Carbonates and Evaporites (2020) 35:95
https://doi.org/10.1007/s13146-020-00622-4

ORIGINAL ARTICLE

Microfacies analysis, diagenetic overprints, geochemistry, and reservoir quality of the Jurassic Samanasuk Formation at the Kahi Section, Nizampur Basin, NW Himalayas, Pakistan

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Accepted: 10 August 2020 / Published online: 28 August 2020

Abstract

In Pakistan, carbonate rocks of Jurassic age are present entirely throughout the Indus Basin. The Jurassic carbonate rocks present in the Attock-Cherat requires a more detailed investigation as of recent discovery of gas in Jurassic carbonate rocks in the lower Indus basin. The evaluation of these Jurassic carbonate units in the Nizampur Basin of Attock-Cherat ranges should integrate the aspects of the depositional sediments, diagenetic history, and geochemistry to understand the reservoir behavior. In this study, the Samanasuk Formation of 90 m was sampled and measured in detail, and samples were collected with ~ 0.3 m interval and some samples were collected where reckoned necessary. Petrographic and microfacies analysis were conducted on about 100 samples; moreover, XRD analysis were performed. The present study aims to determine the depositional facies, diagenetic processes, and geochemical elements of this carbonate succession of the in an effort to explore their effect on reservoir quality. The Samanasuk Formation comprises eight microfacies assigning three facies belts including peritidal, lagoon, and shoal of a carbonate ramp. The recorded diagenetic processes include dolomitization, compaction, micritization, neomorphism, dissolution, and cementation in which dolomitization played an important role in enhancing the reservoir quality. In relation of their impacts on reservoir properties, the grainstone facies associated with peritidal facies and dolomudstone facie associated with carbonate sand and shoal shows the greatest reservoir quality, whereas lagoonal facies has the lowest reservoir quality. This study represents an approach to use the depositional facies, diagenetic alterations, and geochemical framework of carbonate succession in the reservoir characterization.

Keywords Microfacies · Dolomudstone · Dolomitization · Lagoon

Introduction

Large portion of hydrocarbon fields are present in carbonate rocks. These carbonate reservoirs contain more than 60% of the global oil and 40% of its gas storage. The correct understanding of the distribution of the reservoir quality is of paramount importance both during production and to foresee the reservoir characteristics during exploration phase. In this respect, the study of analogue outcrop is important. The integrated petrographic, microfacies and geochemical aspects of the carbonate rocks help in the reconstruction of the reservoir characteristics. Petroleum play is the perception of the model of how source rock beds, reservoir rock, regional top seals, and traps combine to produce petroleum accumulation at specific stratigraphic horizons. Correct interpretation of boundaries, overall geometry, and sedimentary facies of the depositional sequence involved in the play is the first crucial

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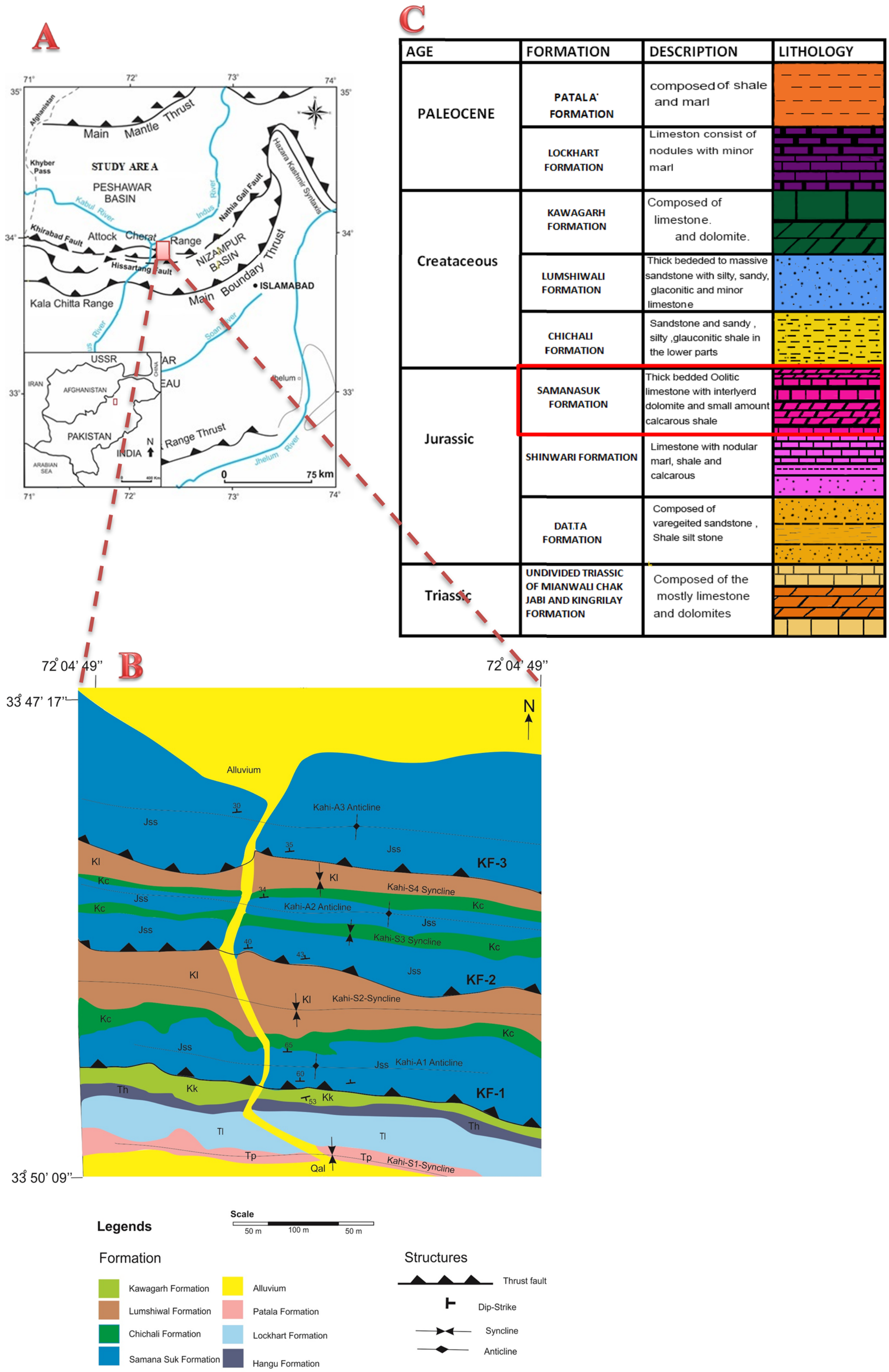
A
Main Mantle Thrust
STUDY AREA
PESHAWAR BASIN
Kabul River
Indus River
Nathia Gali Fault
Hazara Kashmir Syntaxis
Khyber Pass
Khirabad Fault
Attock Cherat Range
Hissartang Fault
NIZAMPUR BASIN
Main Boundary Thrust
ISLAMABAD
Kala Chitta Range
Soan River
Jhelum
Range Thrust
Jhelum River
USSR
IRAN
AFGHANISTAN
PAKISTAN
INDIA
ARABIAN SEA
75 km
C
AGE
FORMATION
DESCRIPTION
LITHOLOGY
PALEOCENE
PATALA FORMATION
composed of shale and marl
LOCKHART FORMATION
Limeston consist of nodules with minor marl
Createaceous
KAWAGARH FORMATION
Composed of limestone. and dolomite.
LUMSHIWALI FORMATION
Thick bededed to massive sandstone with silty, sandy, glaconitic and minor limestone
CHICHALI FORMATION
Sandstone and sandy, silty ,glauconitic shale in the lower parts
Jurassic
SAMANASUK FORMATION
Thick bedded Oolitic limestone with interlyerd dolomite and small amount calcarous shale
SHINWARI FORMATION
Limestone with nodular marl, shale and calcarous
DATTA FORMATION
Composed of varegeited sandstone , Shale silt stone
Triassic
UNDIVIDED TRIASSIC OF MIANWALI CHAK JABI AND KINGRILAY FORMATION
Composed of the mostly limestone and dolomites
B
72° 04' 49"
72° 04' 49"
33° 47' 17"
33° 50' 09"
N
Alluvium
Kahi-A3 Anticline
Jss
Kl
Kc
KF-3
Kahi-S4 Syncline
Kahi-A2 Anticline
Kahi-S3 Syncline
KF-2
Kahi-S2-Syncline
Kahi-A1 Anticline
KF-1
Th
Kk
Tl
Tp
Qal
Kahi-S1-Syncline
Legends
Scale
50 m
100 m
50 m
Formation
Kawagarh Formation
Lumshiwal Formation
Chichali Formation
Samana Suk Formation
Alluvium
Patala Formation
Lockhart Formation
Hangu Formation
Structures
Thrust fault
Dip-Strike
Syncline
Anticline

◂**Fig. 1** **a** Tectonic map with location of the study area lying in Attock-Cherat Ranges bounded by Peshawar Basin to the north and Main boundary Thrust to the south. **b** Inset view of the geological map (Awais et al. 2012) of Kahi Gorge in Nizampur basin. **c** Stratigraphic column of the study area

step in the assessment of hydrocarbon prospect (Moses et al. 1992). In Pakistan, Jurassic age carbonate rocks are present entirely throughout the Indus Basin and have been vastly studied. Similar Jurassic carbonate rocks are present in the Attock-Cherat Range of Nizampur basin and have not yet been studied in appropriate detail. With the recent discovery of gas in Jurassic carbonate rocks in the lower Indus basin, a detailed investigation of Jurassic carbonate system in the Attock-Cherat Range is imperative. Therefore, this study aims to identify depositional facies, diagenetic behavior, and geochemistry of carbonate succession of Middle Jurassic Samanasuk Formation and study their impact on the reservoir's quality. A detailed petrographic analysis was performed on the carbonate rocks of the Samanasuk Formation.

Regional geology

The study area is located in the northern margin of the River Indus and southern edge of the Attock-Cherat Range. It is located between longitudes 72°04′49″E–72°07′25″ and latitudes 33°47′17′N–33°50′09′N (Fig. 1b). The study area is tectonically (Fig. 1a) surrounded by the region of active thrusting and folding in the foreland of the 2489 km long Himalayan highland in Pakistan, thus, displaying a complicated structural arrangement (Yeats and Hussain 1987). The Attock-Cherat Range is situated between Peshawar Basin on the north and Kala Chitta Range on the south (Burbank and Johnson 1982). The boundary between Attock-Cherat Range and Kala Chitta Range is marked by Hissartang Thrust in Nizampur basin, where it splits the southern slab of Attock-Cherat Range from Kala-Chitta Range (Yeats and Hussain 1987). Movement along the Hissartang thrust deformed the rocks of Attock-Cherat Range and Kala-Chitta Range (Ghauri et al. 1991). In Attock-Cherat Range, sediments of Pre-Cambrian to Paleocene are outcropping. Attock-Cherat Range has gone through extreme deformation and shortening producing different thrust faults and numerous large- and small-scale folds due to closeness to the Main boundary thrust (MBT). Regionally, the rocks exposed in the Attock Cherat Range and those exposed at the Kahi gorge are highly folded. The Kahi gorge lies in the Himalayan foothills of Nizampur valley in Khyber Pakhtunkhwa of NorthWest Pakistan. However, moving from south to north in the study area, the foremost major structure located in the southern part of the region is the Kahi-1 (KF-1) Thrust. Jurassic rocks are thrusted over Cretaceous Kawagarh Formation along this thrust. After Kahi-1 (KF-1) Thrust the next fault is Kahi-2 (KF-2) Thrust, due to which Lumshiwal Formation of Middle Cretaceous age is thrusted over Jurassic Samanasuk Formation. Moving towards north encounters Kahi-3 (KF-3) Thrust. Along this major thrust, Lumshiwal Formation of Middle Cretaceous age (Kl) is thrusted over Samanasuk Formation of Jurassic (Jss) (Awais et al. 2014). Figure 1c, a simplified stratigraphic column, illustrates the stratigraphy of Southern Nizampur Basin.

Field investigation

The Samanasuk Formation in Kahi section is 90 m (m) thick and is composed of greyish limestone interbedded with greyish brown dolomite, locally with sharp contact (Fig. 3). A detailed fieldwork was carried out to observe facies and investigate important field features as well as to collect samples for petrographic and geochemical analysis. The sampling was done for ~ 0.3 m interval and samples were taken when a specific diagenetic feature was observed. Figure 2 shows a detailed log of Samanasuk Formation in the Kahi section. Inset view of the log shows the outcrop view and photomicrographs at several intervals. Various bioclasts were also observed which are predominantly present in mudstone and packstone facies, discussed in detail in the next section. Ooidal and peloidal grainstone and packstone beds are commonly repeated and are thick compared to other facies beds. In the study area, the lowermost 25 m part of succession is mainly comprised of orange gray, medium to thick-bedded oolitic dolomite, dolomite, and dolomitic mudstone alterations of bioclastic mudstone, ooidal grainstone, and peloidal grainstone. Oolitic dolomite indicates non-mimic replacement of carbonate grains (Folk 1974). The middle part of the succession (24–65 m) mainly consists of bioclastic and dolomitic mudstone with cyclic interval of ooidal peloidal grainstone, peloidal packstone, and peloidal bioclastic grainstone. The uppermost 20 m part of succession consists of thick, cyclic interval of bioclastic mudstone, peloidal bioclastic grainstone, ooidal grainstone, and ooidal peloidal grainstone. In this part, grainstone is dominated over mudstone and packstone facies. The Samanasuk Formation in its lowermost part is composed of thick-bedded oolitic limestone (Fig. 3c) having a thickness of 6 m which is repeated after several intervals. Closely above lies interbedded micritic limestone. This sequence is in turn bounded by thick brownish dolomite having clear contact with the host limestone (Fig. 3d). Bedding parallel stylolites and calcite filled fractures are found within this rock unit (Fig. 4a, b). Thickness of this interval is 3 m. At several intervals, medium bedded bioclastic limestone that is parallel bedded and irregular in shape is present (Fig. 4c). Small vugs can also be seen in this bioclastic bed (Fig. 4d).

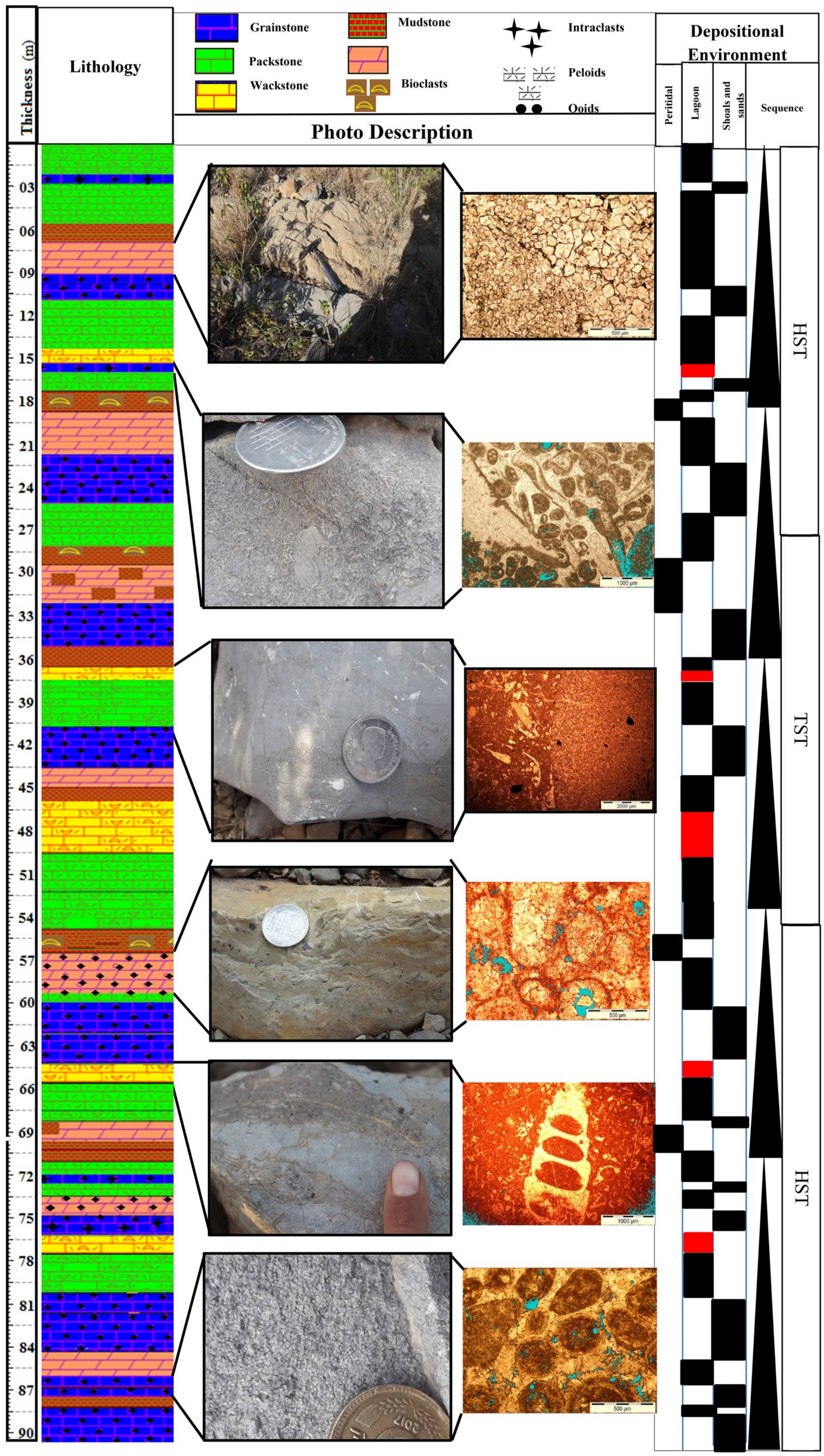

Fig. 2 Detailed log of Samanasuk Formation at Kahi gorge showing outcrop photographs and photomicrographs at several intervals with their depositional environment

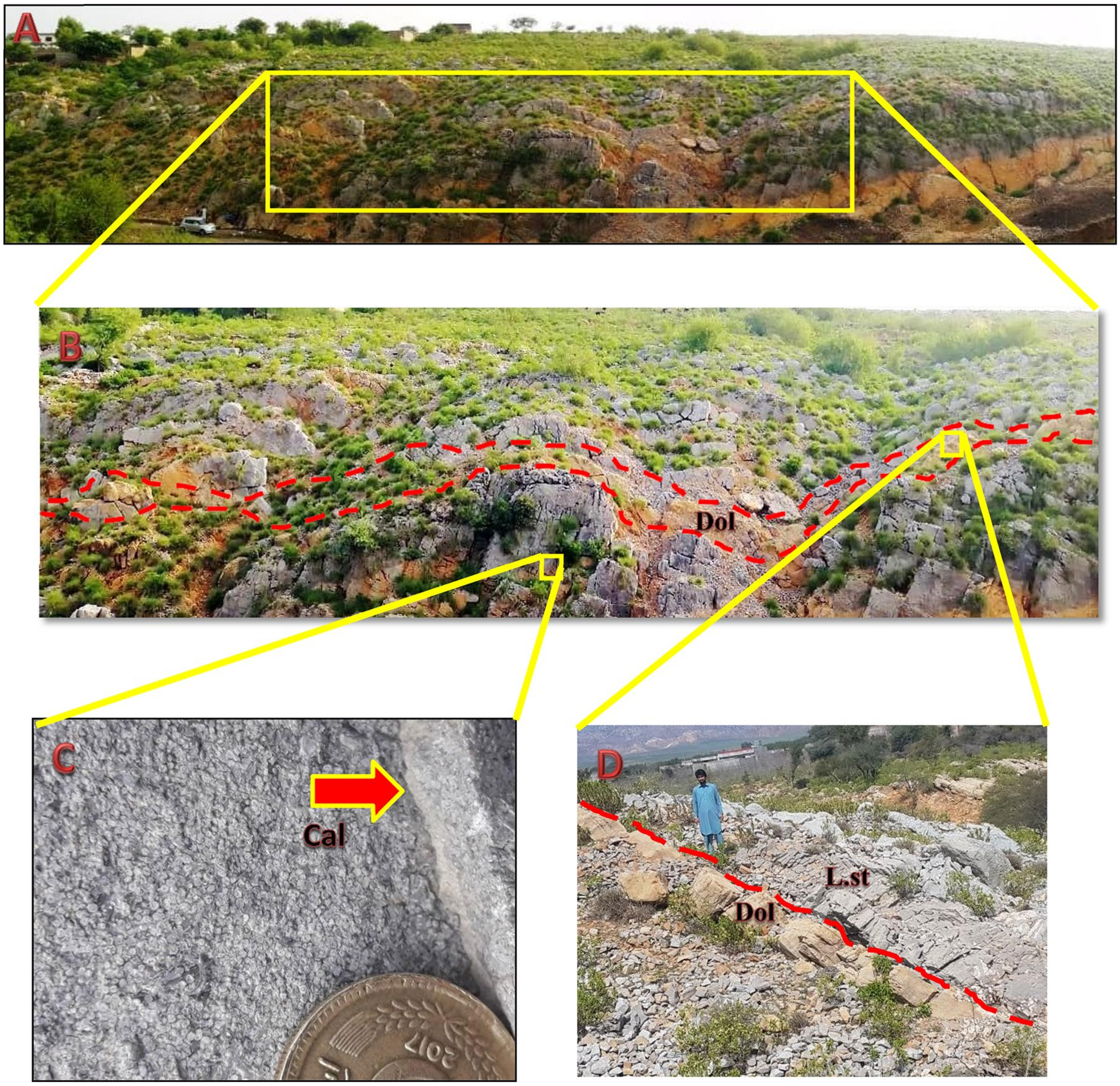

Fig. 3 **a** Panoramic view of the study area in Kahi gorge. **b** Close of view of the study area having brown bed of dolomite. **c** Close up view of the oolitic limestone of Samanasuk Formation, arrow indicates the calcite vein cutting the host limestone. These oolites are the diagnostic feature of Samanasuk Formation. **d** Contact between the brown dolomite and limestone

Methodology

Using standard techniques, the carbonate succession of 90 m was sampled and measured in detail in the Kahi section of the Nizampur basin in Attock-Cherat Range, and samples were collected with ~ 0.3 m interval; moreover, some samples were collected where reckoned necessary. One hundred and eight rock samples were cut and polished. Thirty three of the polished samples were stained using potassium fericyanide and Alizarin Red-S solution using Dickson (1965) method to differentiate between dolomite and calcite phases. Eighty seven thin sections were prepared for studying petrographic observations using conventional microscopy. The carbonate microfacies were categorized using Dunham (1962) classification. The dolomite texture was designated following the classification of Sibley and Gregg (1987), besides, the dolomite texture was also classified using the schemes of Friedman (1965), Shukla and Friedman (1983) and Mazzullo (1992). X-ray diffraction (XRD) was performed to identify the bulk mineralogy and percentage composition of the selected samples. X-ray diffraction analysis was executed using PANalytical X'PERT PRO X-ray diffractometer (Cu-Kα radiation ~45 kV, 40 mA). Diffraction of X-rays (Bragg's Law) was caused by the mineral phases when it reached a certain angle. The resultant chart from the diffractometer showed the X-ray diffraction array that had linear scale rectified at 2Θ degrees and the maximum intensity of the diffracted peaks was observed at the vertical

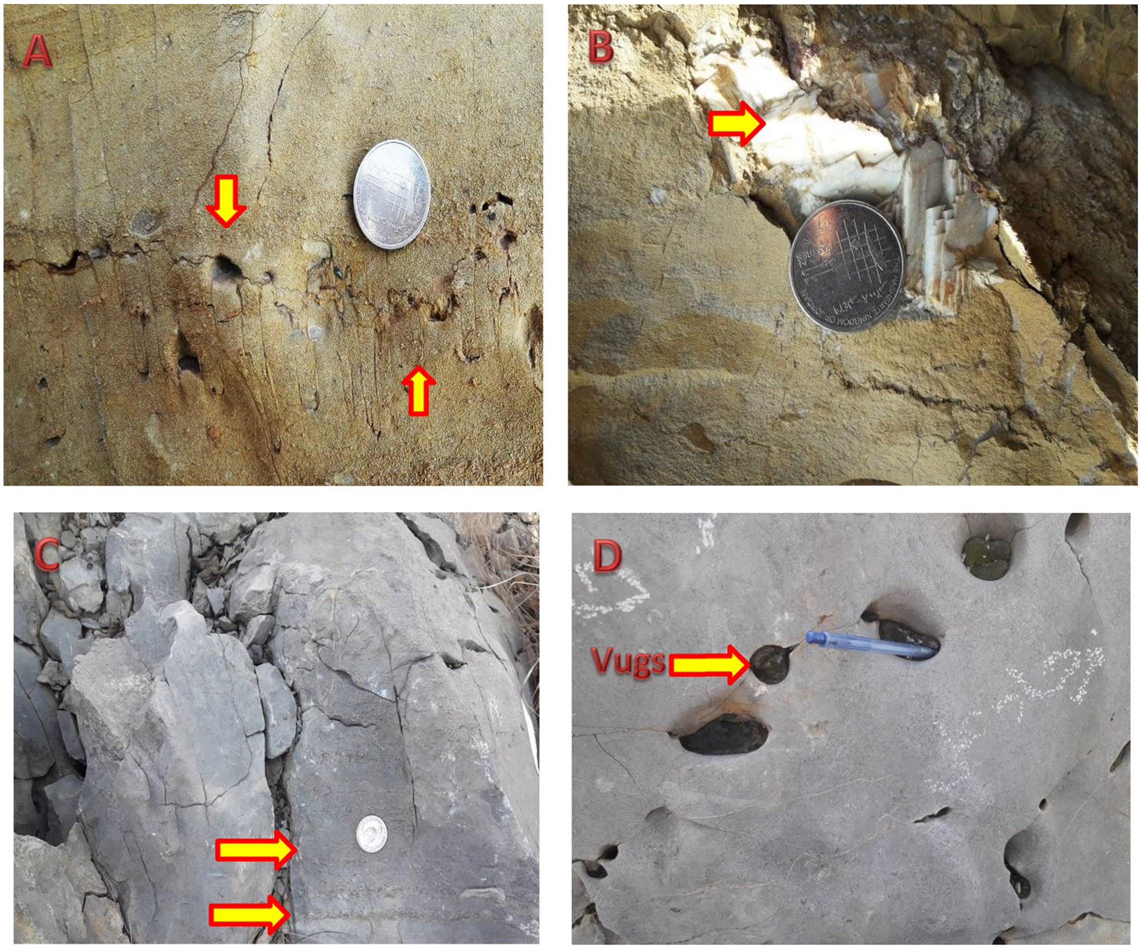

Fig. 4 **a** Brown dolomite bed having multiple stylolites as indicated by the arrow as well. These multiple stylolites also indicates multiple episodes of mechanical compaction that postdates the dolomite formation, small vugs can also be seen as shown by arrow. **b** Calcites patches formed in brown dolomite during late stage diagenetic event. **c** Bioclastic material formed parallel to the bedding indicated by an arrow. **d** Vugs formed in bioclastic limestone due to dissolution

axis. Minerals were identified by comparing the resulting peaks with the standard set of patterns assembled by Joint Committee on Powder Diffraction Standards (JCPDS). Reservoir properties were accomplished by grouping the visual percentages estimation from photomicrographs impregnated with blue epoxy resin and data was obtained from 2.4 cm diameter plugs to calculate permeability. Different types of porosity types were measured based on image investigation of 87 thin-sections with 400 point counts per thin-section. Information combined from the aforementioned quantification was assembled to determine depositional facies, diagenetic events, and evaluate the reservoir's quality.

Microfacies determination

Field analyses, grain configuration, texture, and structure studied in the thin sections resulted in the recognition of eight microfacies assembled in three facies associations which were related to three depositional environments including peritidal, restricted lagoon, and high-energy shoal present on the inner part of a homoclinal carbonate ramp. Facies analyses were performed using standard facies model for ramps by Flügel (2010). The illustration and physical appearance of the main individual sedimentary facies, as well as identified facies associations within the studied intervals, are presented in Table 1 and discussed in further sections.

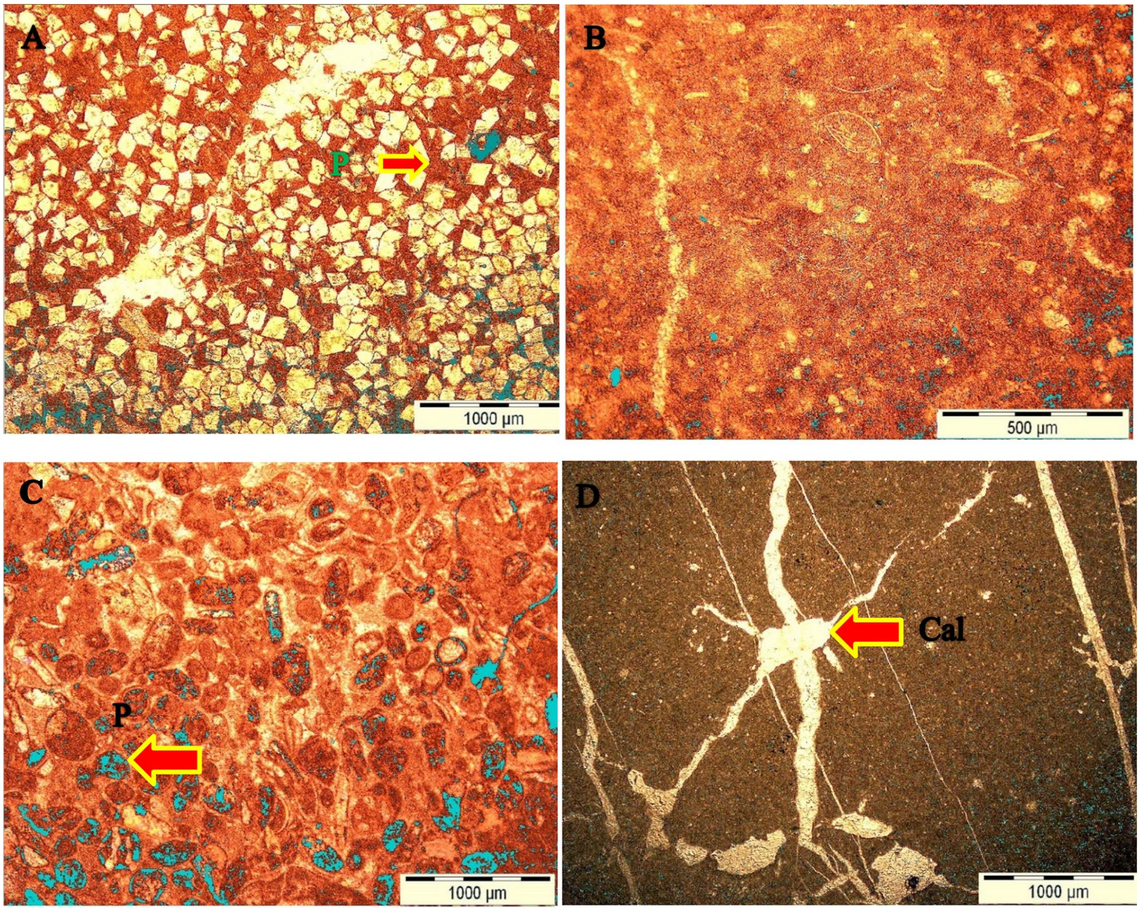

Fig. 5 Photomicrographs of Samanasuk Formation. **a** Dolomudstone facies with calcite veins. Intercystalline and vuggy porosity (P) can also be seen in this facies (**b**) Bioclastic mudstone facies, arrow indicates bioclasts (Bc), a calcite vein is present. **c** Peloidal packstone facies with moldic porosity. **d** Mudstone facies with multiple sets of calcite veins

Dolomudstone (SF-1)

These facies consist of euhedral dolomite crystals of medium to coarse size (80–100 µm). Some calcite veins can also be seen, these are the late-stage calcite veins cutting through the dolomite. Lime mud-dolomite boundary is quite sharp at places. Late-stage calcite veins cut through these dolomitic (Fig. 5a). These facies contains high intercrystalline porosity and small vugs.

Interpretation

The dolomudstone microfacies is devoid of skeletal remnants and has been inferred as a peritidal carbonate environment (Wanas 2008; Aghaei et al. 2013; Beigi et al. 2017; Adams and Diamond 2019).

Bioclastic mudstone (SF-2)

This facie contains bioclasts of bivalves and gastropods (locally micritized) ranging from 5–15% present in lime-mud. Some calcite veins crosscut the lime mud (Fig. 5b).

Interpretation

Presence of bioclasts and Intraclastic material present in mudstone indicates the deposition occurred in the peritidal zone (Flügel 2010; Ranjbaran et al. 2007).

Peloidal packstone facies (SF-3)

The peloidal packstone microfacies consist of Peloids and ooids as allochems. Peloids are a principal constituent of this microfacies and vary in proportion from 85–95%, ooids 15–20%, bioclasts 15–25%, and intraclasts 10–15%. Here the bioclasts and some of the intraclasts have been

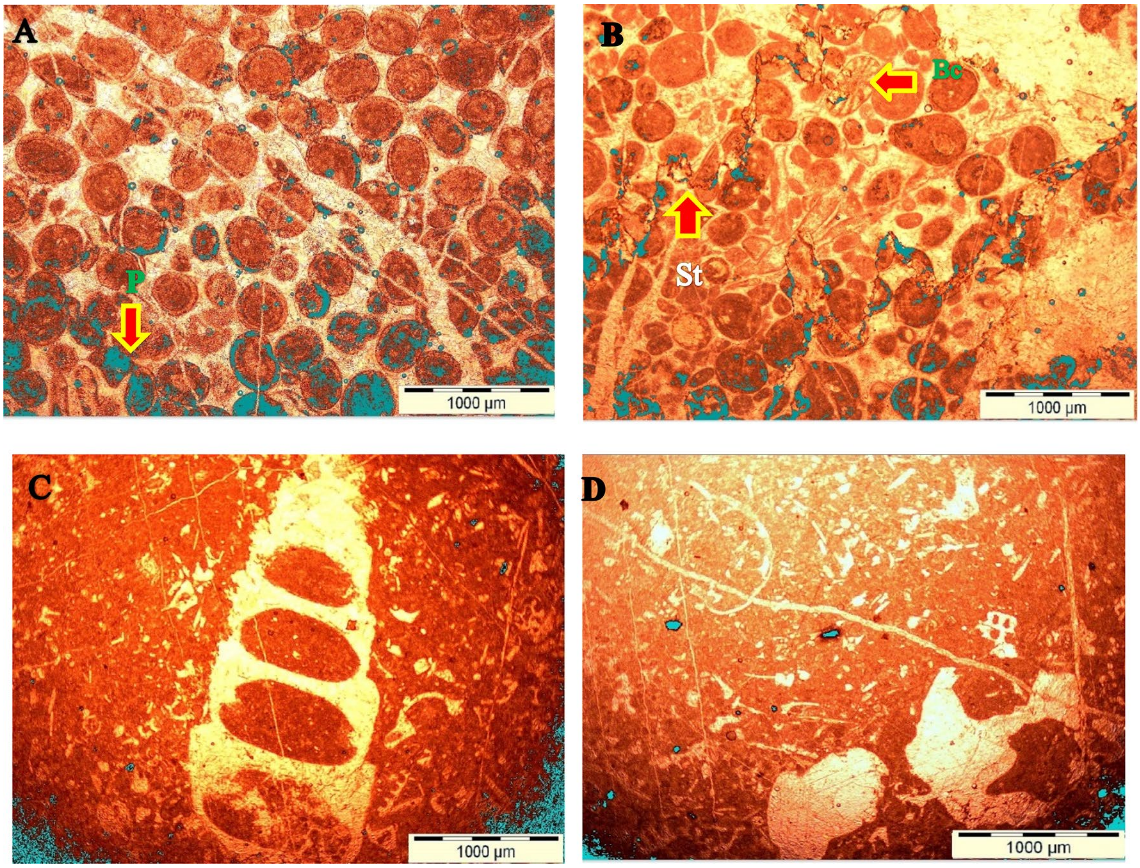

Fig. 6 Photomicrographs of Samanasuk Formation (**a**) Ooidal grainstone facie, the porosity (P) can be clearly seen formed due to dissolution. Some calcite veins also cross cut the ooids. **b** Ooidal bioclastic grainstone facie having stylolites (St) and bioclastic (Bc) material. **c** Bioclastic packstone facie, bioclast of gastropod can be seen having micrite envelops. **d** Bioclastic Wackestone facie

micritized. Peloids and micrite are present in a ratio between 40–60%. Calcite filled cement is present between some of the grains (Fig. 5c). Oomoldic porosity is common in this facie.

Interpretation

Richness of peloids with a low variety of skeletal grains and bioclast suggests restricted subtidal lagoonal water. Iron oxides staining around the pressure solution seams indicate slow sedimentation. These types of facies are identical to those defined by Wanas (2008) and Amel et al. (2015) for lagoon settings nearby the fringe of carbonate sand and shoals.

Mudstone (SF-4)

This microfacies is dominantly composed of very fine lime mud. Several calcite veins can be cross-cutting each other (Fig. 5d).

Interpretation

The presence of homogeneous and non-fossiliferous pure micrite indicates that the deposition occurred in a lagoonal environment (Wilson 1975; Flügel 2010; Hussein et al. 2017).

Ooidal grainstone facies (SF-5)

Ooids are the dominant constituent of this microfacies and vary in proportion from 75 to 85% and bioclasts 5–10%. The Ooids are micritized ranging from 40 to 150 μm and are cemented by sparite/microspar. The ooids are dissolved yet their micrite envelopes are still visible. Various calcite veins cut across the fabric of the sediments (Fig. 6a). The porosity type of this facies is oomoldic porosity.

Interpretation

Well sorted medium to coarse-grained ooids and occasional cross-bedding suggest that the oolitic grainstone are typically formed in an agitated marine environment above fair-weather wave base, as in shoal environment (Harris 1979; Burchette and Wright 1992; Flugel 2010; Insalaco et al. 2006; Beigi et al. 2017).

Ooidal bioclastic grainstone facies (SF-6)

These facies consists of grainstone with cemented intergranular space. The allochems are present as ooids 40–60%, bioclasts 20–30%, and intraclasts 10–15%. Stylolites and micro-fractures are abundant. Calcite veins of various sizes cross-cut the allochems and the intergranular cements (Fig. 6b). In this facie, the porosity is intergranular and oomoldic.

Interpretation

Ooidal bioclastic grainstone microfacies consist of ooids and skeletal fragments formed at shallow waters with moderate to high energy resulting in the reworking of bioclasts and the production of ooids. This grainstone is typical of high-energy, shoal environment (Reading 1996; Hashmie et al. 2016).

Bioclastic packstone (SF-7)

Allochems in these micro facies can be identified as bioclasts of bivalves and gastropods (50–60%), ooids (5–10%), peloids (10–15%), and intraclasts (5–10%). Calcite cementation filled intraskeletal pore spaces. The intraclasts and bioclasts show micritization. Calcite veins of various sizes cross-cut the allochems and the intergranular cements (Fig. 6c).

Interpretation

In low energy shallow lagoonal environment, the existence of some of the micritized skeletal fragments proposes a low rate of sedimentation (Sallam et al. 2015).

Bioclastic wackestone (SF-8)

In this microfacies, the bioclasts of various sizes are present. Biomolds are filled by calcite cement. A few patches of dolomite crystals are also present. Multiple calcite veins cross-cut the bioclasts as well as the host wackestone fabric. Major allochems are bioclasts of bivalves and gastropods ranging from 45–55%, micrite is present between 40–60%. The intraclasts and bioclast display intense micritization (Fig. 6d).

Interpretation

Occurrence of peloids, intraclasts, and bioclasts which includes remains of echinoids, pelecypods, gastropods, and remnants of green algae together with micrite envelops suggest that deposition occurred in medium energy, shallow subtidal settings in a lagoonal environment (Wilson 1975; Flügel, 2010). These facies are compared to the facie described by Wanas (2008) for open inner ramp environments nearby the margin of carbonate shoals (Amel et al. 2015; Sallam et al. 2015; Beigi et al. 2017).

Depositional environment

Based on the above facies distribution, the Jurassic Samanasuk Formation has been interpreted to be deposited in peritidal environment which refers to the supratidal and intertidal zone (Shinn and Robbin 1983), lagoonal environment, carbonate sand shoals on an inner ramp facies belt (Lasemi 1995; Kavoosi et al. 2009; Kavoosi 2016). Shoaling upward cycles with occasional lime mudstone at the base followed by bioclastic grainstone with rounded, worn, and coated bioclasts grainstone and some well-formed oolites and/or peloids grainstones are repeatedly present in the Samanasuk Formation as shown in Fig. 2. Field-based investigations and petrographic examinations observed that shelf facies are the pure carbonate depositions that are hardly affected by the terrigenous influx. Thus, indicating cyclicity is caused by sea-level changes or shoreline fluctuation and not by the variation in the clastic sedimentation (Kwon et al. 2006; Wilmsen et al. 2010). The sea-level rise and fall as depicted during the deposition of the Samanasuk Formation is considered to be the local transgressions and regressions of the shoreline. Thus, it cannot be equated with the global eustatic sea-level rise and fall. Vail et al. (1984) have cautioned for such curves to be correlated with the global eustatic curves and suggested that different local and regional subsidence and sediment supply rates can produce apparent transgressions or regressions that may not be synchronous with the global cycles. The distribution of sedimentary facies in vertical and lateral successions suggests that the depositional settings are revealing steady environmental variation beginning with peritidal flat then lagoonal and to carbonate shoal in inner ramp settings (Burchette and Wright 1992). The studied microfacies can be associated with three facies associations that are related to three depositional environments. First, peritidal flat facies association (SF1–SF2) categorized by the presence of bioclastic material in mudstone with no substantial facies change and occurrence of euhedral dolomites crystals, which are revealing an inner carbonate ramp arrangement developed in semi-arid to arid environmental conditions (Burchette and Wright 1992; Read 1985). Second lagoon facies (SF3, SF4, SF7, SF8) that consists of lagoonal

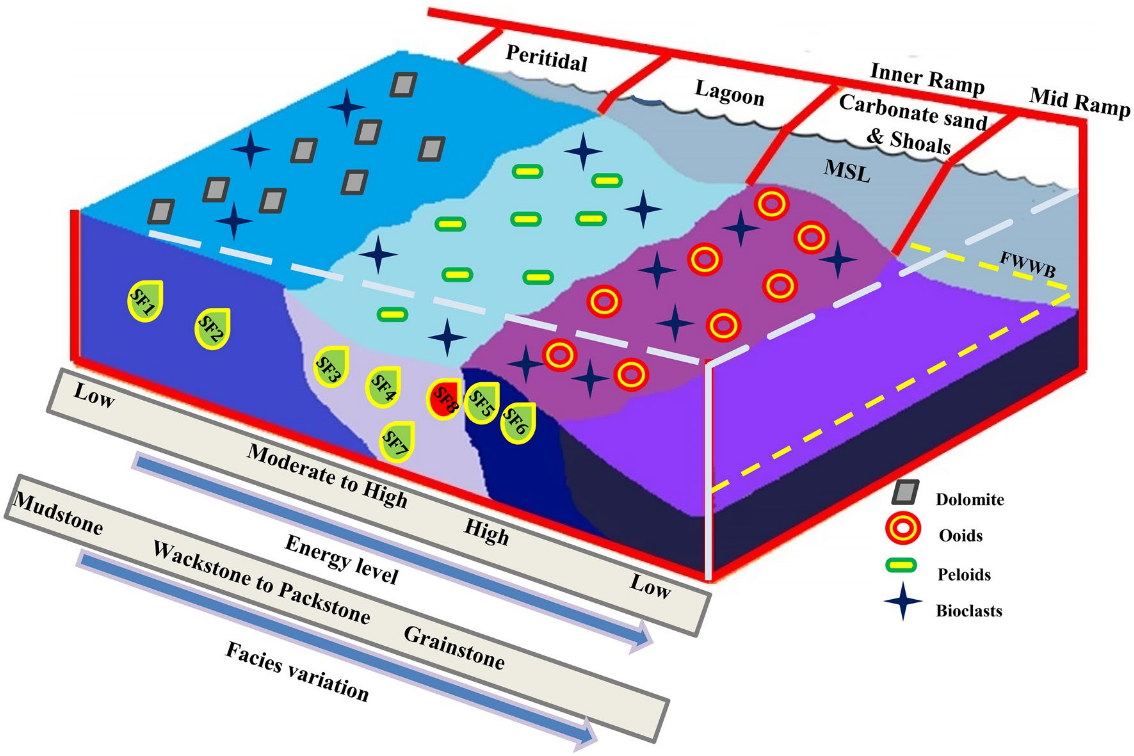

Fig. 7 Proposed depositional model for Jurassic Samanasuk Formation. *MSL* Mean sea level, *FWWB* Fair weather wave base

facies rich in Peloids and micritic matrix which suggests sedimentation had occurred in a restricted region behind shoals (Brachert 1992; Beigi et al. 2017). Third, high energy shoal setting dominated by grain-dominated facies (SF 5-SF 6) and lacks micrite envelops and presence of allochems such as ooids, peloids and intraclasts deposited in a high energy regime which are the features of the shoal facies settings in an inner ramp environment (Burchette and Wright 1992; Reolid et al. 2007), which shows high reservoir quality. A proposed depositional model is shown in Fig. 7.

Diagenesis

The Samanasuk Formation has evidenced several diagenetic features related to physical and chemical compaction, cementation, micritization, neomorphism, dissolution, and dolomitization. The diagenetic processes have enhanced the reservoir quality/characterization; however, some of the diagenetic changes deteriorated the value. The prime importance is given to the process of dolomitization as these alterations had greatly influenced the reservoir properties.

Compaction

The rocks of the Samanasuk Formation have gone through the process of physical and mechanical compaction. Mechanical compaction is evident from broken micrite envelops, deformed grains, and grain to grain sutured contact. Whereas, stylolite and pressure dissolutions seams can be seen as a product of chemical compaction (Fig. 8a, b).

Cementation

In Samanasuk Formation, calcite cement is the main cementing mineral that can also be found as an outcrop in the form of calcite patches and calcite veins. The cements had completely or partially filled the fractures and pore spaces. Different types of cements have been found including granular, equant, drusy, elongated blocky, isopachous fibrous, and syntaxial overgrowth calcite crystals in skeletal fragments and ooids (Fig. 8c–f). These types of cements are significant in filling the basic intergranular porosity. The granular blocky cement is mainly formed in shoal facies and comprises medium to coarse-grained calcite that generally fills intraparticle and fractures along with intergranular spaces present in the Samanasuk Formation. These types of cement suggest that the diagenetic alterations might have occurred in marine phreatic settings (Tucker and Wright 1990; Moore

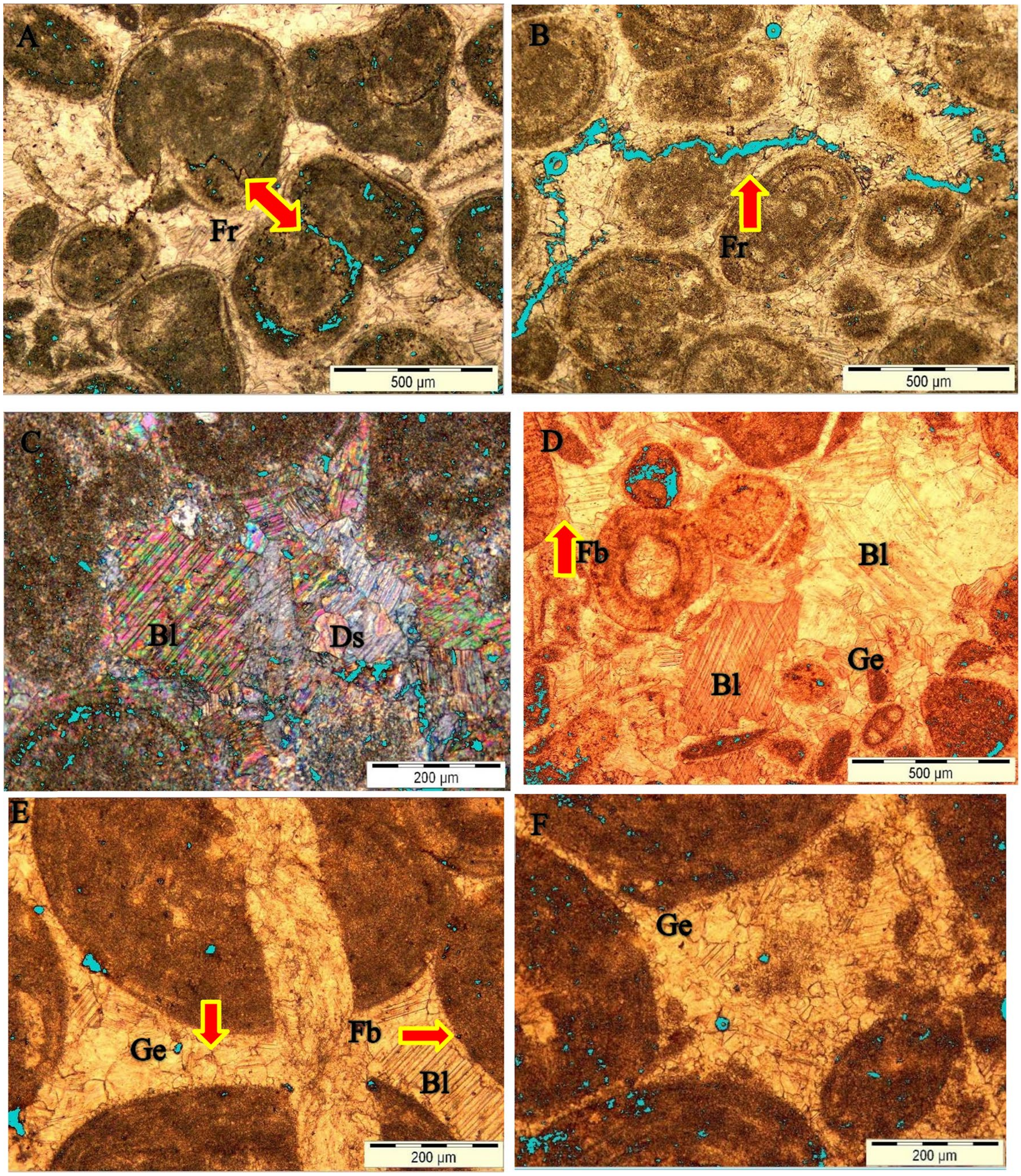

Fig. 8 Showing different diagenetic events in Jurassic Samanasuk Formation (**a**) Oolitic grainstone with microstylolite and microfractures (Fr) due to compaction. **b** Oolitic grainstone with microfractures and partial dissolution. **c** Oolitic grainstone cemented by blocky (Bl) and drusy (Ds) calcite. **d** Oolitic grainstone with intergranular porosity lined by fibrous cement (Fb), the large vugs are filled by blocky (Bl) calcite, locally equant calcite (Ge) cement. **e** Isopachous fibrous (Fb) cement formation around the ooid, also granular equant (Ge) and blocky cement (Bl) can be seen. **f** Granular equant (Ge)

2013). Crystalline mosaics of granular equant cement involve anhedral to subhedral crystals in intragranular and intergranular spaces. This type of cement is normally originated in grainstone facies with moldic porosity and is formed in shallow marine conditions, such circumstances indicate that cementation might have occurred in meteoric settings as well as burial environments (Choquette and James 1987).

Micritization

Micritization is one of the most common diagenetic features which are developed in almost all allochem frames as in ooids, peloids, and bioclasts up to various extent (Fig. 9a). It is a common process that usually occurs in shallow marine

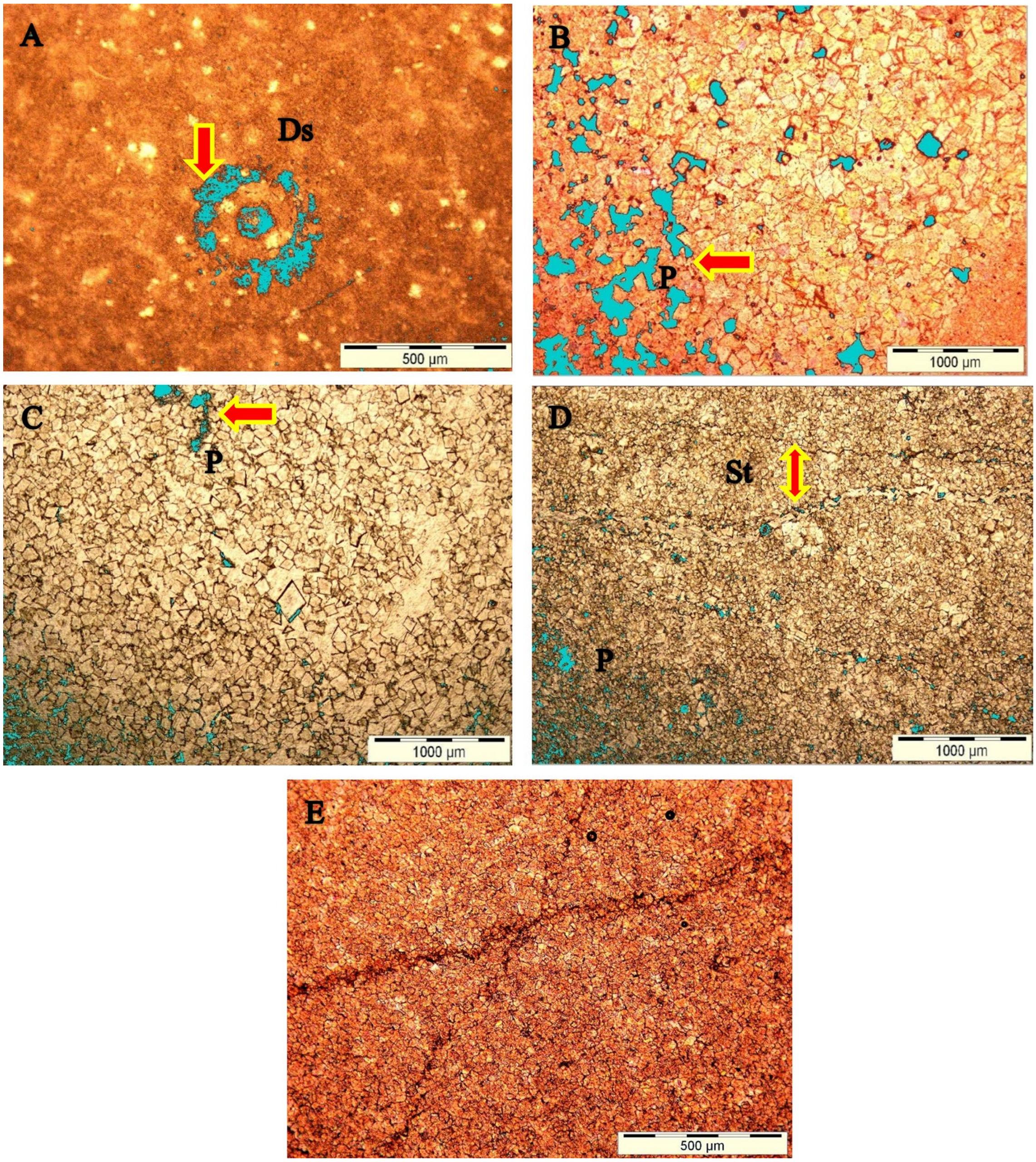

Fig. 9 Photomicrographs of Samanasuk Formation (**a**) micritization of oomoldic porosity (P). **b** Euhedral dolomite, where intercrystalline porosity (P) is clearly visible. **c** Euhedral dolomite rhombs (Dol-1) are clearly evident with porosity (P) (**d**) Planer –S dolomite (Dol-2) with stylolites (St). **e** Fine grained anhedral dolomite (Dol-3). Pyrite coating can be seen clearly around the stylolite (St) late stage fracturing can also be seen

environments and is caused by micro-organisms such as endolithic algae and fungi (Bathurst, 1975; Read, 1985). Facies where intensive micritization has occurred it has been suggested that deposition took place under slow sedimentation rates to allow microbial activity for a longer period under marine phreatic conditions (Harris 1979).

Neomorphism

The alteration of aragonite and high magnesium calcite grains to low magnesium calcite is an essential measure in carbonate diagenesis, since it modifies the reservoir characteristics of limestones and their geochemical compositions

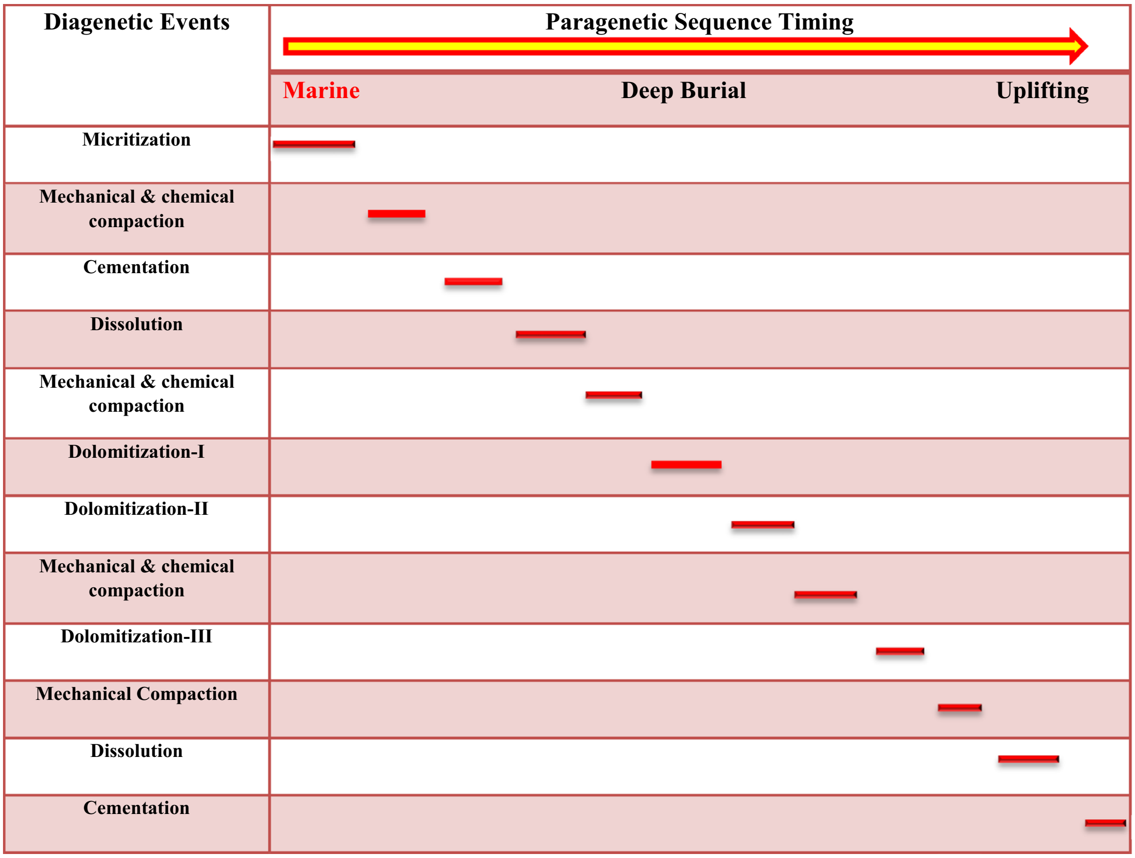

Fig. 10 Proposed paragenetic sequence of Samanasuk Formation

(Al Asam and Veizer 1982). Neomorphism is clearly visible in Samanasuk Formation in most of the grainstone facies. Sparite is formed by aggrading neomorphism (secondary recrystallization) after magnesium ions have been removed from micrite as shown in Fig. 8e, such process generally takes place in meteoric settings (Budd and Haitt 1993).

Dissolution

In this study, dissolution is evident in an indirect way in the form of calcitized bioclasts. Mainly, these calcitized bioclasts suggest that their original or primary mineralogy was prone to dissolution and resulted in reprecipitation of calcite within the cavity. The moldic porosity is well-established in ooids, peloids, and skeletal fragments (Fig. 9a). Vuggy porosity is very evident in dolostones but is hardly seen in dolomudstone. The vuggy porosity formed by the dissolution can be seen in dolomites as shown in Fig. 9B

Dolomitization

Diagenetically 3 types of dolomites were identified based on Sibley and Gregg (1987) dolomite textural classification which are (1) Coarse-grained planer e euhedral dolomite (Dol-I), (2) medium-grained planer s subhedral dolomite (Dol-II), and (3) fine-grained nonplaner anhedral dolomite (Dol-III). Dol-I consists of coarse dolomite rhombs forming about 90% of the rock and appeared to be well developed with distinct crystal boundaries. The dolomite crystals observed range in size from 40 to 100 μm (Fig. 9c). These early formed dolomite crystals replaced the matrix and grains of the precursor rock. The coarse crystalline dolomite formation in these dolomites suggests that calcite or dolomite replacement originated from shallow burial dolomitization episode which is interpreted as late diagenetic processes (Amthor et al. 1991). This type of dolomite has high vuggy porosity. Dol-II crystals size ranges from 40 to 80 μm. Small scale calcite veins and microstylolites crosscut the precursor dolomite (Fig. 9d) at decreasing depths and occur in contact with early formed dolomite-I. This type of dolomite has moderate porosity. The formation of this type of dolomite suggests shallow burial environment as the original texture is still preserved due to interminable dolomitization event (Friedman 1965). Dol-III is densely packed fine-grained dolomite crystal ranging in size from 20 to 40 µm. Multiple sets of small-scale pressure solution seams can be easily seen having Iron oxide coating (Fig. 9e). The anhedral form of dolomite crystals suggests that dolomite is formed at elevated temperature in deep burial conditions as compare to euhedral dolomite which is formed at temperature ranging from 50 to 100 °C (Shah et al. 2016). This type of dolomite has very low porosity.

Paragenetic sequence of Samanasuk Formation

Based on the above mentioned diagenetic analyses, a detailed paragenetic sequence has been established of Jurassic Samanasuk Formation (Fig. 10). The eogenetic events which altered the primary depositional structures include widespread and extensive micritization. This micritization indicates that there was sufficient time for the microbial organism for micritization, such events take place generally in marine phreatic environment (Flügel 2010). Besides the formation of the micrite envelopes, other marine diagenetic events include early mechanical and chemical compaction, cementation of sediments by isopachous fibrous, and dursy calcite cements. The early burial at shallow depths starts tamping sediments melodramatically (Shinn et al. 1977). Mechanical compaction due to overstrain pressure and tectonic stresses, induced micro and macro fractures. Chemical compaction due to these stresses produced stylolites in multiple horizons of the formation. The mechanical and chemical compaction occurred during shallow and deep burial. The formation of equant mosaic and blocky granular calcite cements filled the inter-granular as well as an intra-granular void suggesting second generation of cements during early diagenesis of the sediments. The fractional dissolution of carbonate grains and neomorphic remains of the bioclasts caused during the alteration from marine phreatic into meteoric phreatic settings. During meteoric phreatic conditions dissolution of allochemical constituents in carbonate sediments and bioclastic fragments has considerably altered the reservoir quality. The inflow of freshwater resulting in the dissolution of carbonate grains has been greatly affected. Dolomitization took place in multiple phases as evident by different texture of dolomite crystals in different facies as well as cross-cutting relationship of dolomite crystals with calcite filled veins or fractures. At late stage, deep burial fractures led Mg-rich fluids through the rock fabric which caused dolomitization generating intercrystalline porosity in dolomitize of these facies. The different types of dolomites have already been discussed. In the later stage multiple uplifting events as suggested by the tectonic setup of the area (Ghazanfar et al. 1990), caused multiple fracturing and cementation phases that overgrow the previous features. This telogenetic fracturing is evident by calcite filled fractures, especially near faulted contact of the rock unit with the underlying Formation.

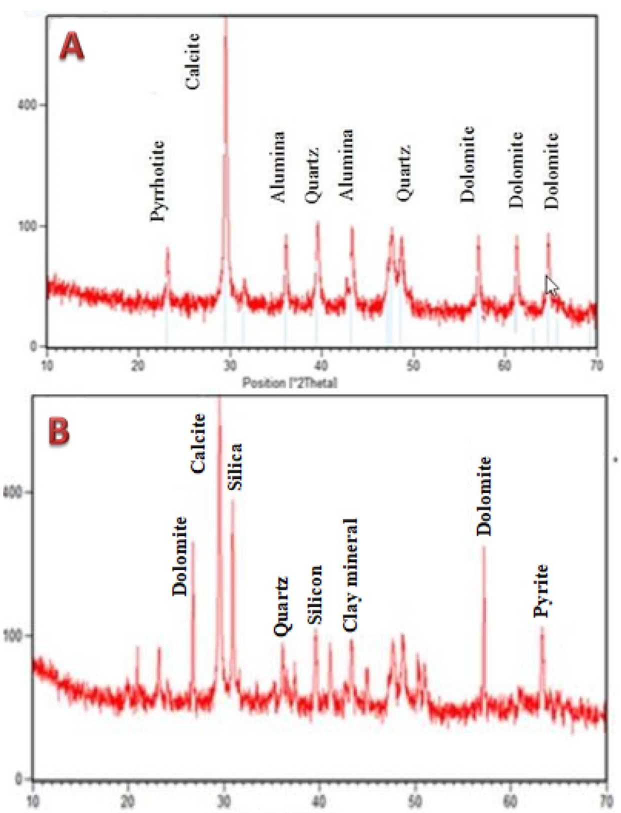

Fig. 11 **a**, **b** Diffraction peaks of the minerals present in major and minor content

Mineralogical investigations

Sharp diffraction peaks were obtained for different samples which were analyzed for the bulk mineralogy. Twenty samples representing calcite and dolomite phases discussed in the previous section were subjected to X-ray diffraction analyses to ratify the petrography of the studied rocks. Mineralogically, the Samanasuk Formation consists mainly of calcite. Along with calcite and dolomite, small diffraction peaks of silica, clay, pyrrhotite, pentlandite, and alumina were identified. Pyrrhotite is an iron oxide mineral that is present in stylolites. The diffraction pattern of the diffraction peaks can also be seen in Fig. 11a, b.

Table 1 Showing details of the porosity and permeability plug analysis of the microfacies its diagenetic alterations which affected its depositional porosity by forming different types of porosity, reservoir quality and reservoir characteristic

Microfacies	Diagenetic alteration	Porosity type	Reservoir quality	Porosity %	Liquid permeability (md)	Air permeability (md)
SF1	Cementation by blocky calcite, dissolution	Moldic & intergranular	Good	10.32	6.46	4.21
SF2	Micrite envelops, cementation by sparry calcite	Intergranular & vuggy	Fair	6.21	0.2	1.3
SF3	Micritization, dissolution, neomorphism by sparry calcite	Intergranular, moldic & vuggy	Moderate	9.37	8.54	7.26
SF4	Multiple sets of veins filled with sparry calcite	Intergranular	Poor	Sample too tight		
SF5	Dissolution, compaction, fibrous & blocky cement	Moldic & intergranular	Good	11.68	7.61	9.27
SF6	Physical & chemical compaction, stylolites, equant & blocky cements, multiple set of veins	Moldic porosity	Moderate	9.57	9.28	5.21
SF7	Micritization & neomorphism	Intergranular	Poor	Sample too tight		
SF8	Micritization, dissolution & neomorphism	Vuggy & intergranular	Poor	2.14	2.82	1.5

Impact of depositional facies on reservoir behavior

The Jurassic Samanasuk Formation is a shallow ramp margin carbonate environment having alternating cycles of mudstone-wackestone to packstone-grainstone facies association. Grain-supported fabric shows a clear drift of decrease in porosity and permeability with a rise in burial depth, while the mud-supported fabric does not display a clear trend of porosity and permeability alteration with depth (Budd 2001). To investigate the effect of depositional facies on reservoir properties, standard helium porosity, and Klinkenberg permeability measurements were performed on the plugs. In the studied carbonate successions, modifications in reservoir in the studied sections high energy shoal environment packstones and grainstones facies represent very good primary porosity which later had been clogged up severely by multiple phases of diagenetic modifications like calcite filled cementation, whereas lagoonal facies have poor to moderate porosity. Table 1 shows a detailed description of the overall studied facies along with the measurements of the plug analyses. It can be seen that the dolomudstone facies and ooidal grainstone facies have good reservoir characteristics as compare to the rest of the facies.

Impact of diagenesis on reservoir behavior

The occurrences of several diagenetic features have significantly affected the reservoir properties of the studied carbonates as seen in the photomicrographs. According to detailed field investigations and petrographic study of the diagenetic features, it is observed that early and late-stage cementation played the most destructive part regarding porosity and permeability reduction. Mechanical compaction in early stages might have reduced inter-granular porosity but late-stage mechanical stresses induced multiple fractures, enhancing average porosity, and permeability of the rock. However, in the studied section, these late-stage fractures were filled with calcite cement. On the other hand, dissolution helped in enhancing the reservoir properties, whereas the interlocking nature in dolomitization reduced the reservoir properties.

Conclusion

Excellent outcrop of Jurassic Samanasuk Formation is exposed in the Nizampur basin of Attock-Cherat Range. In the present study, an attempt was being made to scientifically study the undeviating relation between the sedimentological characteristics of carbonate rocks and reservoir quality. Field investigations and petrographic observations revealed that Jurassic Samanasuk Formation consists of eight microfacies types which are ooidal grainstone, ooidal bioclastic grainstone, peloidal packstone, bioclastic packstone, bioclastic wackestone, dolomudstone, and mudstone. These different types of microfacies suggest that Samanasuk Formation was deposited in different depositional settings which include peritidal flats, closed inner lagoons, and shoals settings that were developed on the inner part of a homoclinal carbonate ramp environment. The studied microfacies carbonate sand and shoal facies had the highest core plug porosity and permeability. Whereas, the peritidal and lagoonal facies had an average to poor (lowest) porosity and permeability. The Samanasuk Formation was exposed to meteoric and marine diagenetic settings which involved physical and mechanical compaction, cementation, neomorphism, micritization, dissolution, and dolomitization. Furthermore, dolomitization improved reservoir quality, whereas cementation and compaction led to reduced quality of the reservoir. Different types of secondary porosity were documented which consist of intragranular, intergranular, moldic, and vuggy. The maximum porosity occurred in grain-supported facies due to partial to complete dolomitization of ooids and dissolution, which in turn improved the quality of the reservoir. Mineralogically besides calcite and dolomite, several other minerals (silica, clay, alumina, pyrite) were identified using X-ray diffraction. Subsequently, these depositional facies, diagenetic alteration, and geochemical investigations of the studied rocks greatly affected the reservoir behavior of Samanasuk Formation.

This study used the sedimentological aspects, depositional facies, diagenetic alteration, and geochemical analysis of carbonate rocks for a more effective reservoir categorization.

Acknowledgements The authors are thankful to National Center of Physics, Islamabad for XRD analyses. Moreover, OGTI is thankful for the plug analysis. Waseem sajjad Phd Scholar, Quaid e Azam University is acknowledged for his contribution during the fieldwork. Dr Shahid ghazi, Punjab University and Auriba shahid Post Doc fellow, Stockholm University is acknowledged for critically reviewing the article. The authors are thankful to the anonymous reviewers for their discussions and suggestions for the improvement of manuscript.

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