement types, diagenetic sequence, and diagenetic impacts on the reservoir characters.

Geological setting

The present study is on the Lower Goru sandstone from the central part of the Lower Indus Basin of Pakistan (Fig. 1). The formation is located in an area where Sargodha high is present in the northern side, Sulaiman fold and thrust belt is situated in the western side, Indian shield is located in the eastern side, and toward the south Jacobabad-Khairpur high is present (Kadri 1995; Afzal et al. 2009; Naeem et al. 2016; Berger et al. 2009; Azeem et al. 2013). Sedimentary rock units in the region consist of Triassic (Wulgai Formation) to Quaternary alluvium (Berger et al. 2009; Fig. 2). Lower Goru Formation of the Early Cretaceous consists of some sand units which are showing good characters of a reservoir, upper portion of the formation is comprised of siltstone, sandstone along with shale, in the basal portion some intercalated limestone and shale are present within the sandstone (Kadri 1995). The Lower Goru Formation is divided into different units named as A, B, C, and D sand units (Mahmoud 2015) (Fig. 2). The sandstone unit present within the formation is suggested to be deposited during sea-level low stand within a shallow marine environment, however, coarse grain deposits were formed on top of the distal sediments of the prior high stand system tract (Berger et al. 2009; Ashraf et al. 2021). Indian Shield rocks to the eastern side are the source of the Lower Goru Formation, these Shield rocks consist of the Precambrian granites and metamorphic rocks. The sandstone units showing reservoir characters are a product of different depositional environments, ranging from deltaic, fluvial, barrier bars, shallow marine, and shoreface to offshore depositional environment

Fig. 1 Geological map of Pakistan showing the location of the Lower Indus Basin inset showing the location of well KD-01 (modified after (Kadri 1995))

(Kadri 1995; Krois et al. 1998; Ashraf et al. 2021). The extensively distributed Cretaceous Sembar Formation acts as source rock in the area (Khalid et al. 2014; Yasin et al. 2017). The stratigraphic section of exploration well KD-01 is shown in (Fig. 3).

Material and methods

A total of 50 samples from the sandstone reservoir intervals from the Lower Goru Formation were used from exploration well KD-01 and analyzed for petrographic microscopy, X-ray diffraction (XRD), and scanning electron microscopy (SEM). Thin sections petrographic analysis have been done for the purpose of determination of the mineralogical composition, cement types and textural framework, and porosity.

The selected core samples of the sandstone were used for porosity recognition, these samples were soaked with blue epoxy to enhance the visibility of carbonate minerals. A total of 300 point counts were used in each thin section to study the modal composition of the sandstone, with the method suggested by (Dickinson et al. 1979; Dickinson et al. 1983). The framework grains of the sandstone of the Lower Goru Formation have been divided into quartz monocrystalline and polycrystalline, feldspar, rock fragments, mica, cement (authigenic clay, carbonate, and silica), and matrix. During thin section point counting study the numbers of pore spaces were also counted. Petrographic analysis and visual porosity were found out through Olympus Bx50 petrographic microscope set with digital camera.

Thin section point count data were also used for intergranular volume IGV estimation. The framework grains of the Lower Goru Sandstone were characterized into quartz,

Fig. 2 Generalized stratigraphy of the study area (modified after (Qureshi, Ghazi et al. 2021))

Fig. 3 Stratigraphic section of the KD-01 Well (modified after (Qureshi, Ghazi et al. 2021))

feldspar, lithic fragments, organic fragments, glauconite, mica, and matrix. To confirm the mineralogical composition using petrographic studies, ten representative sandstone samples were analyzed by XRD. Information about the clay mineral presence in the reservoir has been derived through the XRD analysis. Back-loading method was used for the XRD analysis.

Furthermore, authigenic minerals, diagenetic texture, quartz overgrowth, and dissolution effect were analyzed using SEM. For SEM, the samples were cleaned, gold coated, and analyzed by using a scanning electron microscope. The prepared samples were investigated in backscattered electron and secondary electron imaging modes. The porosity and permeability results

were derived through petrographic and SEM analysis. The minerals distribution and pore morphology was observed by using FEI quanta 400 FEG SEM. The Hydrocarbon Development Institute of Pakistan (HDIP) provided the helium porosity and permeability information of the sandstone samples from the KD-01 well.

Fig. 4 Photomicrographs and SEM images **a** Well KD-01, 3142 m, Glauconite (G), deformed mica (dm), monocrystalline quartz (Qm), **b** Well KD-01, 3142 m, XPL view clay coatings on quartz grains mc is mud clasts red arrows show the quartz overgrowth **c** Well KD-01, 3145 m, framework grains of sandstone, glauconite (G), monocrystalline quartz (Qm), potassium feldspar (Kf), zircon (zr) **d** Well KD-01, 3150 m, intergranular porosity **e** Well KD-01, 3150 m, intergranular porosity within deformed mica authigenic quartz (QA), **f** Well KD-01, 3151 m, intergranular porosity within feldspar grains, authigenic feldspar (QA), intergranular porosity (IGP), feldspar dissolution (FD) **g** Well KD-01, 3155 m, glauconite (G), potassium feldspar (Kf), and red arrows show quartz overgrowth **h** Well KD-01, 3155 m, intergranular pores within leached feldspar (sp)

Results and discussions

Petrography and modal composition

Petrographic investigations reveal that the sandstone is composed of detrital constituents, accessory minerals, cement, matrix, and pores (Fig. 4, Table 1). The detrital constituents include quartz, feldspar, glauconite, and lithic fragments with some minor amount of mica, zircon, and rutile. The Lower Goru reservoir sandstone is mainly medium to coarse grained (Table 1). The major detrital mineral found out in

the studied sample is Quartz. Monocrystalline detrital quartz is dominant and polycrystalline quartz is less abundant. Mineralogically the Lower Goru reservoir sandstone is predominantly consisting of quartz, feldspar, and rock fragments. The overall framework of the grains consists of 40 to 50 percent of monocrystalline quartz grains, these grains are subangular to rounded. Polycrystalline quartz is less common with an average of 1.2%. The dominant monocrystalline quartz suggests derivation from plutonic rocks Folk 1974. Medium to coarse grained polycrystalline quartz was identified which shows the information about the metamorphic sources. The second most abundant detrital component identified in the sandstone was feldspar which is about 14 to 20 percent of the total framework. The feldspar grains are subangular to subrounded in shape. K-feldspar is the dominant type of feldspar while plagioclase is less common. The feldspar grains display partial to wide range leaching. SEM analysis and petrographic analysis show that feldspar is highly altered and fractured feldspar. The lithic grains constitute about 4 to 7% of the framework grains and are dominantly comprised of mud clasts, grains of igneous material, chert, and foraminiferal debris (Table 1). The organic fragments were observed in all the samples of the sandstone ranging from 1 to 4%. The fragments became compacted during compaction and lie parallel to bedding.

Rounded green color grains of glauconite (Fig. 4a) are there in almost all the investigated sandstone of the Lower Goru Formation (Table 1). The glauconite is present in the form of tiny grains, cement, and pellets in the sandstone. The glauconite range from 0.5 to 3% with an average of 2.1% of the total framework. The glauconite grains are rounded to subrounded and elliptical in shape. The glauconites display light green color under plane-polarized light and exhibit green to dark green color under the cross-polarized light (Fig. 4b). Among the framework grains the matrix and cement act as cementing materials. About 1 to 2 percent of the framework composition is consists of matrix and are mostly clay minerals of detrital nature or formed diagenetically. Zircon and sphene grains are also observed in the Lower Goru Formation (Fig. 4c.) Trace amounts of biotite and muscovite are existing in all the analyzed samples (Fig. 4c). Grains of biotite and muscovite are deformed or turned due to compaction.

Sandstone classification

Based on the total quartz, feldspar, and lithic fragments (Q-F-L) plot of the framework grain composition (Table 1) on the background diagram of (Folk et al. 1970), the sandstones studied from the Lower Goru Formation are classified as arkose and feldspathic arenite (Fig. 5). According to (Pettijohn et al. 1987), the rock will be considered as arenite

Table 1 Modal composition of the sandstone of the Lower Goru Formation from the Lower Indus Basin

Sample No	Depth	Qm (%)	Qp (%)	Kf (%)	Plagioclase Feldspar (%)	Lf (%)	Recalculated (100%)			GL (%)	Hm (%)	M (%)	Mx (%)	Authigenic minerals				IGV = Primary porosity + cement
							Q	F	L					Chlorite	Quartz	Ferroan Calcite	Pyrite	
KD-1	3132	44	1	15	1	5	68.18	24.24	7.58	2	1	1	2	25	1	1	1	32
KD-2	3133	45	1	17	2	4	66.67	27.54	5.80	2	2	1	2	20	2	1	1	28
KD-3	3134	46	1	15	1	3	71.21	24.24	4.55	1	1	1	1	23	3	2	2	36
KD-4	3135	40	0.5	18	1	4	63.78	29.92	6.30	3	1	1	1	24	4	1	2	34
KD-5	3137	45	1	17	1	2	69.70	27.27	3.03	2	1	1	1	25	2	1	2	32
KD-6	3140	43	2	17	1	3	68.18	27.27	4.55	2	2	1	3	21	3	2	1	32
KD-7	3142	45	2	18	1	2	69.12	27.94	2.94	2	1	2	1	22	2	1	1	31
KD-8	3143	44	1	19	1	5	64.29	28.57	7.14	1	1	1	2	18	4	1	2	29
KD-9	31,744	47	1	16	1	2	71.64	25.37	2.99	3	2	1	1	22	3	1	1	31
KD-10	3146	50	1	17	1	2	71.83	25.35	2.82	1	1	1	1	20	3	1	1	29
KD-11	3147	43	2	14	2	3	70.31	25.00	4.69	3	1	2	3	22	2	2	1	33
KD-12	3148	44	1	15	2	3	69.23	26.15	4.62	3	1	2	3	25	3	2	2	39
KD-13	3149	45	0.5	16	1	2	70.54	26.36	3.10	3	1	2	2	24	1	2	1	32
KD-14	3150	44	2	15	1	2	71.88	25.00	3.13	3	2	2	3	22	1	2	1	32
KD-15	3152	45	1	17	1	3	68.66	26.87	4.48	2	2	2	3	21	1	1	1	30
KD-16	3155	46	1	16	1	3	70.15	25.37	4.48	3	2	2	2	21	1	1	1	28
KD-17	3157	45	1	17	1	4	67.65	26.47	5.88	2	2	2	2	19	2	1	2	28
KD-18	3160	47	2	14	1	3	73.13	22.39	4.48	2	2	2	2	21	1	2	1	29
KD-19	3162	42	1	15	1	4	68.25	25.40	6.35	2	2	1	2	25	2	2	1	34
KD-20	3165	45	2	17	2	3	68.12	27.54	4.35	2	2	1	2	21	1	2	1	29
KD-21	3167	46	2	18	2	3	67.61	28.17	4.23	2	1	1	1	20	2	1	1	27
KD-22	3170	45	1	16	2	3	68.66	26.87	4.48	1	1	1	1	23	4	1	1	32
KD-23	3172	44	2	16	1	4	68.66	25.37	5.97	1	1	1	1	24	2	1	2	32
KD-24	3173	47	1	17	1	3	69.57	26.09	4.35	2	1	1	2	21	2	1	1	29
KD-25	3175	46	1	15	1	3	71.21	24.24	4.55	2	2	1	1	23	2	1	2	33
KD-26	3177	46	2	16	1	2	71.64	25.37	2.99	2	1	1	2	22	2	2	1	33
KD-27	3178	45	1	18	1	2	68.66	28.36	2.99	3	2	1	3	20	1	2	1	31
KD-28	3180	46	1	15	1	3	71.21	24.24	4.55	2	1	1	2	23	3	1	1	33
KD-29	3182	43	1	16	1	3	68.75	26.56	4.69	1	2	2	2	23	3	2	1	33
KD-30	3185	47	1	15	1	4	70.59	23.53	5.88	3	1	2	2	19	2	1	2	28

Fig. 5 Sandstone modal data plot of the total quartz-feldspar-lithic fragments (Q-F-L) on the background ternary diagram of Folk (1974)

if the total matrix is less than 15%, and it will be considered as wacke if the percent of matrix is inbetween 15 and 75%. Based on the percentages of the matrix presented in (Table 1), the sandstones can be classified as arenites. The classification system used in this study is based on the QFL ternary diagram of (Folk 1974) and (Dickinson et al. 1983).

Reservoir properties

Porosity and permeability

The helium porosity of the investigated core samples ranges from 7.2 to 20% with an average of 12.4% (Table 3). Horizontal permeability concentrates from 0.04 to 0.24 mD with an average of 0.23 mD. Porosities were also assessed by the petrographic point count analysis. Porosity estimated by thin section analysis of the sandstone range from 2 to 4%,

averaging 2.53%. In the analyzed sandstone samples, three pore types were identified by petrographic and SEM analysis. The pore types are primary intergranular pores (Fig. 4d), intercrystalline pores, and solution pores (Fig. 4e–f) are the three main pore types identified by petrographic and SEM analysis. The intergranular pores volumes are estimated to range from 27 to 39% and are reduced by mechanical compaction, chlorite cementation, and to a minor extent by quartz, pyrite, and ferroan calcite cementation. The solution pores are caused by feldspar dissolution (Fig. 4g–h).

Mineralogy by X-ray diffraction analysis

The XRD analysis of the Lower Goru sandstone reveals that the most abundant mineral is quartz ranging from 50 to 55% (Table 2). The feldspar is the second-highest mineral found in the sandstone composition ranging from 11 to 20%, while the highest clay mineral is chlorite with a composition ranging from 10 to 30%. Chlorite and mixed concentrations of illite and smectite are identified as common clay minerals. Carbonate minerals like calcite, dolomite, are also present diffractogram are given in (Fig. 6).

Diagenesis of the Lower Goru sandstones

The Lower Goru sandstone has experienced complex diagenesis, which has severely influenced the mineralogy and reservoir characters. Cementation, compaction, and pressure solution are considered as the principal diagenetic events (Table 3).

Cementation

Cementation is a significant process of formation of consolidated rock from loose sediments and causes a reduction in

Table 2 Whole rock mineralogy determined by XRD

Sample ID	Quartz %	K-Feldspar %	Plagioclase %	Chlorite %	Dolomite %	Anhydride %	Pyrite %	Mixed layers I/S %	Calcite %
KD-1	50	10	3	30	0.5	1	0.5	4	1
Kd-2	54	16	4	14	2	2	1	3	4
KD-3	54	12	9	16	1	2	1	3	2
KD-4	50	15	8	17	1	2	1	4	2
KD-5	53	11	10	18	1	1	2	3	1
KD-6	50	10	7	23	2	1	2	2	3
KD-7	51	12	9	20	1	2	1	2	2
KD-8	54	11	4	23	1	1	2	2	2
KD-9	50	10	8	21	2	1	1	3	4
KD-10	53	8	7	22	1	2	1	4	2

Fig. 6 X-ray diffractograms of the investigated showing the presence of the Chlorite, illite and Koalinite

Table 3 Helium porosity and permeability of the core samples from KD-01 Well

Sample ID	Depth (m)	Helium porosity (%)	Permeability horizontal (mD)	Permeability vertical (mD)	Grain density (g/cm ³)
1	3141	20.3	0.23	0.15	2.66
2	3142	18.2	0.22	0.12	2.71
3	3145	15.8	0.33	0.11	2.7
4	3146	17.1	0.24	0.16	2.65
5	3147	16.8	1.09	0.01	2.71
6	3150	4.2	0.59	0.04	2.72
7	3152	11.3	0.21	0.03	2.7
8	3155	13.9	0.06	0.03	2.7
9	3156	12.4	0.02	0.01	2.71
10	3157	8.5	0.03	0.04	2.73
11	3160	9.8	0.03	0.04	2.72
12	3165	10.6	0.04	0.21	2.71
13	3167	7.2	0.11	0.02	2.72
14	3170	10.11	0.22	0.10	2.73
15	3175	11	0.04	0.12	2.72

porosity. Quartz, ferroan calcite, pyrite, and clay minerals cementation are the four major types of cement in the lower Goru sandstone as identified by SEM, thin section studies, and XRD analysis.

Quartz cementation

In the Lower Goru sandstone, quartz cement acts a quartz overgrowth and pore filling (Fig. 7a–b). The investigated samples show quartz overgrowth on the grains of detrital

quartz. SEM analysis of the investigated sandstone shows that authigenic quartz formed in the pore spaces by replacing the clay matrix (Fig. 4e–f, 9c–e). The distribution of authigenic quartz in the studied sandstone is chiefly controlled by chlorite cementation. The source of quartz cement in the sandstone has been questioned for a long time concerning internal silica source or external source (Gier et al. 2008; Islam 2009; Xi et al. 2015). The solubility of SiO₂ is low in the closed system with controls of water and significant incongruity in permeability

Fig. 7 **a** Well KD-01, 3160 m, red arrows shows quartz overgrowth **b** Well KD-01, 3162 m, General overview intergranular porosity **c** Well KD-01, 3165 m, Ferroan calcite (FC) occluding intergranular porosity, intergranular micro porosity (IGMP) within chlorite cement **d** intergranular pore lined with chlorite, authigenic quartz (QA), feldspar dissolution (QA), chlorite cement (Ch). **e** Well KD-01, 3166 m, intergranular pore partially blocked by grain rimming chlorite, authigenic quartz (Ch), dissolution feldspar (FD), intergranular porosity (IGP) **f** Well KD-01, 3168 m, chlorite cement occluding intergranular pore and blocking pore throats, intergranular porosity (IGP), chlorite cement (Ch)

and porosity, the advective flow, diffusion, or thermal convection could elucidate long distance and enormous transmission of external SiO_2 into sandstones (Bjørlykke et al. 1988; Bjørlykke 2011; Bjørlykke and Jahren 2012). Hence, the possible internal origin of silica in the sandstone is feldspar dissolution, clay mineral diagenesis, and volcanic rock fragments (Bjørlykke and Egeberg 1993; Hyodo et al. 2014; Sajid et al. 2020).

Calcite cement

Calcite is another type of cement recognized in the Lower Goru sandstone (Fig. 7c) which mainly occurs as pore filling or replacement mineral of detrital grains or clay matrix. It occurs as a minor poikilotopic cement that may infill intergranular porosity. In few samples, it replaces

Fig. 8 SEM images of the **a** Well KD-01, 3170 m, pore throat are seriously affected by chlorite lining, chlorite cement and a layer of illite/smectite **b** Well KD-01, 3172 m, grain rimming chlorite cement, authigenic quartz and sheet like mixed layer illite/illite–smectite which postdate the chlorite, authigenic quartz (QA) **c** Well KD-01, 3175 m, compaction texture possibly deformed mica **d** Well KD-01, 3176 m, intergranular pore lined by chlorite cement which rigorously restricts pore throat diameter, intergranular porosity (IGP), chlorite cement (Ch), authigenic quartz (QA)

detrital grains. In few samples, the calcite shows evidence of partial dissolution.

Clay minerals cementation

Chlorite cementation

This is the most significant authigenic phase preceding both quartz overgrowth and feldspar dissolution. SEM analysis shows that the chlorite has euhedral shapes and is organized in a rose pattern (Fig. 7d–f). The dissemination of authigenic quartz is generally controlled by the range of chlorite cementation. Persistent chlorite cementation confines existing space for quartz precipitation. This cement could partly or entirely block the intergranular porosity and generally confines the diameter of pore throats (Fig. 7d–e). Chlorite occurs as grain rimming cement and is considered responsible for preserving the porosity in various deep reservoirs sandstones seemingly by inhibiting quartz overgrowth cementation and pressure dissolution (Pittman and Larese 1991; Berger et al. 2009; Chen et al. 2011; Bahlis and De Ros 2013).

Illite and smectite cementation

A minor amount of sheet-like structures was observed by SEM analysis most probably sheet-like mixed layers of illite and illite–smectite (Fig. 8a–b). Mixed-layer illite–smectite

occurs a pore-filling cement or pore-lining grain coating cement was observed in SEM images in the analyzed samples. Mixed-layer illite–smectite is formed by the compaction of mud intraclasts or transformation of detrital smectite convert to mixed-layer illite–smectite with increasing burial depth.

Compaction

Mechanical compaction of the Lower Goru reservoir sandstone has been initiated after deposition. In this stage deformation of less competent mineral occur. Compaction resulted in deformation of micas, organic fragments, and mud clasts (Fig. 7c). Chemical compaction or pressure dissolution was identified between the framework grains by the presence of curved to convex contacts among the framework grains. The thin section studies reveal that the early stage chlorite cementation disallowed significant compaction of the sediments.

Dissolution

Generation of secondary pores and development of porosity occurred because of the dissolution of less competent grains generates the secondary pores and increases the porosity of a reservoir sandstone (Yu et al. 2019). SEM analysis of the Lower Goru sandstones reveals a huge amount of less competent mineral altered because of dissolution. Dissolution in the feldspar grains caused intergranular porosity in the sandstone. The secondary pores suggest that the carbonate cement and feldspar dissolution generated the secondary porosity (Fig. 7c–d). Various feldspar grains display strong

diagenetic alterations and dissolution and replacement by calcite or kaolinite.

Mineral replacement

The mineral replacement process includes the dissolution of one mineral and instantaneous precipitation of a different mineral (Baiyegunhi et al. 2017). The potassium feldspar is most affected, and the plagioclase is less affected in the lower Goru sandstone. The replacement of feldspar by albite or calcite caused the formation of new pores in the sandstone (Fig. 7c). SEM observations reveal that K-feldspar grains are also generally transformed to sericite and kaolinite. Albite precipitation occurred favorably in the microfractures, grains contact margins, and cleavages of the sandstone.

Diagenetic sequences

Based on the identified textures and structures of diagenesis in the rock are grouped into early diagenesis, burial diagenesis, and late diagenesis. The diagenetic regime defined by (Worden and Burley 2003) was used in this study to classify the diagenetic events. Based on the identified textures and structures the Lower Goru sandstone reservoir diagenesis in the rock are grouped into three categories (Fig. 9). Original mineralogy, geochemistry of pore water, and existence of other hydrocarbon-related fluids are affected in early diagenesis. In the Lower Goru sandstone, the early diagenesis processes include chlorite cementation, illite–smectite/smectite cementation, grain leaching, quartz cementation (Dar et al. 2021). The precipitation of pyrite occurs in the late phase of diagenesis glauconite alteration occurs due to reducing

Fig. 9 The paragenetic sequence of reservoir sandstone of the Lower Goru Formation

Fig. 10 Burial and thermal history diagram of the Lower Indus Basin

conditions just after burial. The burial history diagram along with geothermal gradient is given in (Fig. 10).

Early diagenesis

Early diagenesis is the process that occurs when the sediments are near to the surface and in close contact with oxygenated surface-supplied water. The mineralogical composition, grain fabrics, geochemistry of the pore water enclosed in the pores, and temperature history are the key elements that influence early diagenesis (Worden and Morad 2003). The process involves in the early diagenesis includes chlorite cementation, pyrite precipitation, illite-smectite/smectite cementation, grain leaching, quartz cementation. The iron-rich chlorite was probably precipitated as a pore-blocking intergranular cement. The mixed-layer sheet like layers of illite/illite-smectite followed by chlorite cementation. Quartz overgrowth overlies and postdates the chlorite cement. The dissolved silica was most probably derived from feldspar dissolution and disintegration of detrital ferromagnesian minerals. These diagenesis processes destroy the primary and depositional porosity of the reservoir. The chlorite cementation and compaction remain in the early and late stage of diagenesis.

Burial diagenesis

Burial diagenesis contains physical, chemical, and biological processes that act on the sediments during deposition and continue until the beginning of metamorphism or an uplifting event take place and exposure to meteoric water

(Schmidt and Macdonald 1979; Baiyegunhi et al. 2017). Burial diagenesis is responsible for all the modifications resulting in the sandstone (Baiyegunhi et al. 2017). With the increasing overburden associated with the mechanical compaction burial diagenesis starts. Burial diagenesis all the modifications occurred to the sandstone after consolidation and before metamorphism (Worden and Morad 2003). An increase in temperature and pressure occurs because of the increasing overburden, this event causes partial dissolution of the less competent minerals and results in the recrystallization of some minerals. From the Petrographic study dissolution of feldspar is also identified in the Lower Goru sandstone. The minerals precipitated by feldspar dissolution are usually grain having clay coating such as smectite and illite, pore filling clays such as kaolinite and chlorite and minor calcite cement (Schmidt and Macdonald 1979). The chemical compaction and pressure dissolution of carbonate cement start during burial diagenesis.

Late diagenesis

The main elements that affect late diagenesis are pressure, increased temperature, and variations in the composition of pore water (Boggs 2009). The above factors cause physical, mineralogical, and chemical changes to develop the equilibrium of sediments with diagenetic environments. The processes include in late diagenesis of the Lower Goru reservoir sandstone were sediment compaction, calcite cementation, and pyrite precipitation (Fig. 9). The petrographic investigation reveals that ferroan calcite was precipitated inside the intergranular pores and substituting the detrital grains.

Partial dissolution of ferroan calcite cement consequently occurred (Fig. 7c). During the late diagenesis, soft grains like mud clast and organic fragments were compressed and micas were distorted. Clay minerals authigenesis causes the transformation of clay minerals like smectite alteration to illite while chlorite recrystallized into illite (Fig. 8a–b).

Diagenetic controls on reservoir quality

Reservoir quality, discussed in this study is porosity and permeability which is a function of depositional control on grain size, provenance and diagenetic controls of compaction and burial, cementation of authigenic clay minerals, and dissolution (Islam 2009; Xi et al. 2015).

The grains packing of investigated sandstone samples shows mechanical compaction as well as chemical compaction. Based on petrological studies and helium porosities measurements the sandstone has a good porosity value. The relationship between burial compaction and ductile grain can be investigated by (IGV) intergranular volume. The IGV indicates the maximum porosity of sandstone that can be predicted ($IGV = \text{intergranular porosity} + \text{pore-filling cement}$) (Chiang and Ding 2013). The compaction of the sandstone was measured by intergranular volume IGV which is a good index of the compaction of the reservoir sandstone. The IGV

value ranges from 27 to 39% (Table 1) an IGV value of more than 26% in a well-sorted sandstone shows porosity reduction by compaction (Paxton et al. 2002).

The binary plot of the intergranular volume values (IGV) versus the volume of the pores (Houseknecht drawings) shows that the porosity destruction in the Lower Goru sandstone reservoir is dominated by compaction than cementation (Fig. 11). A plot of IGV versus cement volume directs that mechanical compaction has played a more significant role than cementation in reducing the primary porosity of the Lower Goru sandstone reservoir. Cementation has also played a role in decreasing porosity and permeability of the Lower Goru sandstone reservoir, however, the mechanical compaction is volumetrically the more significant.

The most abundant authigenic cement types occluding the pores are quartz, ferroan calcite, and clay minerals. At the same time, this sandstone retains excellent porosity because it has survived during the compaction processes. However, they do not have a good permeability value. Most of the primary porosity of the Lower Goru sandstone was destroyed by the authigenic clay minerals cementation or occasionally by the replacement of feldspar (Fig. 7c, e). During diagenesis, intergranular porosity is reduced by cementation and slightly enhanced by the dissolution of minerals, and pores produced by dissolution are filled by cement where porosity is generated (Fig. 7c–d). Also, the porosity of the Lower Goru sandstone has been reduced by early chlorite

Fig. 11 Intergranular volume IGV plot against volume of cement in the Lower Goru sandstone reservoir (modified from Houseknecht 1988)

cementation as observed in SEM analysis. According to XRD analysis chlorite is the dominant clay mineral in the Lower Goru sandstone. Chlorite coating is one of the most important diagenetic features of the Lower Goru sandstone. Sandstone with chlorite cementation normally has high porosity and permeability (Baig 2016). Evidence from the Lower Goru sandstone suggests that pore-lining chlorite can grow by direct precipitation from pore water without precursor clay rims (Berger 2009).

Similarly, pores are filled by quartz overgrowth, causing reduction in porosity, and pore throats are affected by overgrowth edges which cause the reduction in the permeability (Fig. 8a–b).

The feldspar and other unstable grains dissolution played a fundamental role in the formation and development of secondary porosity in the sandstone (Fig. 7ab). With an increase in burial depth, pressure and temperature, and water chemistry porosity and permeability were decreased by precipitation of authigenic minerals (Fig. 8b).

Even though carbonate cement is observed in a minor amount in the Lower Goru sandstone reservoir and has a strong control on reservoir quality, carbonate cement causes a reduction of porosity and permeability of the sandstone reservoir. The depositional environment is one of the major elements governing the reservoir quality of a sandstone grain size, texture, matrix, framework grains, and mineralogical composition are directly related to the environment of deposition of the reservoir sandstone (Bjørlykke 2014). The Lower Goru sandstone has undergone strong compaction, cementation, therefore, producing dissolution pores as well as intercrystalline microspores. Diagenetic evolution of sediments has undergone the processes of mechanical compaction cementation, dissolution, and rock pores have undergone dramatic primary intergranular pore reduction early cementation development of secondary pores in large amount cementation in late stage.

Conclusions

The petrographic analysis of the investigated samples shows that detrital grains of the Early Cretaceous Lower Goru Sandstone are dominated by quartz, feldspar, rock fragments, glauconite, and micas and sandstones are fine to medium grained and moderately to well sorted. The identified cement are quartz, ferroan calcite, dolomite and anhydrite, and clay minerals. Based on petrographic studies the sandstone is categorized as arkose and lithic arkose.

Petrographic and SEM analysis revealed that the pore structure is predominantly composed of primary intergranular macropores, secondary intergranular macropores, and intercrystalline micropores. The reservoir sandstone has a

maximum porosity of 20% and an average of 12%, while permeabilities 0.04–0.24 MD are very low.

The Lower Goru sandstone experienced considerable diagenetic variations like mechanical compaction, chlorite cementation, dissolution of feldspar, carbonate cementation, quartz cementation, and clay mineral alteration. The reservoir properties of the Lower Goru sandstone have been significantly affected by diagenesis. Diagenesis has influenced the porosity and permeability of the reservoir sandstone. Primary porosities including intergranular pores, intercrystalline pores, have been significantly reduced because of the strong mechanical compaction and authigenic cementation. Porosity is reduced mainly by chlorite, ferroan calcite, quartz, and clay matrix to a lesser extent. Chlorite cement was precipitated as grain rimming and pore occluding intergranular cement. The permeability of the sandstone reservoir has been reduced because of pore blocking of the chlorite and quartz cement.

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Author contributions QUZZD designed this research and collected the relevant literature. PR supervised this study and provide access to lab facilities. CB help in petrographic analysis. GS provides petrographic analysis and diagenesis analysis. RIA provides software support for this study. UA provided help in diagenetic sequence study. ZS provide help in XRD analysis and MM provide interpretation of data.

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Declarations

Conflict of interest None.

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