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Reservoir heterogeneities due to diagenesis in Jurassic Samana Suk Formation Kahi section Nizampur Basin North West Himalayas Pakistan

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Abstract

The porosity and permeability determine the reservoir quality of sedimentary rocks, which is fundamentally influenced by both depositional and diagenetic processes. The Jurassic carbonates are targeted in many regions for oil and gas exploration. The current study is carried out to elaborate on the diagenetic alterations and their effect on reservoir properties. A thick outcrop of the Jurassic Samana Suk Formation is studied in the Kahi section of Nizampur Basin Northwest Himalayas, Pakistan, to study and relate the trend of lithological variations and depositional settings. Field investigation revealed that the Samana Suk Formation is extensively distributed in the area and primarily made up of interbedded limestone and dolomite units. The original unaltered limestone has a thick-bedded and oolitic to bioclastic nature. Different types of dolomites have been recognized based on colour contrast and sedimentary features. Moreover, saddle dolomite cement, calcite cementation, and mechanical and chemical compaction have also been observed. The petrographic studies show different types of diagenetic alterations that affected the Samana Suk Formation, including micritization, bioturbation, mechanical and chemical compaction in the form of fractures and stylolites, various calcite cementation, which includes the various cement types that range from isopachous, blocky, granular equant, fibrous, and dog tooth cementation, along with dissolution that occurred in different diagenetic realms. Pyritization was rarely observed. Moreover, different phases of dolomites were identified, ranging in size and shape, i.e., finely crystalline to coarse crystalline and planar euhedral to non-planar anhedral. The stable oxygen isotope values of these dolomites show depletion from original marine signatures and suggest burial-related fault-controlled dolomitization events. Overall, diagenetic processes like dissolution, fracturing and dolomitization increased the reservoir potential. On the contrary, the overburden and cement precipitation result in a decrease in the reservoir properties.

Keywords

Diagenesis, Dolomites, Reservoir, Jurassic, Samana Suk Formation.

Introduction

Carbonate rocks act as a significant hydrocarbon reservoir and attract the keen interest of many researchers. Even with a simple mineralogical form, these carbonates show a wide range of compositional modifications controlled by many variables, including depositional environment, tectonic events, climate and diagenesis (Tucker & Wright, 1990). Diagenesis describes all the physical, geochemical, and biological post-depositional changes which greatly impact the reservoir's porosity and permeability (Rahman & Worden, 2016). The complexities in the carbonate rocks make it very hard to predict the reservoir quality in terms of porosity and permeability. The porosity generation and distribution in the carbonate rocks are generally controlled by three factors, including the deposition followed by diagenesis (Vuggy, Moldic, etc.) and compactions, i.e., fracture porosity (Khan et al., 2022). The petrographic study and geochemical attributes are crucial for interpreting reservoir properties. Microscopic studies help to identify the different constituents of rocks/grains along with the detailed classification of the rocks and sediments. Petrography helps to interpret the depositional environment and determine the diagenetic characteristics that occur during the deposition or after the deposition of a rock (Scholle & Ulmer-Scholle, 2006). The foremost alterations triggered by various diagenetic events include bioturbation, replacive and cement dolomitization, biogenic micritization, cement precipitation, dissolution by unsaturated fluids via rock fluids interaction, fracturing i.e., tectonic and overburden, mechanical and chemical compaction, neomorphism, and pyrite precipitation (Scholle & Ulmer-Scholle, 2006; Tucker, 2007; Khan et al., 2022). The diagenetic alterations may eliminate the original depositional fabric that occurred in all diagenetic reals, i.e., shallow marine, meteoric and deep burial regimes (Lapponi et al., 2014). Carbonate rocks' textural and reservoir characteristics are likely to be affected by many factors, including structural and stratigraphic setting, which is a function of facies type and prior diagenetic modifications (Machel, 2005). The carbonate rocks are highly reactive to diagenesis, and different diagenetic events play a very vital role in influencing reservoir characterization (Salem et al., 2005; Khan et al., 2020; Khan et al., 2022). Therefore, porosity and permeability can be better understood by disclosing the detailed diagenetic history (Baiyegunhi et al., 2017; Khan et al., 2022). For a better understanding of reservoir properties, it is very important to know about the origin of porosity and its effect on reservoir quality.

Previous work on the Samana Suk Formation includes various stratigraphic aspects, sedimentological observations, and geochemical attributes from the upper Indus Basin (Khan et al., 2020; Khan et al., 2021; Khan et al., 2022). In the literature, the Jurassic Samana Suk Formation in Nizampur Basin is studied for its depositional environment, where various facies are recognized both on outcrop and in thin section microscopy (see Khan et al., 2020). The carbonate unit of the Samana Suk Formation in the Nizampur Basin is generally characterized as limestone and dolomites. The limestone is commonly described as ooidal and peloidal grainstone, packstone facies (Khan et al., 2020). However, no such comprehensive study has been carried out to highlight the diagenetic study and its influence on reservoir properties of the Jurrasic Samana Suk Formation. Although many authors studied the Samana Suk Formation for the reservoir properties, there is still a research gap and a lack of comprehensive information on diagenetic behaviour. This research effort aims to identify and establish the diagenetic alterations and geochemistry of the Samana Suk Formation in the Kahi section, study the influence of diagenesis, and relate it to reservoir potential. Detailed petrographic studies and advanced geochemical analysis were conducted to investigate Jurassic carbonate successions.

Geological setting and study area

The studied Samana Suk Formation is located in the Nizampur Basin, which is bounded by the River Indus and Attock-Cherat Range from the northern and southern sides, respectively. The Nizampur Basin is a part of the lesser Himalayas, North Pakistan (Fig. 1a). Tectonically, it is a part of the active thrust and fold belt of a long Himalayan foreland, characterized by very complicated structural configuration (Yeats & Hussain 1987). Similarly, the Kahi Gorge is a part of the Sub Himalayas and lies in the Nizampur valley of Khyber Pakhtunkhwa, NW Pakistan (Khan et al., 2020). In the study area from south to north, Kahi-1 thrust (KF-1) is the major structure that characterizes the study area's southern part, along which the Jurassic carbonate successions are thrusted over the Cretaceous Kawagarh Formation. KF-1 is followed by the Kahi-2 (KF-2) thrust. Moving further north, the major thrust, i.e., Kahi-3 (KF-3) thrust, is encountered in the area along which the Middle Cretaceous Lumshiwal Formation is thrust over the Jurassic Samana Suk Formation (Khan et al., 2020). Fig. 1b illustrates the stratigraphic position of sedimentary succession exposed in the southern Nizampur Basin. Lithologically, the field mosaic illustrates the grey to dark grey of the Samana Suk Formation, which comprises thick-bedded limestone units with subordinate marl in places and displays shale intercalations (Shah, 2009; Khan et al., 2020). The research work is performed only on the carbonate portion. A major part of this Formation is covered by Limestone, which is oolitic and consists of some shale beds. In the study area, the lower contact of the Samana Suk Formation is transitional with the Shinwari Formation contact, while the upper contact is disconformable with the Chichali Formation (Shah, 2009).

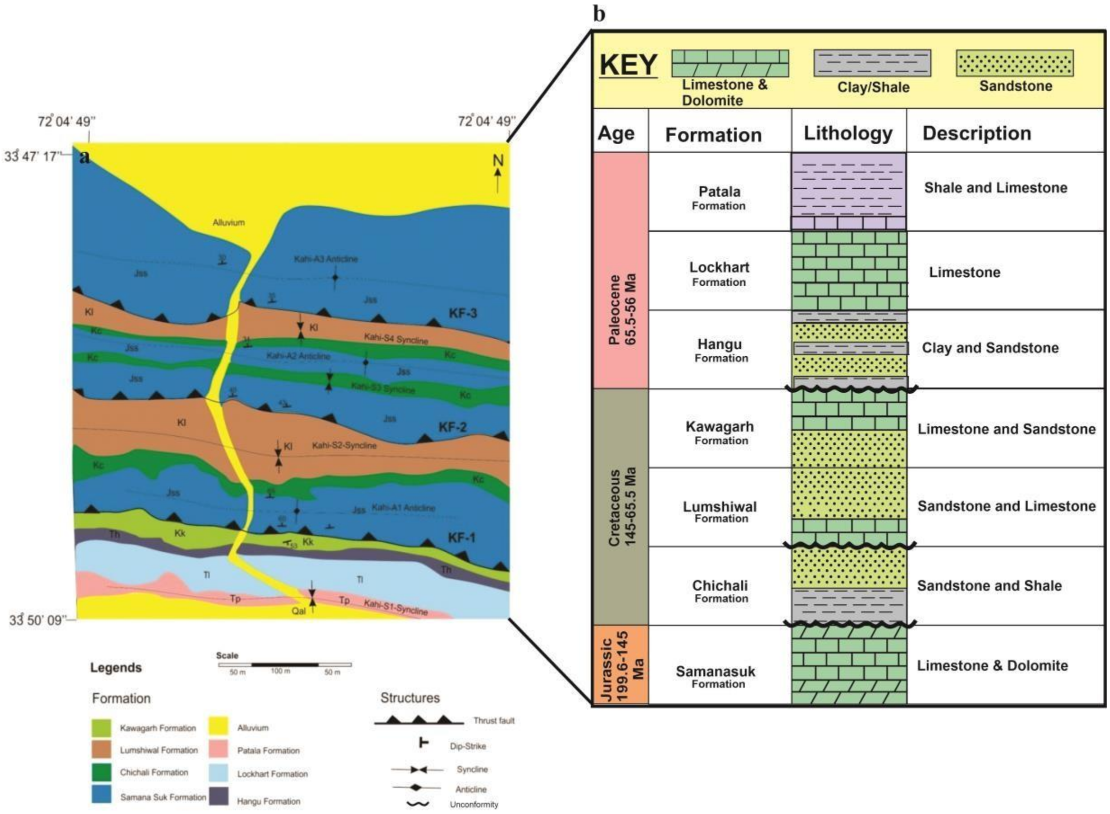

Fig. 1. (a) Geological map of the study area. (b) Stratigraphy of the study area (Khan et al., 2020).

Material and methods

90-meter thick outcrop of the Samana Suk Formation in the Kahi Gorge of Nizampur Basin is measured and sampled. Overall, 27 thin sections were prepared from representative samples, which were then studied under an optical microscope for different diagenetic alterations and to observe the reservoir heterogeneities. The samples were once-half stained with alizarin-red S and potassium ferricyanide mix solution to distinguish dolomite phases from the calcite phases (Dickson, 1965). The petrographic studies were undertaken on thin polished sections illustrating the main lithological components, which were organized according to crystal shape, size, and texture. The dolomite was classified based on Sibley and Gregg (1987) and Adabi (2009), and their relationships with matrix and various cement types were also determined to link with porosity reduction and creation. The texture of carbonate rocks is classified by using Dunham's (1962) carbonate classification scheme. During the petrography, various diagenetic features were recognized and noted. The major emphasis is given to the process of dolomitization as various kinds of dolomites are documented; therefore, the geochemical characteristics of dolomites were also determined. The identified dolomite phases in the petrography were further studied for stable oxygen and carbon isotope analysis in the Isotope Application Division of the Pakistan Institute of Nuclear Science and Technology (PINSTECH). All $\delta^{13}C$ and $\delta^{18}O$ values were expressed per mill (‰) relative to Vienna Pee Dee Belemnite (V-PDB).

Results

Field observations

In the study section, the Samana Suk Formation display oolitic greyish limestone with strata-bound dolomite of brown color (Fig. 2a, b). The dolomite shows a sharp contact with limestone (Fig. 2c). In the field, various types of dolomites were observed, which were differentiated through color contrast. At places, the dolomite occurred in the form of patches (Fig. 2d). Saddle dolomite cement mostly occurs as a later cementing phase and occluded the free space in the form of vugs, veins and fractures (Fig. 2e, f). Moreover, calcite cementation also occurred in the form of veins (Fig. 2h). Varying amplitude stylolites reflect chemical compaction and can be related to the compressive tectonic events (Fig. 2g, i).

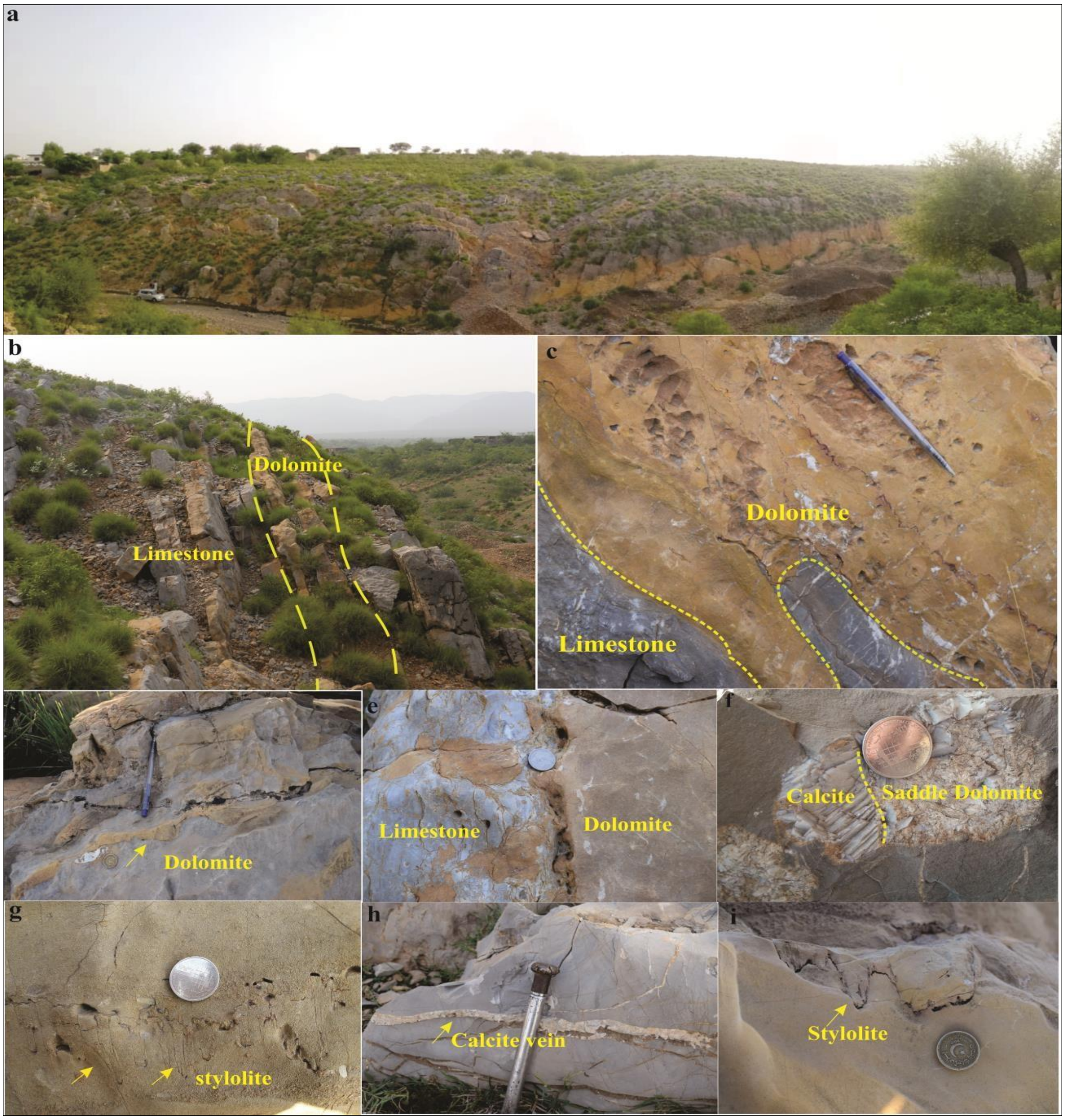

Fig. 2. Field photographs; (a) Paranomic view of the study area. (b) Alternations beds of limestone and dolomite. (c-e) Contact between limestone and dolomite. (f) Contact between calcite and saddle dolomite cement. (g) vuggy porosity along with stylolites. (h) calcite veins. (i) Stylolites in dolomite.

Petrographic Analysis

The various diagenetic phases encountered during the field were also observed under the optical microscope. Diagenesis accounts for all the physical and chemical processes which affect sedimentary rocks from the period of their burial, including deposition and weathering, till the onset of metamorphism (Mackenzie, 2005). A comprehensive field study, petrographic observations and geochemical understanding of these carbonates are very important for interpreting the processes that control their formation and diagenetic modification. A brief history, timing and occurrences of these diagenetic alterations observed in the Samana Suk Formation were studied and documented in detail.

Eogenetic stage

Marine diagenetic setting

Micritization

Micritization is the first step of diagenesis, which decreases permeability by filling up the available pore spaces. During eogenesis, the contact of water and carbonate sediments in the marine phreatic zone causes the initial micritization of carbonate sediments (Reid & MacIntyre, 2000; Beigi et al., 2017). However, such an initial phase is also majorly controlled by biogenic activities (Vincent et al., 2007; Flugel, 2010). The micritization in the Samana Suk Formation has occurred around the rims of bioclasts and ooids (Fig. 3a, b). It has caused the obliteration of ooids' inner laminations, whereas, in some places, it has micritized the whole ooid. The sedimentation rate and water depth majorly influenced the micritization of the grains (Khan et al., 2022).

Bioturbation and burrowing

The mud-to-wackestone facies are observed to be mostly influenced by the drilling effects of digger organisms in lower energy environments of lagoonal settings. This effect creates heterogeneities in texture and color contrast of sediments due to oxygen penetration (Fig. 3c). The drilling effects of digger organisms cause this process. The formation is deposited in a carbonate ramp environment and discloses a wide range of facies. Here, the bioturbation and burrowing are limited to calm lower energy. Therefore, it has little to no influence on the reservoir quality of the Samana Suk Formation.

Isopachous rim cement

Unlike ordinary cementation, the high-Mg aragonite and calcite composition is unusual in marine phreatic settings (Flugel, 2010). It displays bladed fabric and appears as an isopachous rim of the first-generation cement (Fig. 3d, e). The growth of such cement occurs off sides of the grainstone texture, in places that occur as overgrowth rims having aragonite composition and commonly postdates micritization (Adabi & Rao, 1991).

Dog-tooth cement

Dog-tooth cement is diagenetically formed with calcite mineralogy and is called HMC (Christ et al., 2015). This cement displays different origins, including meteoric, moderate burial and occasionally marine conditions (Flugel, 2010). The rarely seen results from the present work's petrographic observations show the dog-tooth cement's marine phreatic environments (Fig. 3f).

Meteoric diagenetic environment

Dissolution

The dissolution process leads to the development of various porosity types, which is evident and observed in the Samanasuk Formation. The Samana Suk Formation shows wide dissolution distributed at the outcrop scale and also on a microscopic scale. The dissolution has occurred in the eogenetic, mesogenetic, and Telogenetic stages and is playing a key part in enhancing the reservoir potential. The eogenetic stage generally causes the fabric selective dissolution (Fig. 3a, h). Later on, the porosity is also destructed by the precipitation of cementing materials.

Granular and equant calcite cement

The near-surface meteoric regime is very favorable to the growth of equant calcite cement in carbonate sediments (Haijun et al., 2006). The granular and equant cements have patchy dispersion of size crystals and promote the formation of the intergranular and pore-filling cements (Fig. 3g).

Mesogenetic stage

Shallow burial

Mechanical compaction

The Samana Suk Formation has experienced shallow to deep burial compaction due to overlying deposition. The compaction has caused re-orientation, fracturing and deformation of grains (Fig. 3h). The microscopic observations show that the grain contacts due to strain concentration result in sutured contacts and grains deformation (Fig. 3g, h). This mechanical compaction has caused a reduction of porosity in grainstone and packstone, whereas less compression is present in mudstones and wackestones.

Deep burial

Chemical compaction

The chemical compaction was observed in the outcrop as well as in the petrographic studies. It is a common phenomenon of diagenesis, and it takes place due to a pressure solution (Lloyd, 1977; Choquette & James, 1990). Deep burial conditions play an important role in increasing pressure solution and eventually brought sutured contacts laterally met to form continuous stylolite structures of various amplitude (Fig. 3i). The filling of stylolites with insoluble materials like oxides, opaque, organic material and its non-dissolution is an obstacle to enhance the reservoir qualities. Therefore, chemical compaction is considered one of the most remarkable diagenetic phases in reducing the reservoir potential.

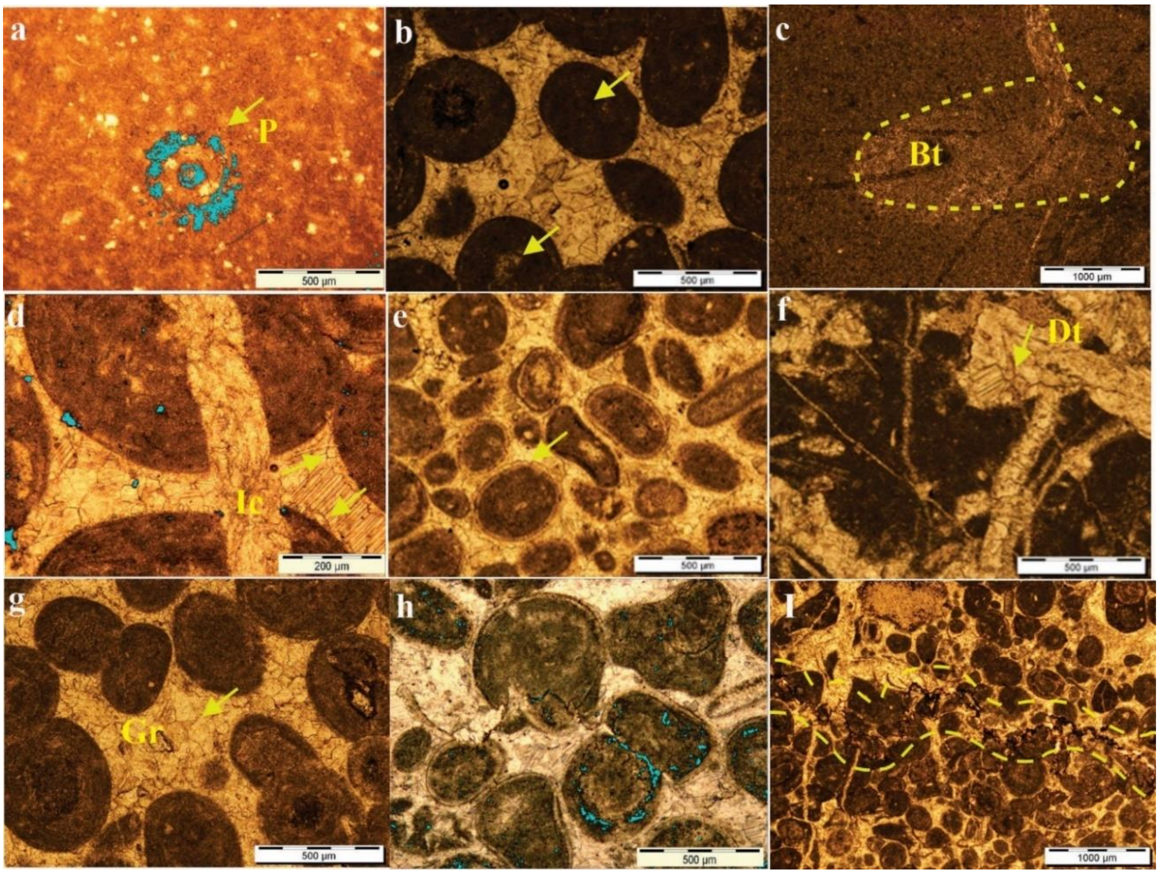

Fig. 3. Photomicrographs showing different diagenetic processes. (a) Micritization along with porosity (P) shown by blue color. (b) Micritization of ooids. (c) bioturbation (Bt). (d,e) bladed fabric first-generation isopachous rim cement (Ic) shown by a yellow arrow. (f) dog-tooth cement (Dt). (g) granular cement (Gr). (h) deformation off the ooid due to mechanical compaction. (i) stylolite structure due to chemical compaction.

Dissolution

The dissolution that occurs in the shallow to deep burial environments is regarded as the second phase of dissolution. This stage of dissolution enhanced vuggy porosity. The creations of vugs enhance the porosity, which, in some cases, if linked with other voids, may lead to an increased permeability. Dissolution of calcite and dolomite cement in later diagenetic stages has been observed in microscopic studies (Fig. 4a).

Fracturing

The fractures observed in the Samana Suk Formation are generally parallel to sub-parallel to bedding planes, indicating the bedding-perpendicular direction of compressional stresses. The petrographic studies show the fracturing result to cut both the cement as well as the original fabrics of limestone and dolomite (Fig. 4b). The fractures in carbonate sediments are either caused by tectonics deformation or burial overburden pressure (Worden & Burley, 2003). The fractures have caused an increase in the porosity and permeability of the rock.

Blocky calcite cement

The petrographic results show medium to coarse-grained blocky calcite cement with distinct euhedral to subhedral crystalline margins (Fig. 4c). The cement is present in the spaces between the grains, fractures, and voids and demonstrates a deep burial diagenetic environment (Flugel, 2010). It resulted in a decrease in the porosity by filling and cementation of calcite spar directly into pre-existing grains.

Telogenetic stage

Dissolution

In the telogenetic stage, the dissolution represents the near-surface environments, i.e., on the outcrop scale, which is majorly controlled by tectonism and topography (Haijun et al., 2006). The porosity observed in dolomites shows that the studied formation has passed through a telogenetic stage, which has been affected by meteoric waters, resulting in porosity enhancement (Fig. 4d).

Other diagenetic aspects of the Samana Suk Formation

Pyritization

The pyrites framboid is also observed in the microscopic observations (Fig. 4e). It is mostly precipitated in shallow to deep burial environments that correspond to reducing conditions and is associated with nearby sulfur-rich diagenetic fluids (Butler & Rickard, 2000; Adams & MacKenzie, 2001; Saleem et al., 2022). The overall diagenetic chronological sequence of the Samana Suk Formation is shown in Fig. 5, which specifies diagenetic phases and environments in chronological order.

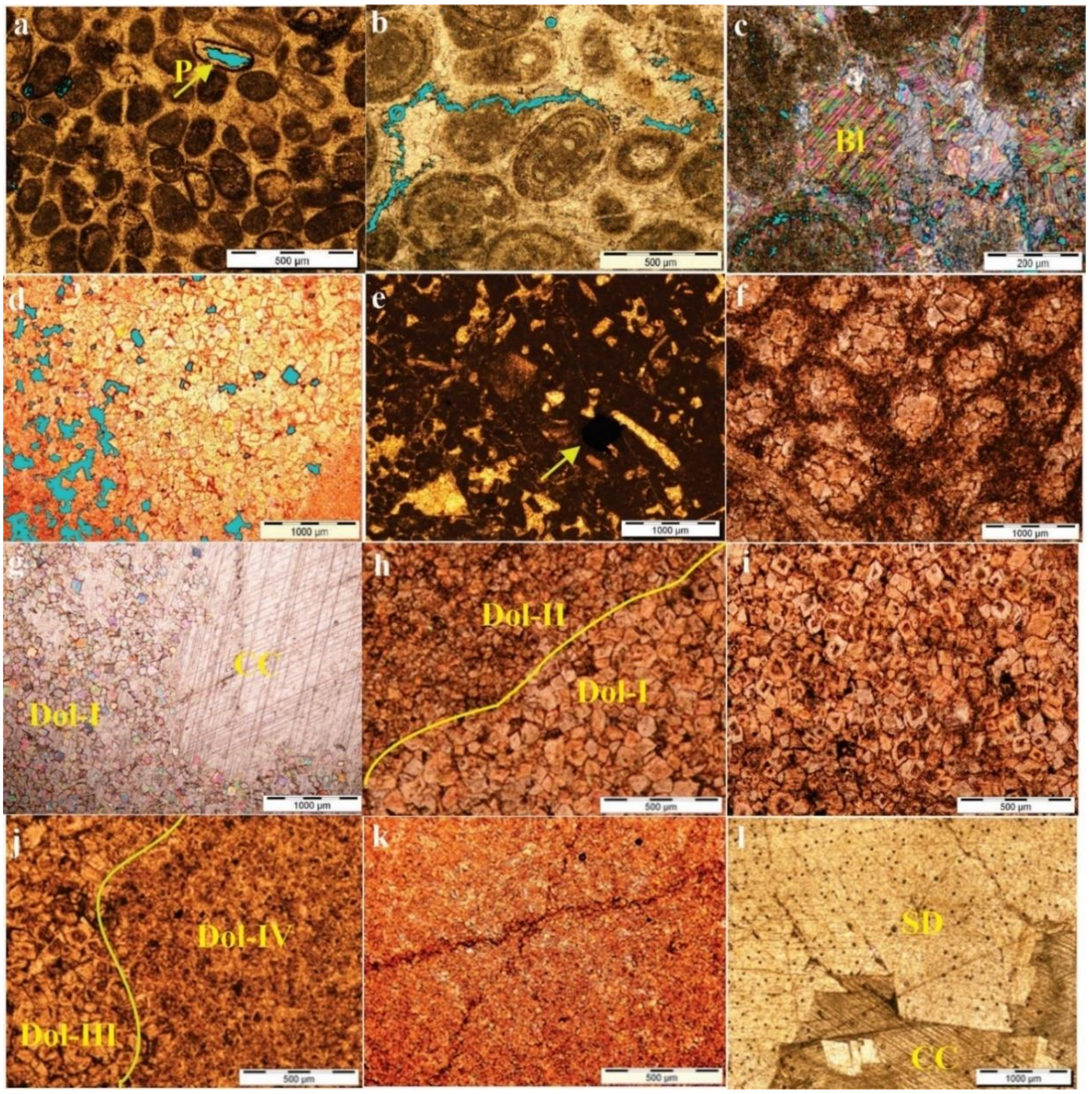

Fig. 4. Photomicrographs. (a) dissolution creating vuggy porosity (P). (b) fracture porosity shown by blue color. (c) blocky calcite cement (Bl). (d) dissolution porosity in dolomites shown by blue color. (e) framboidal pyrite cube. (f) Dol-I preserved the inherited oolites of host limestone. (g) Dol-I in contact with calcite cementation (CC). (h) sharp contact of Dol-I and Dol-II. (i) coarse-grained planar euhedral zoned dolomite (Dol-III). (j) Dol-IV post-dating Dol-III. (k) Dol-V having multiple stylolites. (l) saddle dolomite (SD) postdating calcite cementation phase (CC).

Dolomitization

In the Samana Suk Formation, two distinctive phases of dolomite, i.e., replacive matrix phase and cementing saddle dolomite phase, are documented. On the basis of Sibley & Gregg's (1987) classification scheme, the replacive matrix dolomite phases are sub-divided into the coarse-grained planar euhedral dolomite (Dol-I) medium-grained subhedral dolomite (Dol-II), coarsely grained planar zoned euhedral dolomite (Dol-III), fine-grained planar zoned euhedral dolomite (Dol-IV), fine-grained non-planar anhedral dolomite (Dol-V). Coarse-grained euhedral dolomite represents the initial phase of dolomitization. The dolomite crystal boundaries are well developed and distinct by the size of the crystal that is ranging from 40-100 µm (Fig. 4f). Dol-I also exhibits the vuggy type of porosity (Fig. 4d). The dolomite type Dol-I also preserved the original oolitic texture of host limestone (Fig. 4f). Dol-I show a contact with calcite (Fig. 4g). Dolomite type (Dol-II) followed the euhedral dolomitization phase-I (Dol-I) and second phase of replacive matrix. It displays variation in texture (i.e., crystal size and crystal shape) from the initial dolomite phase Dol-I. Dolomite type (Dol-II) exhibits planar crystal boundaries and subhedral texture. The crystal size ranges from 40 to 80 µm (Fig. 4h). Dolomite type Dol-II occurs in sharp contact with dolomite Dol-I (Fig. 4h). Dolomite (Dol-III) shows coarse-grained zoned crystals having a perfectly rhombohedral core surrounded by a successive zone. The crystal size of Dol-III varies between 55 to 110 µm (Fig. 4i). This zone dolomite is tightly packed with moderate porosity. Fine-grained planar euhedral zoned dolomite (Dol-IV) consists of well-developed zones crystals with sizes ranging from 30 to 60 µm (Fig. 4j). This dolomite (Dol-IV) type also occurs in sharp contact with coarse crystalline planar zone euhedral dolomite Dol-III (Fig. 4j). Fine-grained non-planar anhedral dolomite (Dol-V) is defined based on crystal shape and size variation. This fine-grained dolomite type ranges in crystal size from 20 to 40 µm having non-planar anhedral crystal shape (Fig. 4k). Dol-V is also crosscut by several small-scale pressure solution seams which are later coated by iron oxide (Fig. 4k). Saddle dolomite (SD) represents a particular type of the cementing phase of dolomite which is also called as baroque or white sparry dolomite. These cementing saddle dolomite phases formed at elevated temperatures from saline brines and usually occur as a fracture vein and pore filling showing a late-stage origin (Sirat et al., 2016). Saddle dolomites are usually characterized by coarse to very coarse crystals with curved faces that usually range from millimetre or larger in size (Fig. 4l). This coarsely crystalline planar to non-planar saddle dolomite has its characteristic undulate extension. The overall diagenetic chronological sequence of the Samana Suk Formation is shown in Fig. 5, which specifies diagenetic phases and environments in chronological order.

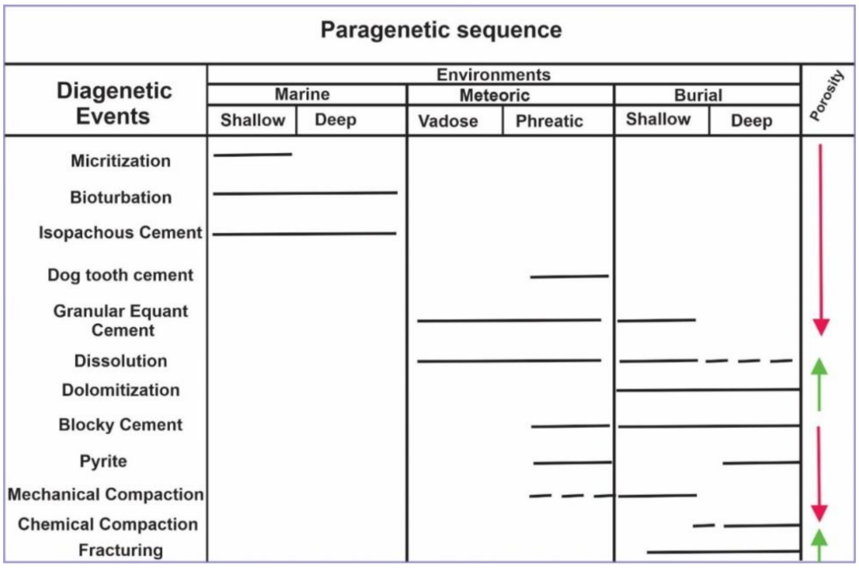

Fig. 5. Paragenetic sequence of various diagenetic phases in chronological order and its relationship to the reservoir potential of Jurassic Samana Suk Formation

Dolomite geochemistry and dolomitization model

Dol-I shows stable oxygen isotope ($\delta^{18}O$) values vary from -5.89 to -4.89% V-PDB while carbon value (δ13C) lies between + 0.30 and +1.43% V-PDB. Dol-II shows $\delta^{18}O$ signatures in the range of -6.37 to -5.95% V-PDB, while $\delta^{13}C$ values range from + 0.38 to +1.33% V-PDB. For dolomite Dol-III, the $\delta^{18}O$ values range from - 6.83 to - 6.20% V-PDB, while the $\delta^{13}C$ values range from + 0.46 to +1.41% V-PDB. The fine-grained planar zoned euhedral dolomite Dol-IV show the $\delta^{18}O$ and $\delta^{13}C$ values range from -7.03 to - 6.56% V-PDB and + 0.46 to +1.31% V-PDB, respectively. The $\delta^{18}O$ ratio of Dol-V ranges from -8.25 to –7.15% V-PDB, while the carbon isotope ratio occurs within + 0.60 and +1.06% V-PDB. Moreover, saddle dolomite (SD) shows a highly depleted oxygen signature of −11.05 to −10.23% V-PDB. However, carbon isotope values are under the range of original marine signatures, which is +1.4 to +1.6% V-PDB.

A cross-plot of $\delta^{13}C$ vs $\delta^{18}O$ of all the analyzed dolomite samples of Jurrasic Samana Suk Formation is shown in Fig. 6. These different dolomite phases show a variable $\delta^{18}O$ and $\delta^{13}C$ values and hence cluster into a broad area of the cross-plot. These different dolomite phases show more negative $\delta^{18}O$ values with respect to the parent limestone, while the $\delta^{13}C$ values are almost comparable and occur within that positive range. So overall, the oxygen $\delta^{18}O$ values show a more negative trend as compared to the host limestone, whereas in the $\delta^{13}C$ values, no consistent trend is followed by these different dolomite phases but shows a slightly enrich or depleted $\delta^{13}C$ values as compared to host limestone. The various phases of carbonate in the Middle Jurassic Samana Suk Formation are then correlated with the original marine (sea) water isotopic signatures (−2.8% to −1.8% δ^{18}O V-PDB and +0.0% to +1.8% δ^{13}C V-PDB) (Fursich et al., 2004). The δ^{18}O V-PDB results of host limestone range from (−3.34 to −4.28‰) while the δ^{13}CV-PDB resultant values range from +1.28 to +1.71‰.

The more negative deviation of δ^{18}O values of different dolomite phases may suggest higher temperature dolomitization as the lighter δ^{18}O values indicate dolomitization at comparatively high temperatures (Khan et al., 2021). The stable oxygen & carbon isotope values of Samana Suk dolomites show that these fabric-destructive dolomites may form in the burial conditions. The trapped sea water may be released with depth as overlying strata, causing overburden pressure, where the various scale fractures and faults act as conduits for hydrothermal fluids migration, which eventually causes dolomitization. The first stage of dolomitization, which preserved the original texture of host limestone (Fig. 7), suggests near-surface shallow burial conditions (Corlett and Jones, 2012; Khan et al., 2021). However, the geochemical values of these different dolomite phases may be altered because of subsequent later-stage dolomitization events as indicated by its lighter δ^{18}O, which suggests shallow burial depth dolomitization (Koeshidayatullah et al., 2020; Khan et al., 2021; Saleema et al., 2022; Saleem et al., 2022). These first stages of shallow burial dolomitization can also be followed by a deep burial dolomitization event. These deep burial dolomites also exhibit depleted δ^{18}O values, which suggest that the dolomitization fluids are isotopically enriched with respect to Jurassic marine signatures (Swart, 2015; Veizer & Prokoph, 2015; Ryb & Eiler, 2018). These dolomite show non-planar anhedral crystal morphology with tight packing, signifying a more rapid growth at elevated temperatures at deep burial conditions (Gregg & Shelton, 1990; Montañez & Read, 1992; Qing, 1998; Al-Aasm & Packard, 2000). Besides these replacive matrix phase dolomitization, the cementing phase also occurs, which consists of saddle dolomite and calcite cement. The more depleted and highly negative trend of δ^{18}O values of saddle dolomite (SD) suggests diagenetic fluids have high temperatures, which is derived from greater depth along the faults than the replacive dolomitizing fluids (Ronchi et al., 2012).

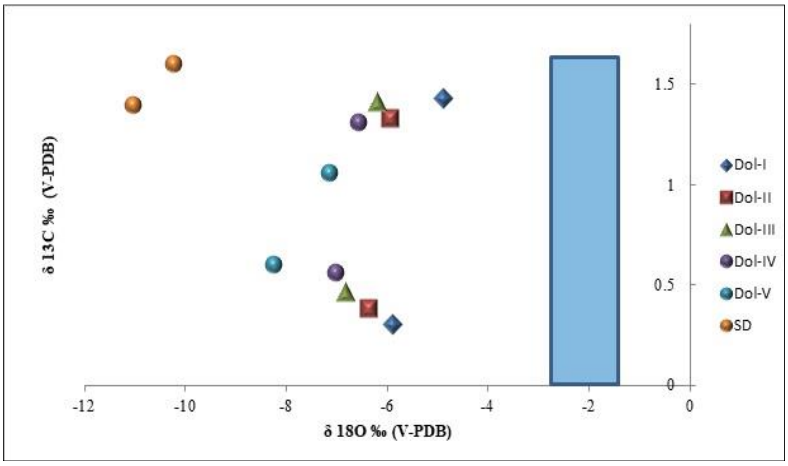

Fig. 6. Cross-plot of δ13C vs δ18O of all the representative samples from different carbonate phases of Jurassic Samana Suk Formation. The blue box show the middle Jurassic marine signatures (Fursich et al.,, 2004).

Effect of diagenesis on reservoir properties

The highly fractured Samana Suk Formation experienced multiple phases of deformation, which has affected its reservoir properties (Fig. 8a). The Samana Suk Formation comprises extremely fractured limestone units and strata-bound dolomitic beds (Fig. 8b). The correlative studies are field scale and from petrographic finding signify the fact, that limestone is less fractures as compared to the dolomitic beds and hence attracting attention toward the positive reservoir characterizations. The bioclasts dissolutions (Fig. 8c) and dolomite have a positive effect on porosity and permeability (Fig. 8d). It is also noted that the different cementation phases play a key role in decreasing the porosity and permeability (Fig. 8e). The inter-granular porosity is mainly controlled by the mechanical compaction that in combination with the later cementation phases generally reduced the reservoir qualities. Moreover, on the outcrop scale, it can be observed that calcite cementation, as well as dolomite cement, have occluded the pore spaces (Fig. 8f). Similarly, the chemical compaction phenomenon also most commonly occurs, which led to the development of low to high amplitude stylolites (Fig. 8g). Commonly, the chemical compaction causes porosity reduction (Moore & Wade, 2001). Moreover, dissolution observed in the dolomites has considerably enhanced the reservoir properties. Dolomitization in the Samanasuk Formation increases intercrystalline porosity and permeability, as shown in (Fig. 8i). However, the dolomite rhombs were closely packed in some places, which infilled the intercrystalline-free spaces. The sum of all signifies the outcome such that the dolomitization and dissolution assisted in improving reservoir potential. On the contrary, different phases of cementation and compaction have adversely influenced the reservoir potential at the outcrop scale.

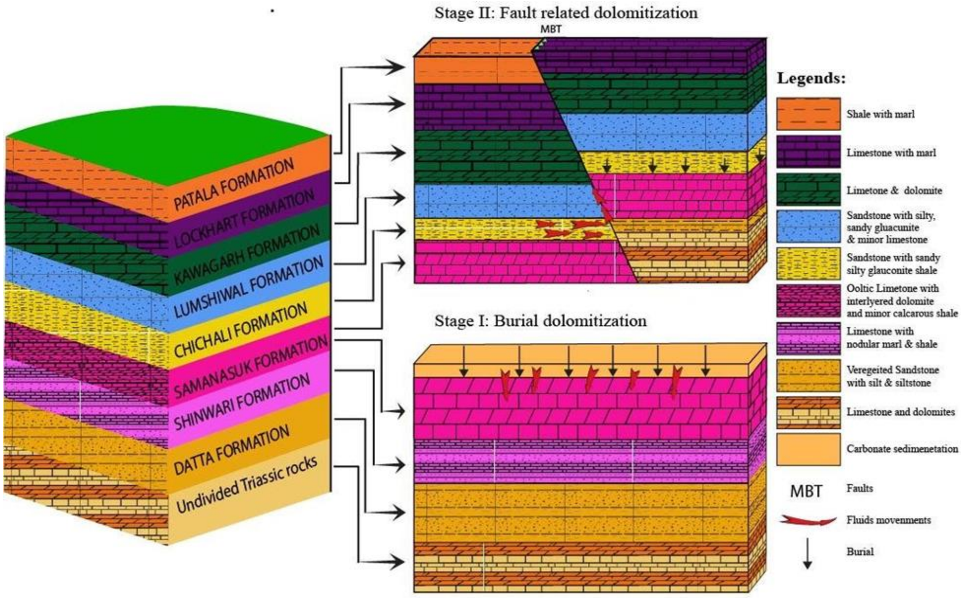

Fig. 7. The dolomitzation model represents the burial and fault-related origin of dolomite types in the Samana Suk formation.

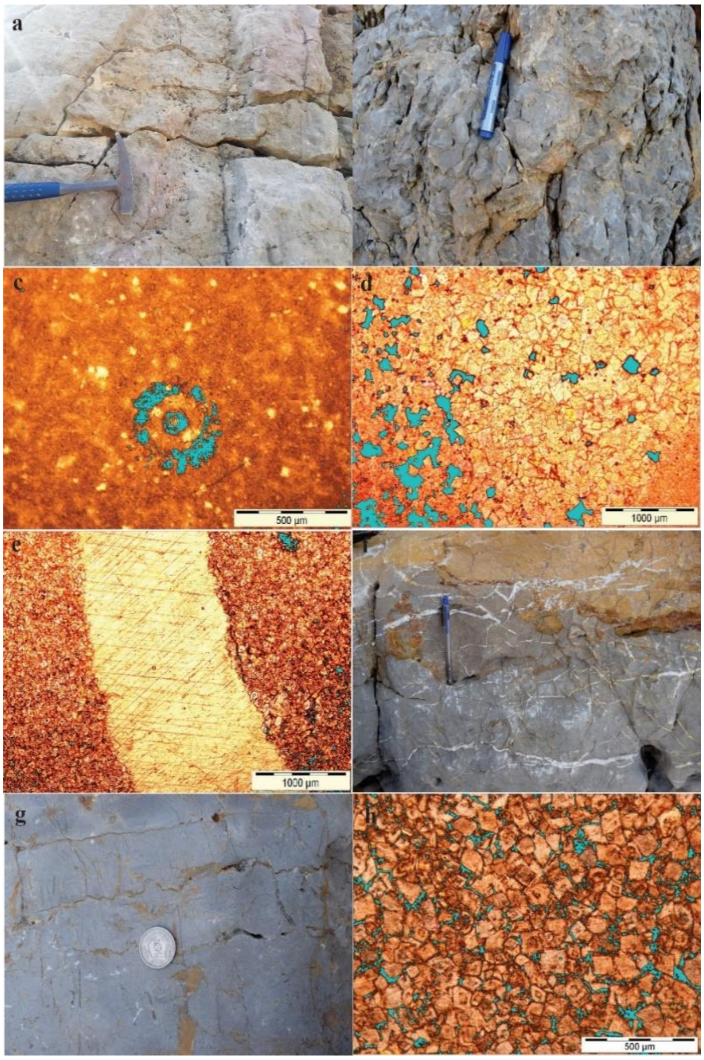

Fig. 8. (a) deformation of original limestone beds. (b) Dolomite is more deformed and fractured than limestone. (c) dissolution of bioclasts. (d) dolomite increased porosity and permeability. (e) early and late-stage cementation has a destructive role in porosity and permeability. (f) occultation of porosity and permeability at outcrop scale by calcite and dolomite cementation. (g) low to high amplitude stylolites suture seams and sutured contacts. (h) intercrystalline porosity and permeability in dolomite.

Discussion

The Jurassic Samana Suk Formation has undergone numerous tectonic deformation events, which have fundamentally influenced its reservior quality. These deformation events play both constructive and destructive roles. The study area is located in the Nizampur Basin, where its northern boundary is marked by the Attock – Cherat ranges and Peshawar Basin (Burbank, 1982). Toward the Northeastern side, the Kherimar hills and Gandghar ranges lie (Hylland, 1990; Talent & Mawson, 1979). The Kalachitta ranges the Nizampur basin from the western side (Yeats & Hussain, 1987). The major Main Boundary Thrust (MBT) is located to the south of the Nizampur basin. The Hissartang Thrust and MBT are passing from the vicinity of the basin, which causes extreme deformation in the area (Ghauri et al., 1991; Khan et al., 2020). This intense deformation includes various major-scale local folds and thrust faults. The Late Cenozoic thrust movement leads to the uplifting of the Kala-Chitta Range and its associated strongly deformed rocks of the Jurassic, Cretaceous and Tertiary age (Ghauri et al., 1991). From south to north, three major thrusts pass through the area, i.e., KF-1, KF-2, and KF-3. The Jurassic sequence underlying the Cretaceous Kawagarh Formation along KF-1 is tracing the gorge from south to north. Moving further north, along the KF-2, the middle Cretaceous Lumshiwal Formation thrust over the Jurassic Samana Suk Formation. The extreme north of the study area is marked by the major Kahi-3 (KF-3) thrust encounters, which cause the thrusting of the Middle Cretaceous Lumshiwal Formation over the Jurassic Samanasuk Formation (Khan et al., 2020).

The field data, petrographic observations and geochemical attributes reveal that the Jurassic Samana Suk Formation has undergone diagenetic alteration through diagenetic processes of marine, meteoric and deep burial conditions. The various diagenetic events were summarized in a detailed paragenetic sequence, which includes micritization, bioturbation, cementations, dissolutions, dolomitizations, pyritization, compactions and fracturing (Fig. 5). Micritization marks the initial phase of diagenesis which occurs in the shallow marine environment (Bjorlykke, 2010; Shakeri & Parham, 2014). The micritization is followed by bioturbation and shallow marine cementations. The isopachous cement fabric is a bladed shape rim cement with a principle of High-Mg calcite (HMC) and aragonite mineralogy that occur very frequently in the shallow marine depositional environment and represents marine phreatic diagenetic zone (Christ et al., 2015). Dog-tooth cement rarely occurs, which represents marine, meteoric, phreatic, and burial diagenetic conditions (Christ et al., 2015). The dissolution affects the carbonate rock in the meteoric diagenetic conditions and creates various porosity at different depths. Later on, the free spaces created by dissolution are filled with cementing material. The equivalent pore-filling calcite cementation occurs very frequently and represents marine, meteoric phreatic and deep burial diagenetic conditions (Christ et al., 2015). The carbonate rocks are also affected by major burial diagenetic events, which include dolomitizations, cementation, compaction, and fracturing. Dolomitization controls reservoir quality (Whitaker & Xiao, 2010). The occurrence and distribution of different dolomite types indicate multiple phases of dolomitization during burial conditions, which were later modified by the tectonic complexity of the area and subsequent circulation of hydrothermal fluids. The periodic dolomitization fluids are interpreted to be derived from deep burial, which infers the Mg^{++} ion and dolomitizes the host rock along the fluid pathway under elevated temperatures. The dolomite phases were sometimes followed by fracturing and consecutive cementation events. The occurrence of pyrite and saddle dolomite cementation in vugs and fractures suggests a deep burial diagenetic setting (Machel, 2004; Saleema et al., 2022a). Dolomitization may increase or decrease porosity, while in some places, it may cause the redistribution of pre-existing pores instead of porosity variation (Purser et al., 1994). The low porosity in the host limestone is due to its syndepositional events like micritization, dewatering, compaction, and cementation. The existence of inter-crystalline porosity directs its creation during dolomitization (Purser et al., 1994), as obvious in euhedral dolomite (Dol-I), which in this case is formed through the dissolution of grains (Fig. 8d, h). The saddle dolomites occur in the fractures and vugs of various dolomite phases, which ultimately decrease the reservoir characteristics by occupying the available pore spaces (Zhao et al., 2014) (Fig. 4f). Both calcite and dolomite cementation lead to porosity reduction by in filling the available pore spaces (Fig. 4i).

Conclusion

The Samana Suk Formation is widely distributed in the Kahi Section of the Nimzampur basin in northwest Himalayas, Pakistan, which is characterized by beds of alternating limestone and dolomite. Several different diagenetic processes have been observed in petrography and field observations. The overall effect of all of the known diagenetic events has impacted the Samana Suk Formation in several different diagenetic realms, including the meteoric, marine, and deep burial diagenesis realms. The results of the study on stable oxygen isotopes showed a larger enrichment of lighter oxygen isotopes, which suggested that fluids circulating at high temperatures were responsible for the dolomitization process. In addition, there was an initial burial, which was followed by fault-related dolomitization. In the current study, the influence of diagenesis on the Jurassic Samana Suk Formation has been investigated extensively to explain the enhancement and destruction of porosity due to the influence of numerous processes that occur in different diagenetic realms. Dissolution and fracturing, considered important factors in improving the quality of a reservoir, are the primary diagenetic processes that control factors of reservoir quality. Meanwhile, the precipitation of various types of cement and compaction have reduced the porosity and permeability of the reservoir by filling the available pore spaces.

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