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Reservoir Characterization and Modelling with Diagenetic Trends of carbonates of the Kawagarh Formation: A Section exposed in the Kala-Chitta Range, Pakistan

Bilal Wadood, Muhammad Awais, Muhammad Bilal, Muhammad Ishaq, Laeiq Ahmad, Zeeshan Zafar
Department of Geology, University of Swabi, KPK, Pakistan

***Email:** bilalwadood@uoswabi.edu.pk

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Abstract: The present research is focused on the diagenetic studies and reservoir characterization of the Cretaceous Kawagarh Formation exposed in the Gandab Village, Kala-Chitta Range, North-Western Himalayan Fold-and-Thrust Belt, Pakistan. The Formation is composed of argillaceous limestone and dark grey marls. A total of thirty three representative carbonate rock samples were collected at equal intervals of three meters. Various diagenetic features including cementation, micritization, pyrite precipitation, neomorphism, fracturing, sparitization and stylolitization were observed in the studied rocks which occur in the marine, meteoric and deep burial diagenetic environments respectively. Such diagenetic features control the reservoir quality of the rock unit. Porosity types include mostly vuggy and fracture while minor stylolitic porosity were noted with quantity ranging from 2.66% to 3.88%. The carbonates of Kawagarh Formation are highly fractured but filling of these fractures due to the precipitation of calcite or micritic mud has greatly reduced its reservoir potential while some unfilled fractures, stylolites and vuggs are the dominant factors that enhance the reservoir potentiality of the Kawagarh Formation. However, the porosity values still not marks the level of reservoir rock. These diagenetic studies revealed very less chances for hydrocarbon accumulation as no significant porosity values have been observed and overall reservoir potential is characterized as poor.

Keywords: Diagenesis, Reservoir, Cretaceous, Kawagarh Formation, Kala-Chitta Range, Pakistan

Introduction

The studied area is located in the Gandab Village, Kala-Chitta Range (KCR), which is positioned at the southern periphery of the Attock-Cherat Range (Figure 1). The KCR is in alignment with the Hazara Mountains (Margala Hills) and Samana Range towards the east and west respectively (Meissner et al., 1974). The KCR is divided into eastern and western blocks and the stratigraphic sequence ranges from the Triassic to Paleocene, however, Miocene Murree Formation is lying unconformably over the Paleocene rocks (Hussain et al., 1990). The Late Cenozoic Hissartang Fault is responsible for the uplifting and deformation of the rocks of the KCR (Yeats and Hussain, 1987; Ghauri et al., 1991).

The previous researches provided information about the depositional environment and biostratigraphy of the Kawagarh Formation (Ahsan and Chaudhry, 2008; Rehman, 2009; Khan et al., 2010). Latif (1970) and Butt (1989) have worked on the biostratigraphy and reported various species of the planktonic foraminifera and assigned Late Coniacian to Campanian age to the Formation in southern Hazara. Fatmi (1977) studied the lithostratigraphy of the Formation in detail. Many workers including Latif (1970), Butt (1986, 1989) and Butt et al., (1990) interpreted the depositional environment of the Kawagarh Formation using paleontological data without emphasizing on microfacies analysis. The microfacies analysis was carried out by Ahsan et al. (1993). Masood et al., (2008) studied the palynological character of the formation and encountered four palynomorphs species in the Kawagarh Formation. Rahman et al. (2016) studied the diagenetic fabric of the Kawagarh Formation exposed in Khanpur Dam Section of Hazara Basin.

In the present study, the detailed field and petrographic studies of the Kawagarh Formation, exposed in Gandab Section, KCR, are conducted to deduce information about the diagenetic trends and their effect on reservoir potential.

Regional Tectonics

The study area is the part of south-eastern KCR (Figure 1). The KCR, Margalla Hills and Attock-Cherat Range are combinedly called as Hill ranges (Yeats and Lawrence, 1982). According to Khwaja and Lisa (2005), these ranges emerge in the east from Hazara-Kashmir Syntaxis and run westward parallel to each other in an arcuate fashion. The tectonic history of the area is indicated by the deformation of the Hill ranges. According to Patriat and Achache (1984) the Indian plate has started penetration deeper into Asia at about About 40 to 50 million years ago. This continent-continent collision is responsible for the formation of Himalaya Ranges (Molnar, 1986). The shortening of Northern Pakistan occurred (about 300 to 400 km) during the northward movement of Indian plate which is accommodated by thrusting and thickening of crust in the south respectively (Coward et al., 1986). Similarly crustal delamination and imbrication cannot account for all the displacement; there must also have been lateral displacement of Asia (Tapponnier et al., 1982; Coward et al., 1986). The KCR is a part of the active Himalayan Foreland Fold-and-Thrust Belt which has progressively been verged southwards in a series of top to the south thrust imbricates along Main Boundary Thrust (MBT), fabricating the regional fault system of Northern Pakistan (Awais et al., 2012).

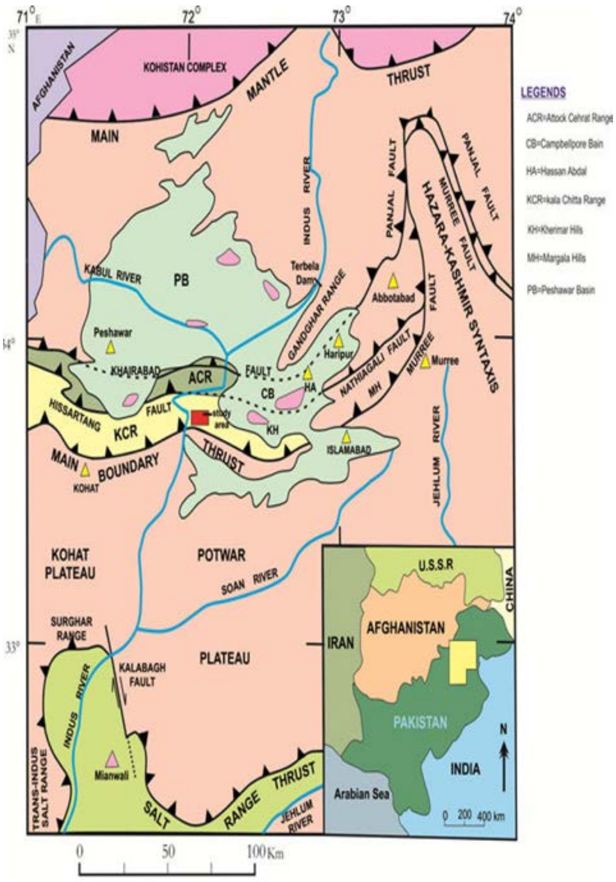

Fig. 1 Generalized tectonic map of the Himalayan Foreland. The study area is shown by red inset (modified after McDougall and Hussain, 1991).

Material and Methods

The stratigraphic section of the Kawagarh Formation exposed in Gandab Section of KCR was measured with the help of Jaccob staff and measuring tape and sampling was carried out. The generalized stratigraphic log of the Gandab Section is constructed (Figure 2). Detailed observation regarding color, bedding and grain size were recorded and also important field features were photographed and recorded. A total of thirty three samples were collected at the interval difference of three meters for subsequent laboratory study. Thin sections were prepared in the thin-section preparation laboratory of Department of Geology, University of Peshawar. Petrographic studies were carried out using polarizing microscope having digital camera fitted system in the Petrography laboratory of Department of Geology, University of Swabi. The alizarin red staining technique is used to differentiate calcite from dolomite. The solution was prepared following the Dickson (1965) method. Corel Draw X6 was used for drawing diagrams.

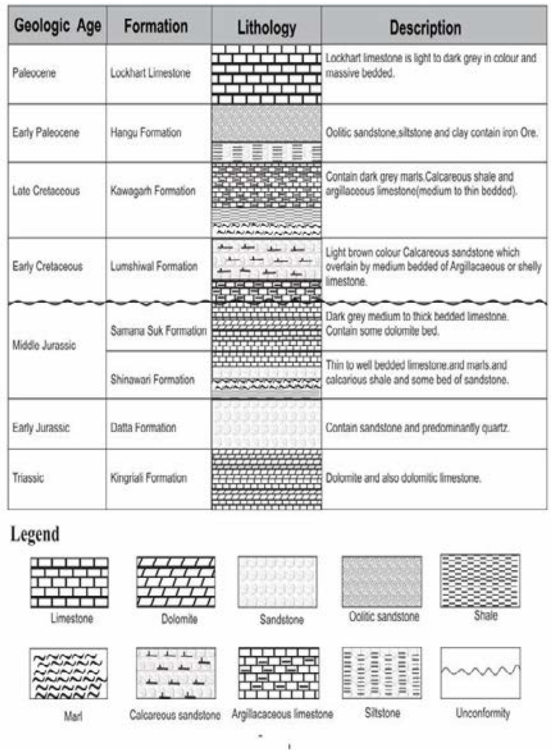

Fig. 2 Stratigraphic column of the Rocks exposed in Gandab section, Kala-Chitta Range, (not to scale).

Results and Discussion

Lithostratigraphy

In the study area, the Kawagarh Formation is 96 meter thick. In the study area the Kawagarh Formation is documented as thin to medium bedded, highly fractured, hard, argillaceous limestone which is yellowish in color on weathered surface and grey on fresh surface. The Formation is also characterized by dark-grey marls. On the weathered surface marl is yellowish grey while dark grey on fresh surface. (Figure 3A and 3B). The upper contact is conformable with the Hangu Formation (Fig. 3C and 3D) while the lower contact is gradational conformable with the Lumshiwal Formation (Figure 3E). The Hangu Formation exposed as a localized small unit and its lower contact conformable with the Kawagarh Formation while the upper contact is conformable with the Lockhart Formation (Figure 3D). Similarly, the lower contact of the Lumshiwal Formation is unconformable with the Jurassic undifferentiated rocks while the upper contact is conformable with the Kawagarh Formation of Cretaceous age (Figure 3E).

Diagenetic Features

The diagenetic fabric of the Kawagarh Formation has been studied in order to find out its diagenetic setting and the effect of the diagenetic phases on the reservoir potential (Figure 4). The paragenetic sequence of diagenetic phases is based on the cross-cutting relationship. Each diagenetic fabric is discussed in detail below (Figure 5).

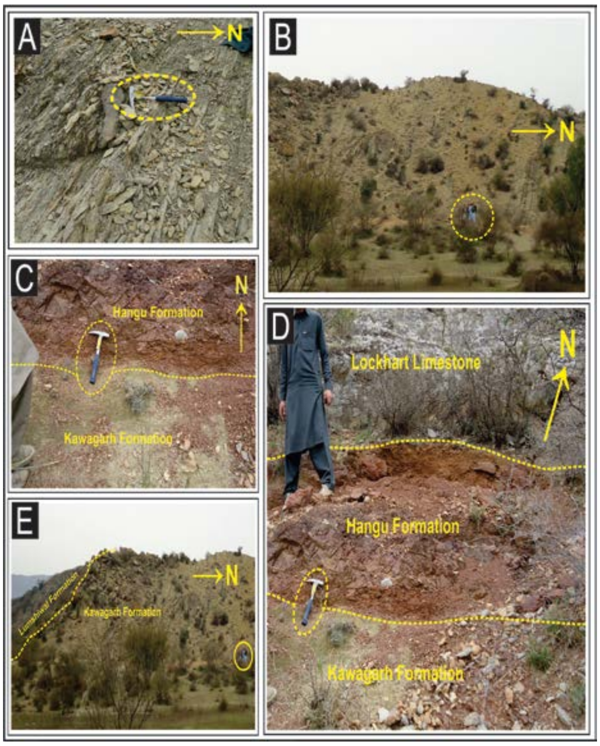

Fig. 3 Outcrop photographs: (**A**) Thin bedded carbonates of the Kawagarh Formation, (**B**) Outcrop of the Kawagarh Formation, (**C**) Contact between the Hangu and Kawagarh Formation, (**D**) Contacts of Kawagarh, Hangu and Lockhart formations, (**E**) Contact between the Lumshiwal and Kawagarh formations.

Cementation

Cementation basically occur in the marine diagenetic environment (Early stage of diagenesis) that reflects the state of $CaCO_3$ saturation (Ehrenberg et al., 2012) where loose particles become compacted through the infilling of the cementing materials in the pore spaces between the particles (McLane, 1995; Bathrust, 1982). In the Kawagarh Formation, sparry and blocky calcite cement is recognized as cementing material which is the product of early-late stage of diagenesis (Figure 6A, 6C, 6E & 6H). Cementation in Kawagarh Formation occurred in different forms. At places the fracture has been later on filled with sparry calcite cement (Figure 6A). Similarly the blocky cement observed in the rock unit has mostly occupied the fracture zone and dissolution cavities (Figure 6H).

Sparitization

Folk (1959) introduced the term “Micro-spar” for the fine-grained size inorganic calcite crystal, grain size ranging between 4 to 30µm (mostly 5-15µm). Petrographically, it is frequently recorded in most of the part of the Kawagarh Formation (Figure 6C).

Neomorphism

Neomorphism is used to describe replacement and recrystallization processes (Tucker, 2001). Meteoric diagenetic setting, with sluggish water through super saturation of $CaCO_3$ shows this type of diagenetic alterations (Heckle, 1983). Petrographically, aggrading neomorphism was recognized in carbonates of the Kawagarh Formation (Figure 6B).

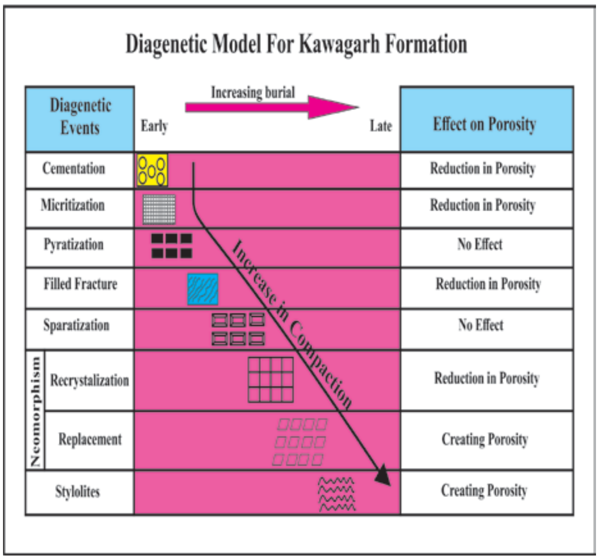

Fig. 4 The Diagenetic model of the Kawagarh Formation of KCR and its effects on reservoir potentiality.

Pyritization

The term pyritization refers to the process of the formation of crystals of pyrite. Generally, the pyrite is formed under reducing conditions, probably promoted during the decay of organic matter, which in turn is induced by anaerobic bacteria or solution of sulphate by reducing bacteria (Hudson, 1982). Petrographically, the very fine black grains are recognized as pyrite crystals which exhibit cubic and euhedral crystal shape (Figure 6C).

Fractures

The term fracture is generally used for the naturally occurring planner discontinuity in the rock due to deformation or physical diagenesis (Nelson, 2001). Petrographically, filled fractures were recognized. Fracturing in the thin section is observed frequently, though most are filled with calcite (veins) which decrease porosity and permeability while some of them are unfilled which increase the reservoir characteristic. The filling of these fractures have been occurred during late burial stage. Some fractures have cross-cut the allochems and other fractures, indicating multiple phases of fracturing (Figure 6A & 6G).

Micritization

Few fossils and bioclasts show micritization process in Kawagarh Formation. Petrographically, micritization is frequently noticed in carbonates of the Kawagarh Formation (Figure 6D). At places the micrite envelopes form while at some places dominantly the whole bioclast has been micritized which shows intense micritization of the rock unit.

Stylolites

According to Buxton and Duncan (1981), stylolites are the product of physiochemical process induced by the burial compaction and tectonic compression. The stylolites in the Kawagarh Formation cross-cut all the diagenetic fabric and this is the final and youngest diagenetic event (Figure 6). The stylolites in the rock unit show no sign of re-activation, which demonstrates negative effect on permeability of the rock unit. Various modes of stylolites are recognized in the Kawagarh Formation. At places the stylolites occur parallel to each other showing the same phase of burial stage (Figure 6F) while at some other places, the stylolites pattern exhibit the cross cut relationship depicting changes/various repeated stages in the burial stage of diagenesis of carbonates (Figure 6G & 6H).

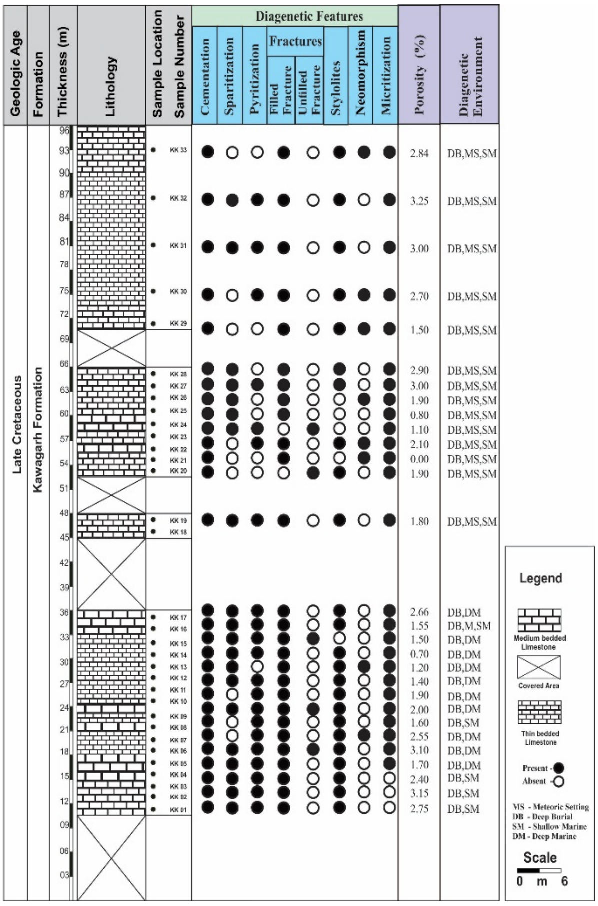

Fig. 5 Showing Diagenetic features, porosity and diagenetic environment of the Kawagarh Formation, KCR.

Diagenetic Environments and Paragenetic Sequence

Diagenetic processes in three diagenetic environments have modified the carbonates of the Kawagarh Formation. The first diagenetic environment is marine environment (Figure 7). After the deposition, the cementation occurred at the early stage of marine diagenesis, as all the allochems in the rock unit are well cemented. Micritization of the allochems as a result of the activity of algae or as a result of mechanical disintegration (El Ghar and Hussein, 2005), bacteria and fungi have taken place in the early stage of the diagenesis on the sea floor. At first, micrite envelope formed around the allochems and then all the allochems are replaced with micrite.

The second diagenetic environment is meteoric diagenesis. During the deposition of the Kawagarh Formation, regression had taken place and as a result, the formation is affected by meteoric diagenesis. Dissolution as a result of undersaturated meteoric water affected the carbonate rocks of this formation and formed vuggy porosity (Tavakoli et al., 2011). After the formation of vuggy porosity, coarse sparry calcite cement precipitated and reduced some of the vuggy porosity.

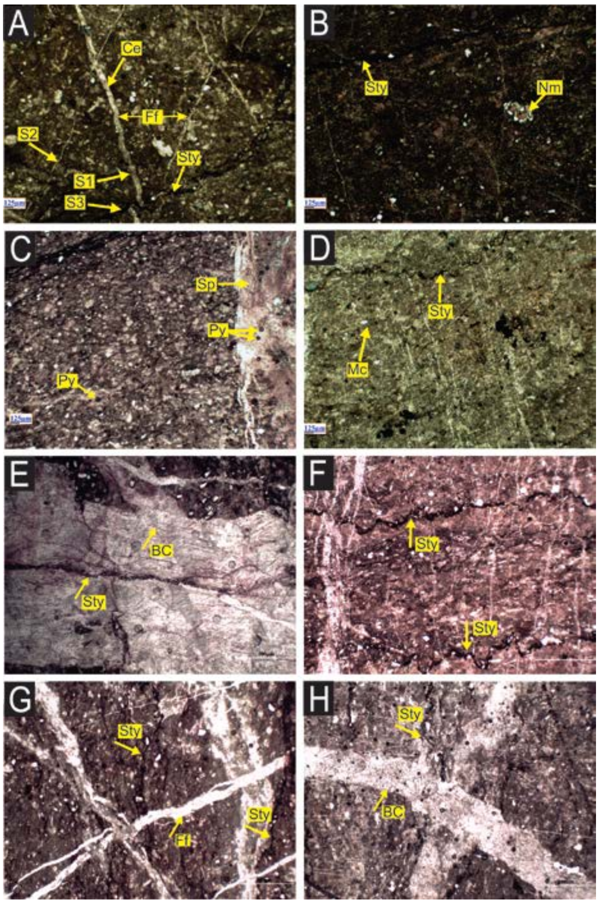

Fig. 6 Showing Photomicrographs of the selected diagenetic features of the Kawagarh Formation, Cementation (CM), filled fracture (FF), Stylolite (ST), Neomorphism (NM), Micritization (MC), Sparitization (SP), Blocky cement (BC), Pyritization (PY). S1, S2 and S3 showing different stages of diagenetic events.

The third diagenetic environment is burial diagenesis. In the burial environment, different diagenetic processes have affected the formation. These processes include compaction, fracturing, sparry calcite and blocky cement precipitation. The burial realms can be divided into shallow and deep burial; however, the boundary is not defined (Flugel, 2013). In shallow burial environment, overburden pressure caused to form tight fabric and shell breakage. By increasing the depth of burial, stylolites have been formed. Fracturing also formed under the pressure in this environment.

Calcite cement was precipitated in the vugs and fractures therefore clogged the voids. The most probable source of the calcite cement is the materials formed as a result of dissolution of carbonates in meteoric environments. Neomorphism of some of the aragonitic allochems to calcite, replacement and formation of pyrite happened in this environment because pyritization occurs at early burial stages (Larsen and Chilingar, 1983). Pyrites are abundantly present in the Kawagarh Formation. Stylolite is formed at the time of burial or due to the tectonic compaction (Buxton and Duncan, 1981). From petrographic observation, it is noted that it is post diagenetic feature as it cross-cuts all fabrics.

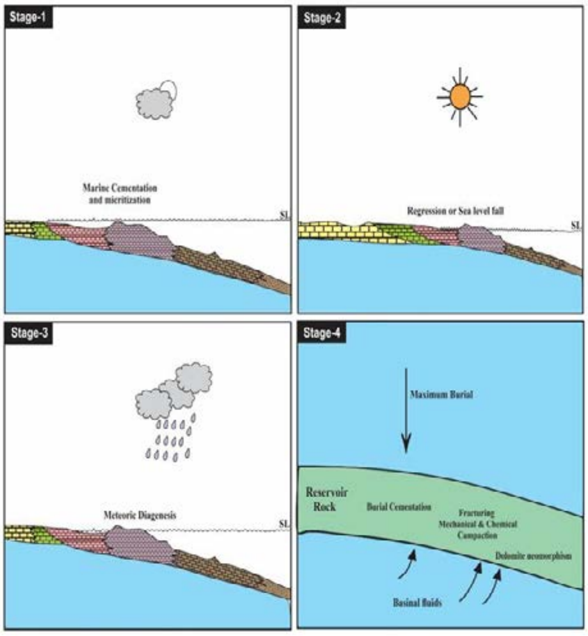

Fig. 7 The Diagenetic model for the Kawagarh Formation of Kala-Chitta Range has four stages (1) Marine (2) regression or sea level fall (3) meteoric and (4) burial digenesis.

Reservoir Characterization

In the present study, the reservoir characterization of carbonates of the Kawagarh Formation is based on the thin section/visual porosity analysis and diagenetic features**.** Mostly vuggy, fracture porosity and stylolitic porosity (Figure 8E) were noted in different thin sections. The recorded stylolitic and vuggy porosity is 3.88%. The average recorded stylolitic porosity is 2.80%. At some part, the porosity increases because of less or negligible cementation. Generally the whole porosity of the formation is supported by vuggy porosity. According to Roehl and Choquette (2012), fracturing may add significant permeability, but it is often unclear how much actual porosity is gained during the fracturing of carbonate reservoir rocks because of the difficulty in measuring this type of porosity. Still, there can be little doubt concerning the benefits that fractures can bring to ultimate reservoir production (Moore & Wade, 2013). Likewise, as the fractures are not connected, therefore the rock unit may not exhibit effective permeability. The stylolites also do not describe the re-activation process that again negatively affected the permeability of the rock unit. Cementation, micritization, neomorphism, cement/matrix filled fracture, pyritization, sparitization and stylolites were recognized as diagenetic features in the studied section. Some diagenetic processes, such as cementation and physical compaction, have negative effects on reservoir quality (Wadood et al. 2019). Sparry calcites and micrite mud cements filled the pore fractures and resulted in a reduction of pore space. Micritization, pyritization and neomorphism are different noticeable diagenetic features which have negligible effect on reservoir quality while stylolite act as storage and conduit for hydrocarbon passage which enhancing reservoir quality. The Kawagarh Formation passes from marine, meteoric and to deep burial diagenetic phases, during these stages the reservoir potential of the formation is highly disturbed and redistributed. In many phases, the porosity reduced while at some stages the porosity also increased. Overall, the Kawagarh Formation has poor reservoir potential and is heterogeneous in terms of reservoir properties (porosity).

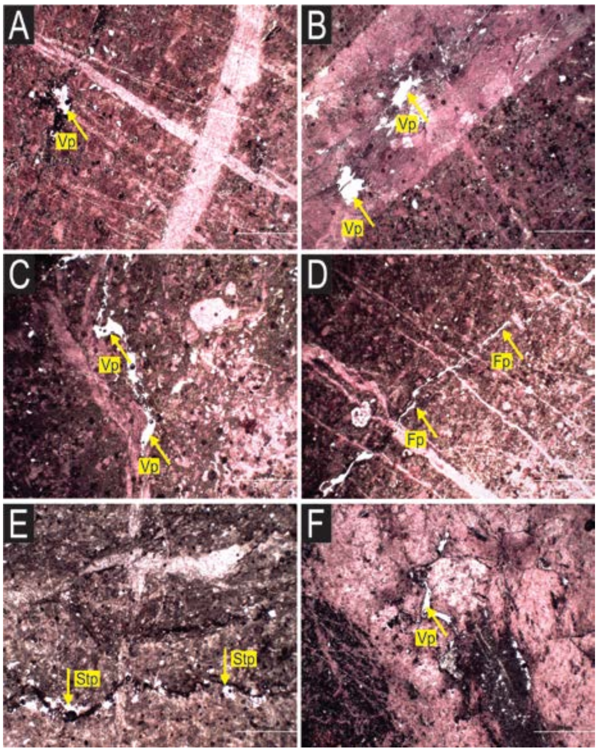

Fig. 8 Photomicrographs of the selected porosity types of the Kawagarh Formation, KCR. Vuggy Porosity (VP), Fracture porosity (Fp) and Stylolitic porosity (STP).

Conclusion

The Kawagarh Formation is comprised of thin to medium bedded, highly fractured, hard, argillaceous limestone.

The diagenetic processes, noticed in the Kawagarh Formation, includes micritization, cementation stylolitization, fracturing, neomorphism, sparitization and pyritization.

The diagenetic environment of the carbonates includes marine, meteoric and burial diagenetic settings. Micritization occurred in marine diagenetic conditions. Dissolution and sparry calcite precipitation took place in meteoric while the compaction, blocky cementation and fracturing occurred in burial diagenetic conditions.

These diagenetic processes have greatly affected the reservoir potential of the rock unit. Based on the present study, Kawagarh Formation is interpreted as poor quality reservoir rock.

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