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Implication of the diagenetic evolution for the diagnosis of reservoir potential of the Amb Formation, western Salt Range, Pakistan

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Abstract

The diagenetic fabric of the Amb Formation in the western Salt Rang, Pakistan is presented as a tool for understanding its diagenetic potential. Three key stratigraphic sections, namely, Zaluch Nala, Ghundai Nala and Kalawahan Nala that represent outcrop exposure of 50.1m, 16.5m and 30.5m respectively, were taken into account. A total of 58 siliciclastic-carbonate rock samples were processed from these three key stratigrahic sections. The facies analysis revealed that deposition of the Amb Formation occurred in the siliciclastic dominated shelf platform, evident from facies AMB 1-AMB 5. These facies revealed the signs of diagenetic alteration caused by the micritization, dissolution, cementation, pyritization, recrystallization, physical and chemical compaction, and fracturing. Identifications of different cement types helped to categorize different phases of digenesis as early marine, shallow burial and deep burial, which in turn helped in the hydrocarbon reservoir potential within each facies e.g. the AMB 1 and AMB 2 have a fair porosity while the AMB 3A, AMB 3B and AMB 4 have poor porosity. The AMB 5 has good porosity. These porosities fluctuated within studied sections and are different from the Kalawahan Section: AMB 1, AMB 2, AMB 3A, AMB 3B and AMB 4 which have poor porosity and Ghundai Nala: AMB 1 and AMB 3A are absent, AMB 3B has fair porosity, AMB 4 has poor porosity.

Keywords: Amb Formation; Late Permian; Siliciclastic-carbonate lithofacies; Western Salt Range; Pakistan.

1. Introduction

The Salt Range, a one of the most extensively researched area, is located in the Upper Indus Basin of Pakistan. The Salt Range is bounded to the north by Potwar Plateau, south by SRT (Salt Range Thrust), east by Jhelum River and to the west by Indus River (Kazmi and Rana, 1982; Jaswal et al., 1997; Fig. 1). The stratigraphic succession of the Salt Range ranges from Pre-Cambrian to Eocene (Fatmi, 1973; Fig. 2), which includes Amb Formation of Late-Permian. The Amb Formation of the Salt Range comprises of siliciclastic-carbonate mixed lithofacies (Shah, 1977).

Previously, the Amb Formation is discussed by various authors in terms of lithology (e.g., Fatmi, 1974; Waagen, 1889-91; Wardlaw and Pogue, 1995) that consists of sandy limestone, sandstone, and shales, having thickness of 47-88 m. The biostratigraphy of the Amb Formation was discussed by Pascoe (1959), Kummel and Tiechert (1970), Balme (1970), Douglas (1968), Grant (1970), P.J.R.G (Pakistan Japanese Research Group) (1985) and Mertmann (2003). The record of *Monodiexodina kattaensis*, a larger benthic foraminiferal species in the Amb Formation indicates Late-Permian (Artinskian) age (Dunbar, 1933; Teichert, 1966; Douglas, 1968). The present research is aimed to understand the diagenesis and its evolution for hydrocarbon reservoir potential of the Amb Formation in the western Salt Range, Pakistan.

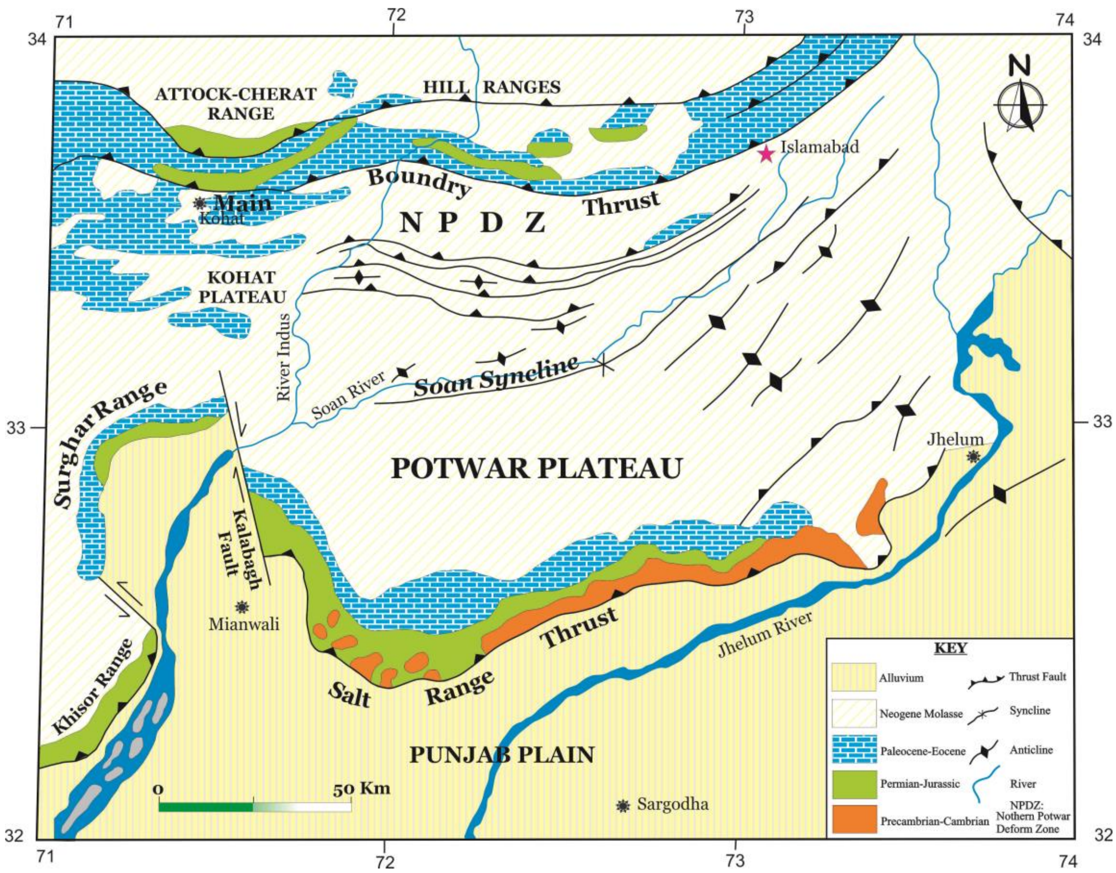


Fig. 1. Map showing the location of the Salt Range (after Kazmi and Rana, 1982; Jaswal et al., 1997).

2. Material and methods

The Amb Formation was studied at three key stratigraphic sections, namely Zaluch Nala (latitude 32°47′00″-32°47′2″ N and longitude 71°38′50″-71°38′51″ E), Ghundai Nala (latitude 32°42′7″- 32°42′8″ N and longitude 71°39′7″-71°39′6″ E) and Kalawahan (latitude 32°45′20″-32°45′20″ N and longitude 71°39′27″-71°39′26″ E). The composite field stratigraphic log of each section is prepared. In Zaluch Nala, the Amb Formation has a total measured thickness of 50.1 m (Fig. 3) and mainly comprised of sandy limestone. A total of 16 samples have been collected from the Zaluch Nala. In the Ghundai Nala, the sequence is upside down and much care is exercised while measuring the stratigraphic thickness of the Amb Formation. It is composed of yellowish coloured thick bedded to massive sandy limestone and subordinate clays. The Amb Formation is 16.5 m thick and 24 samples were taken from the Ghundai Nala (Fig. 4). In Kalawahan Nala, the measured stratigraphic thickness of the Amb Formation is 30.5 m (Fig. 5) that constitute medium to thick bedded, yellowish grey sandy limestone with subordinate greenish clays. A total of 18 samples were taken from Kalawahan Nala. A total of 58 rock samples were collected from these three key stratigraphic sections. The samples collected from the outcrop are subjected to the lab for thin sectioning. Thin sections were prepared and classified into six microfacies based on field and petrographic observation as AMB 1: Thick bedded sandy fusulinid packstone microfacies, AMB 2: Medium bedded bioturbated sandy wacke-packstone microfacies, AMB 3A: Bryozoans rich packtone facies, AMB 3B: Diverse bioclastic wackestone facies, AMB 4: Mud-wackestone microfacies interbedded with organic rich clays, AMB 5: Medium bedded quartz arenite microfacies, according to Dunham (1962) for carbonate and Pettijohn et al. (1987) for siliciclastic rocks, respectively. The present study is focused on the diagenetic evolution of the Amb Formation and its effect on reservoir potential.

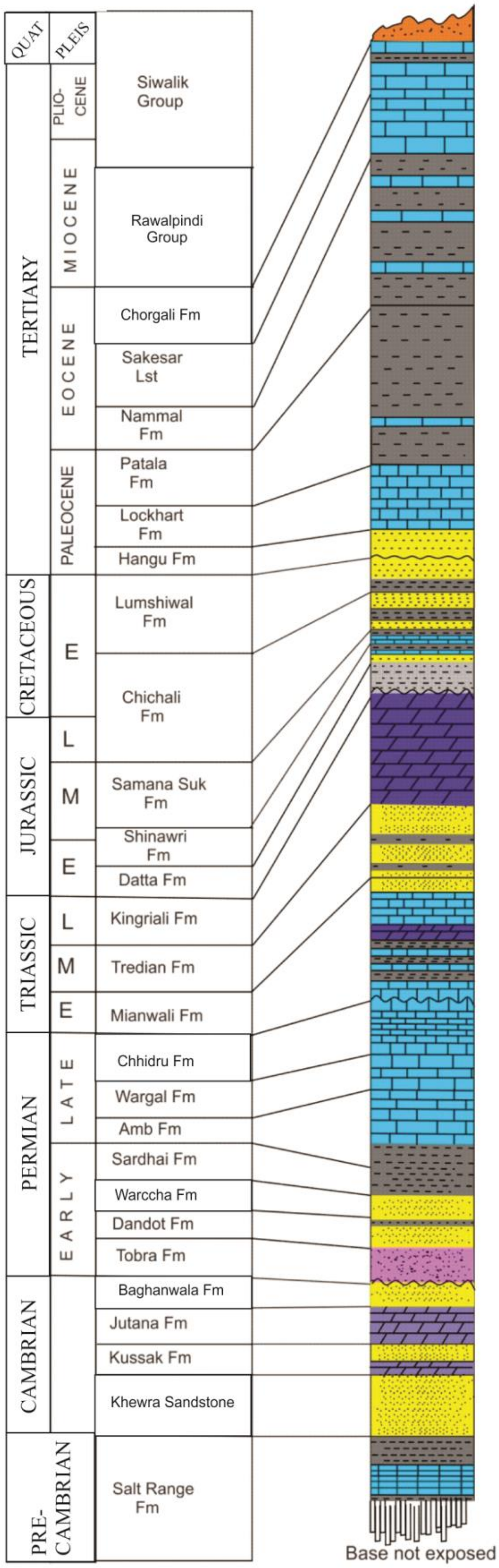


Fig. 2. Generalized stratigraphic Column of Salt Range (Fatmi, 1973).

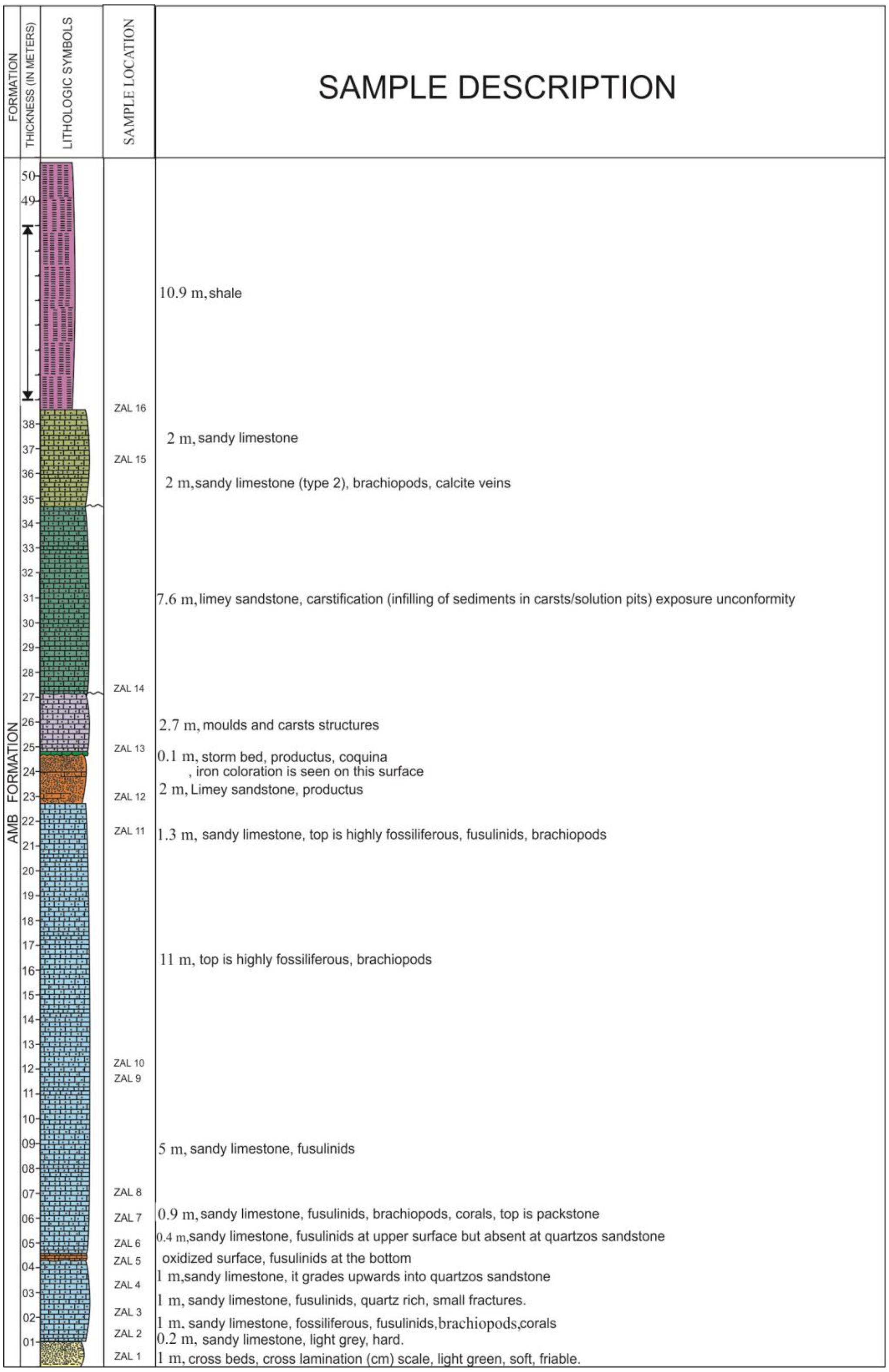


Fig. 3. Composite Stratigraphic log of the Amb Formation exposed in the Zaluch Nala Section, Salt Range, Pakistan

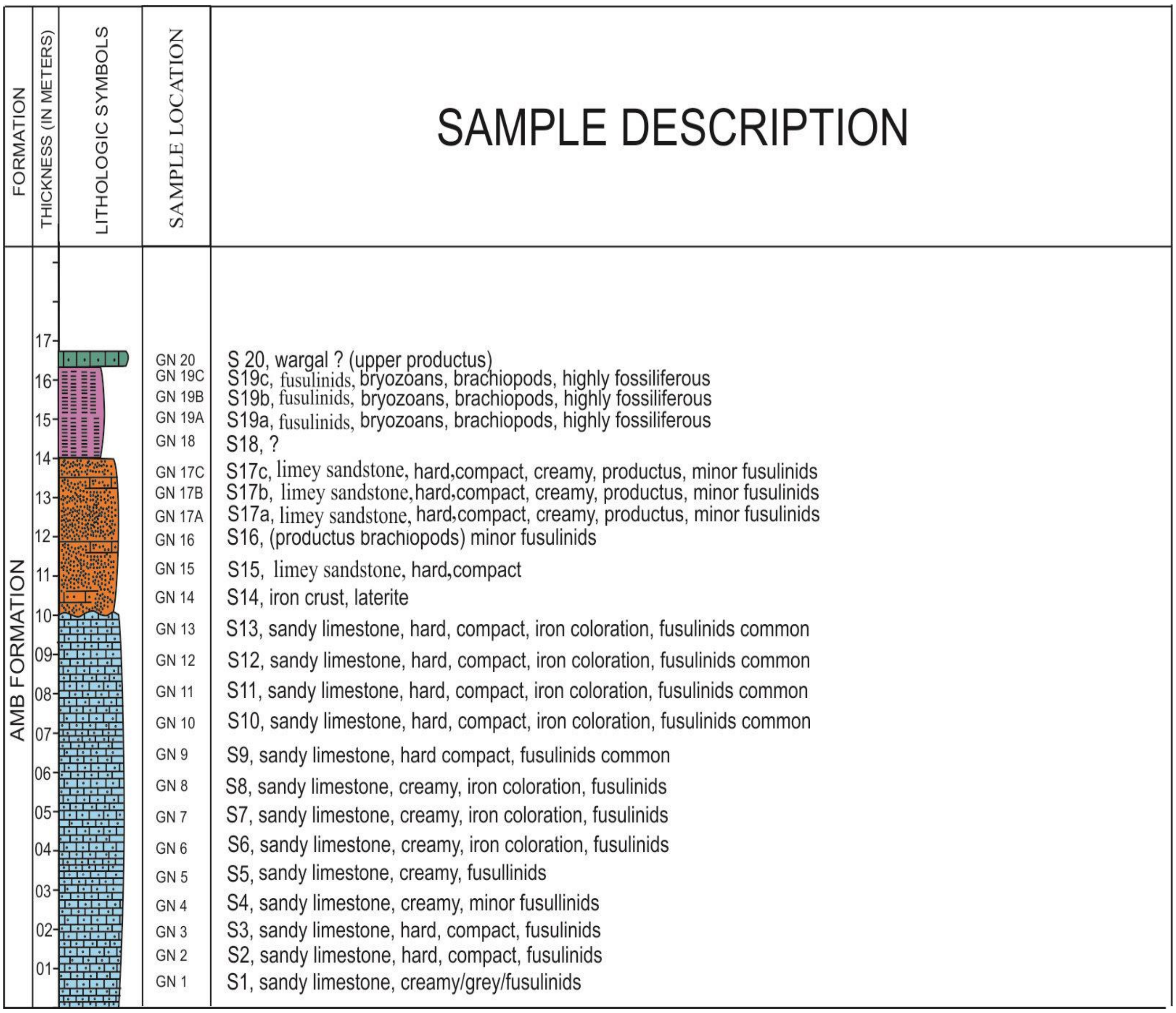


Fig. 4. Composite Stratigraphic log of the Amb Formation exposed in Ghundai Nala Section, Salt Range, Pakistan

3. Results

3.1. Diagenetic fabric

Diagenesis incorporates all the physical, chemical and biological processes that affect the sedimentary rocks before the threshold of metamorphism (Tucker and Wright, 1990). Understanding these processes have high economic importance, because diagenetic criteria account for many of the petrophysical properties of the carbonate rocks and determine its reservoir potential (Flügel, 1982). Major diagenetic processes affecting the Amb Formation are the micritization, dissolution, cementation, pyritization, recrystallization, physical and chemical compaction, and fracturing.

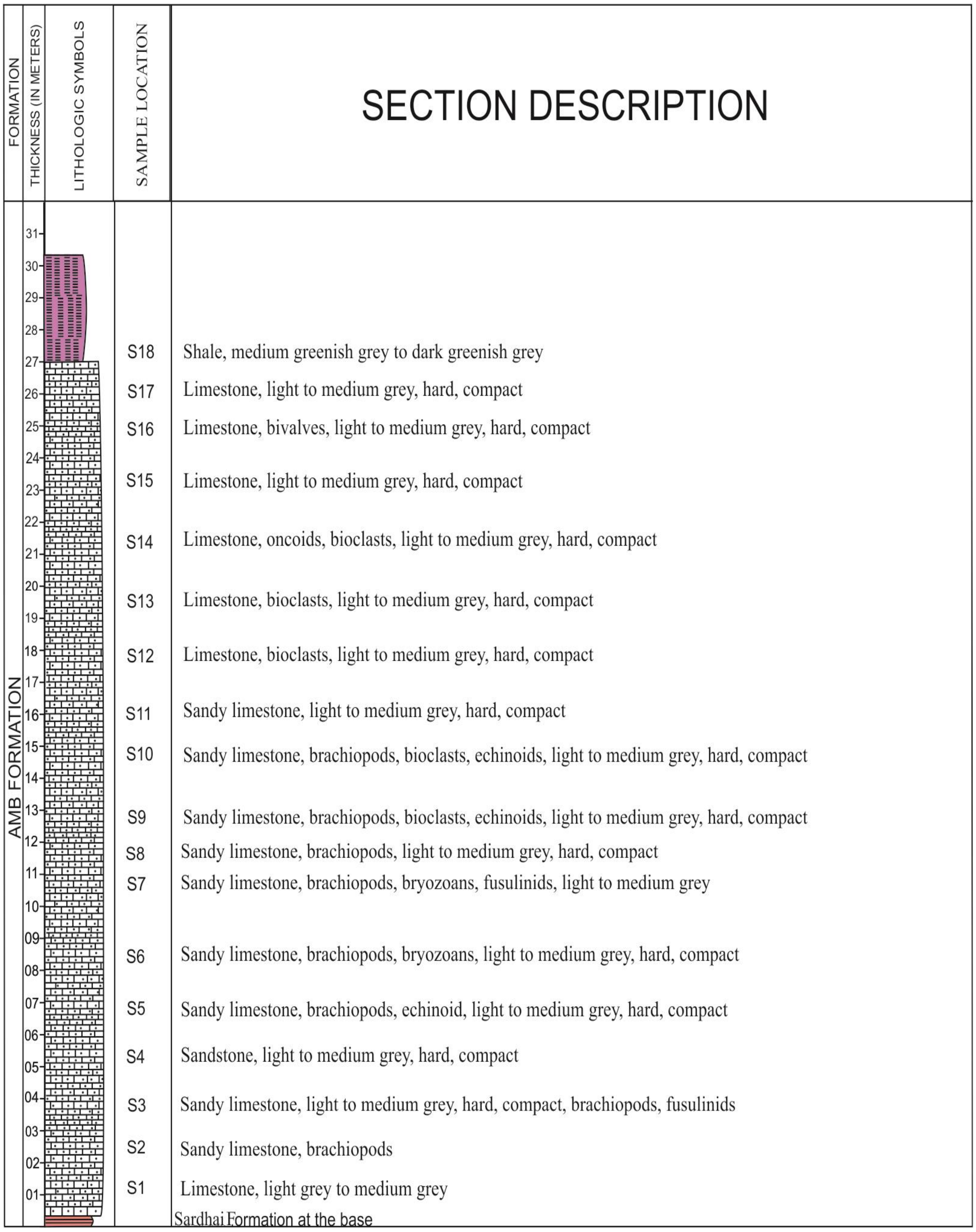


Fig. 5. Composite Stratigraphic log of the Amb Formation exposed in the Kalawahan Section, Salt Range, Pakistan

3.1.1. Micritization

Micritization is caused by endolithic algae and usually occur within the photic zone of the shallow marine setting (Tucker and Wright, 1990). Micritization is not very common but is observed in the AMB 1, AMB 2, AMB 3B and AMB 4 facies (Plate 6A-D).

3.1.2. Dissolution

Most of the grains have undergone dissolution and reprecipitation in the voids. Dissolution of carbonate rocks occur as a result of undersaturation of pore fluid that lead to dissolution of metastable carbonate grains and cement (aragonite/high-magnesium calcite; Flügel, 2004). This process may take place soon after the deposition or much later when rock is uplifted (Tucker and Wright, 1990). Dissolution has been identified in AMB 1 and AMB 2 facies (Plate 4B and 4D).

3.1.3. Cementation

a) Granular cement

This type of cement is characterized by equidimentional calcite grains that precipitate in the interparticles pores, generally without any substrate control (Flügel, 1982, 2004). This type of cement is usually formed in meteoric-vadose, meteoric-phreatic and burial environments (Flügel, 1982). Granular cement has been identified in AMB 1 facies (Plate 1A).

b) Fibrous cement

This type of cement is characterized by fibrous calcite crystal that grows normal to substrate (Flügel, 1982, 2004). They are predominantly high-Mg calcite and aragonite. Fibrous cement is found in marine-phreatic, meteoric vadose and marine-vadose environments (Flügel, 1982, 2004). This type of cement has been identified in AMB 1, AMB 2, AMB 3A and B and AMB 4 facies (Plate 1B, 1D, 3A and 3D).

c) Acicular cement

This type of cement is predominantly composed of aragonite and high-Mg calcite and have needle shaped crystals. This type of cement is found in marine phreatic environment (Flügel, 1982, 2004). Acicular cement has been identified in AMB 1, AMB 2, AMB 3A and B and AMB 4 facies (Plate 1C, 2A, 3B and 3C).

d) Syntaxial overgrowth cement

This type of overgrowth cement is characterized by calcite cement formed around the echinoderms fragments as overgrowth in optical continuity, and is formed in near-surface marine, vadose marine and meteoric-phreatic environments (Flügel, 1982, 2004). This type of cement has been identified in AMB 2, AMB 3A and AMB 4 facies (Plate 2B, 2D and 4A).

3.1.4. Pyrite precipitation

Pyrite is the most abundant iron sulfide mineral that occur in carbonate sediments. It is an isometric mineral that occurs in various forms i.e. cubic, pyritohedral and octahedral. It also occurs as formboids or sphere composed of aggregate minute crystals. Pyrite forms in reducing environments provided the source of iron and sulfur exist (Scholle and Ulmer-Scholle, 2003).

In the Amb Formation, two phases of pyrite precipitation are recognized in all the microfacies. The first phase represents an early stage of diagenesis because they are mainly associated with bioclasts i.e. fusilinids and bryozoan colonies. The second phase represents a deep burial phase of diagenesis and hence formed much later. They are mainly present along sutured seams and along stylolites (Plate 4C, 5A-5D).

3.1.5. Recrystallization

Recrystallization is characterized by change in the size, shape, arrangement of crystals without change in mineralogy and obliteration of original crystals. It depends on clay content and can create microspar and pseudospar (Flügel, 2004). It happens either in early marine diagenesis or later in deep burial diagenesis (Tucker and Wright, 1990). In case of the Amb Formation, recrystallization is common and in most cases the matrix has been sporadically recrystallized. In some facies the bioclasts are also recrystallized. It has been recognized in AMB 1, AMB 2, AMB 3B and AMB4 facies (Plate 2C).

3.1.6. Physical compaction and pressure solution

Physical compaction takes place as a result of tectonic stresses and overburden pressure in pre and post cementation phases. It reduces thickness of sediments, porosity, permeability and leads to breakage and distortion of grains and produces compressed fabrics (Flügel, 1982, 2004). In Amb Formation the effects of physical compaction are identified by the presences of fractures and physically deformed quartz crystals (Plate 7C, 9B, 8B and 10B).

Chemical compaction is also known as pressure-solution phenomena. It starts at various depths of overburden and/or tectonic stresses (Tucker and Wright, 1990). It causes to reduce thickness of sediments, porosity and permeability. Chemical compaction is expressed by formation of stylolites and other pressure solution seams (Flügel, 2004). Stylolites have been recognized in all the facies (Plate 7A, 7D, 8D, 9A and 9D).

3.1.7. Fracturing

Fractures are commonly found at various horizons and represent a late diagenetic phase. In all the cases these fractures have been filled by calcite, which is indicative of burial diagenesis. In case of the Amb Formation, calcite filled fractures have been identified in the AMB 1, AMB 2, AMB 3A and 3B and AMB 4 facies (Plate 7B, 8A, 8C, 9C and 10A).

4. Discussion

4.1. Reconstruction of the diagenetic history

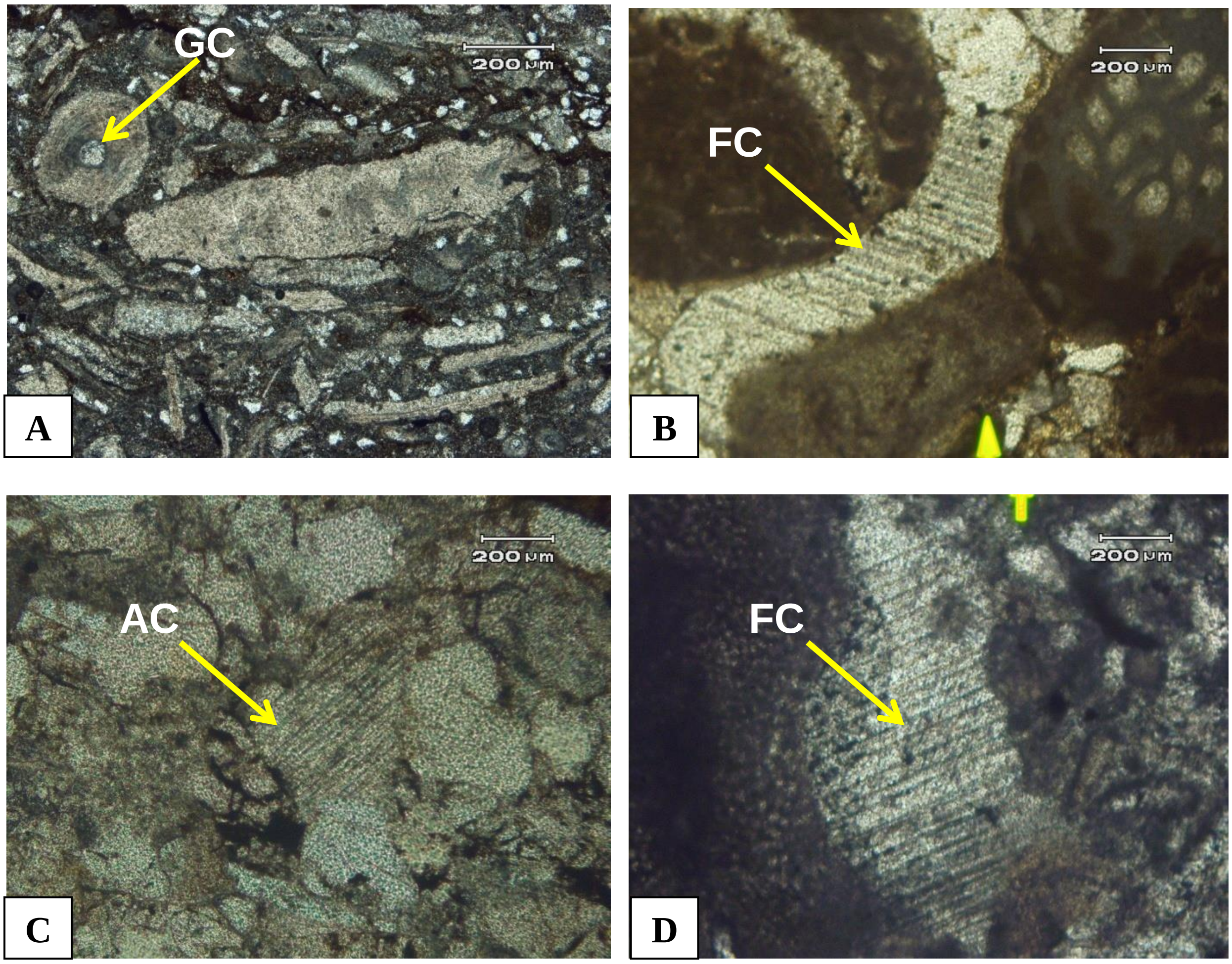
Detailed petrographic work for diagenetic fabric helped in the reconstruction of the diagenetic history of the Amb Formation. Different diagenetic events have been recognized in the Amb Formation in three different sections i.e. Zaluch Nala, Ghundai Nala and Kalawahan section. These different diagenetic events can be discriminated into three major stage of diagenesis, which are discussed below in detail.

4.1.1. Stage 1: Early marine diagenesis

Soon after the deposition of sediments and initial re-arrangements of the grains, microbial activity starts (Tucker and Wright, 1990) which can be identified from the rock thin section by the presence of micritic envelopes around bioclasts and some allochems. Cementation in early marine diagenesis happens because of the initial high porosity where water is replenished through the pore space and precipitation occurs (Flügel, 1982, 2004). Although, the fibrous and acicular cements can be found in other diagenetic environments (e.g., Flügel, 1982, 2004) it is placed in early marine diagenetic environment due to shape and chemistry according to Kendall and Tucker (1973), James and Choquette (1983) and Flügel (2004) along with an early stage of pyrite precipitation. The pyrite precipitation is mostly associated with bioclasts i.e. fusulinids and bryozoan colonies (Plate 4C) in the identified microfacies.

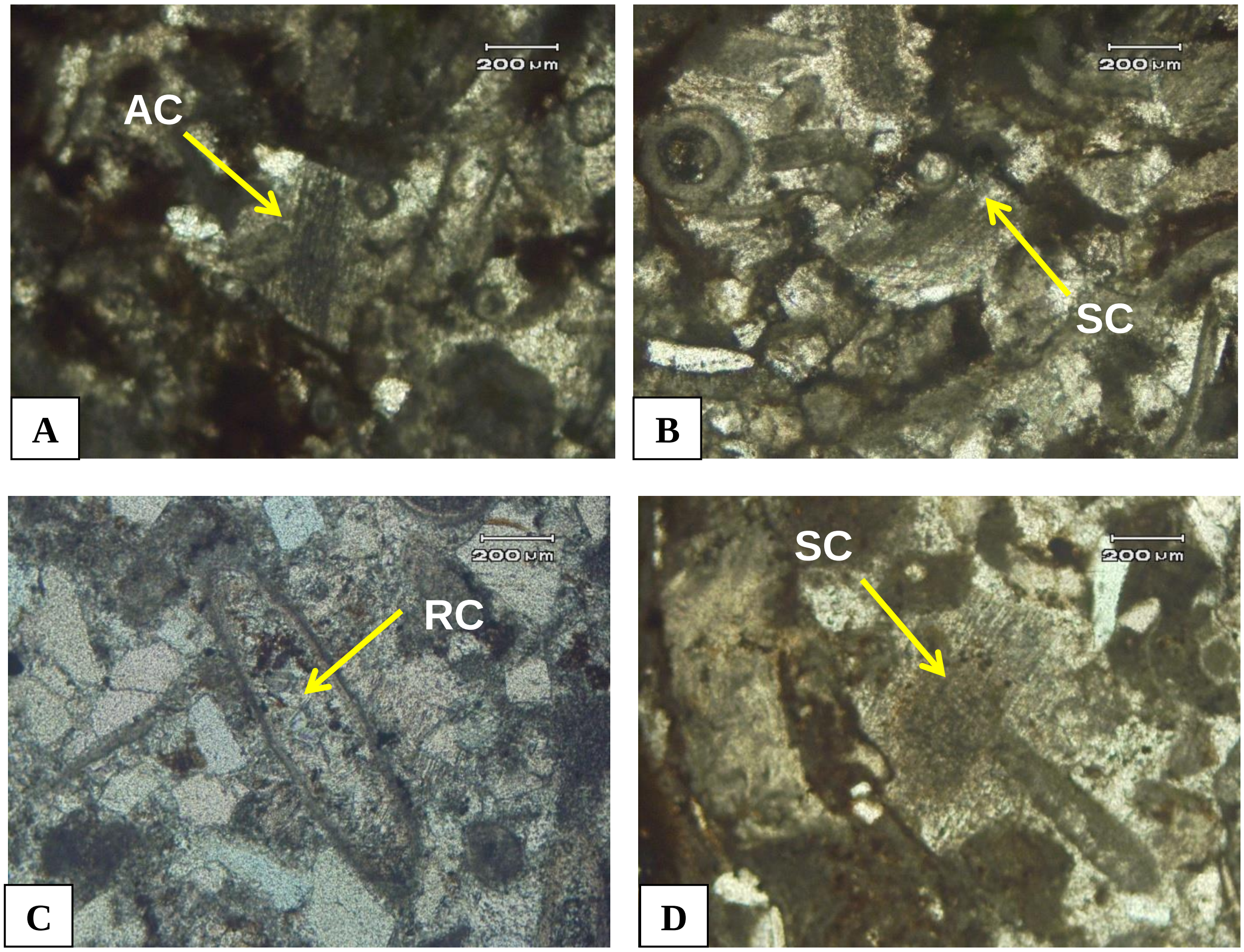
In the Zaluch Nala section, different diagenetic events like early pyrite precipitation, micrite envelopes and some early marine cement like acicular and fibrous cements are common. In case of Kalawahan section an early stage of pyrite precipitation is common throughout. There are minimum signs of microbial activity and hence mild micrite envelopes or micritization is recognized along with presence of acicular cement (early marine cement) in AMB 3A, 3B and AMB 4 microfacies (Plate 3B). While, in the Ghundai Nala both AMB 1 and AMB 3A microfacies are absent. In rest of the microfacies like AMB 2, AMB 3B and AMB 4 microfacies micrite envelopes are common. Early pyrite precipitation and cementation i.e. acicular and fibrous cements are also common.

Plate 1



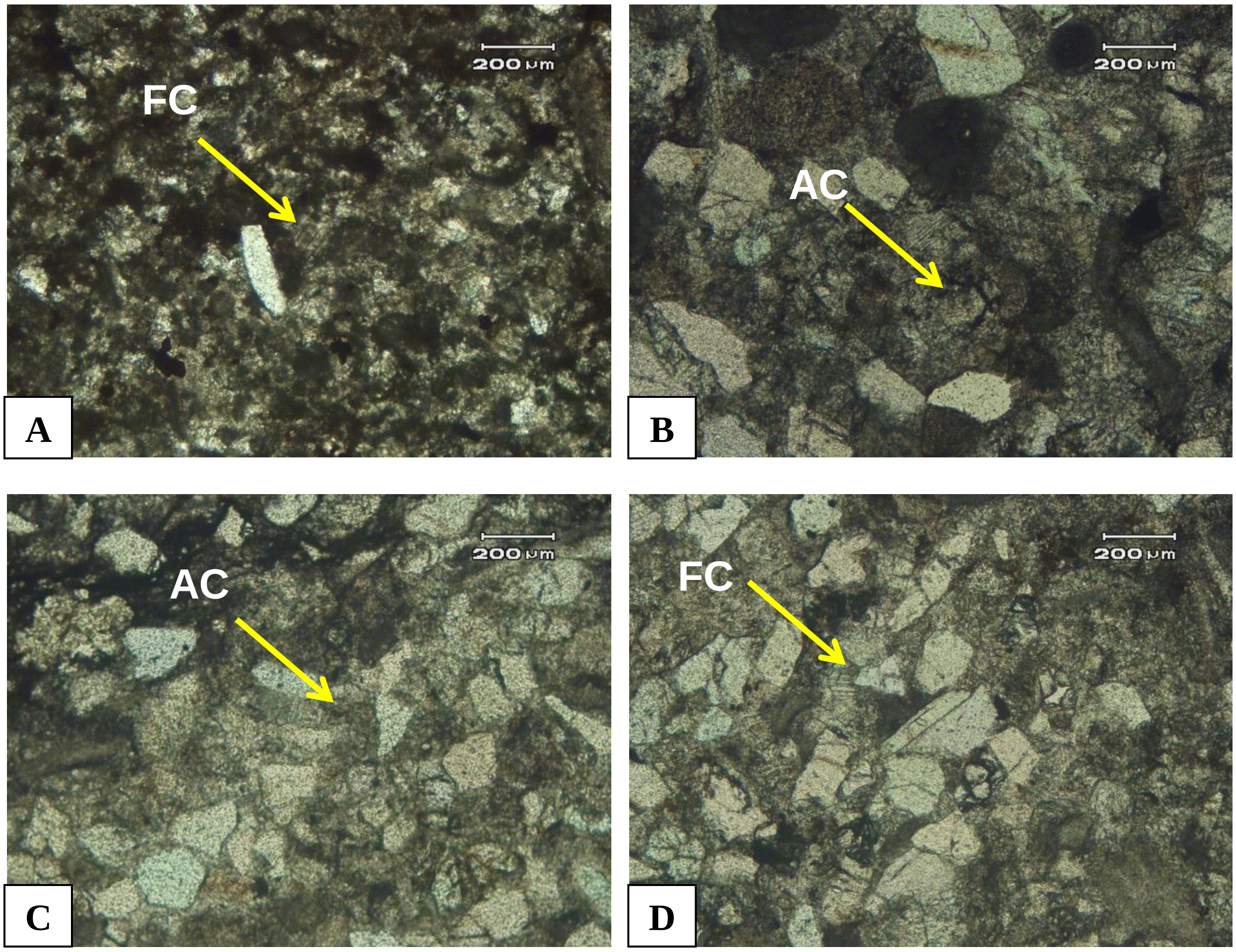
A. Photomicrograph displaying Granular cement (GC) in a brachiopod spine in the AMB 1facies.
B. Photomicrograph displaying Fibrous cement (FC) in the AMB 1 facies.
C. Photomicrograph displaying Acicular cement (AC) in the AMB 1 facies.
D. Photomicrograph displaying Fibrous cement (FC) in the AMB 2 facies.

Plate 2



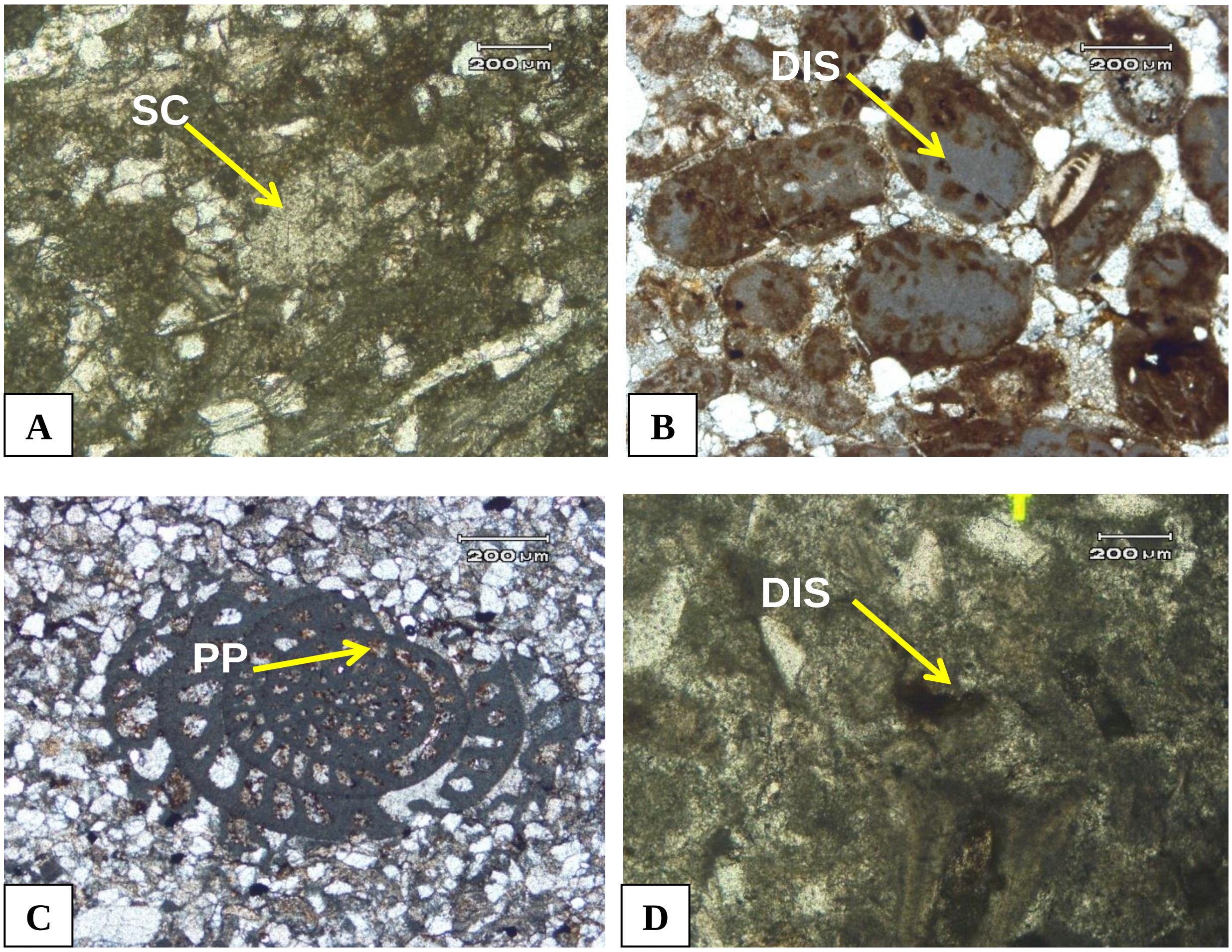
A. Photomicrograph displaying Acicular cement (AC) in the AMB 2 facies.
B. Photomicrograph displaying Syntaxial overgrowth cement (SC) in the AMB 2 facies.
C. Photomicrograph displaying recrystallized calcite cement (RC) in the AMB 2 facies.
D. Photomicrograph displaying Syntaxial overgrowth cement (SC) in the AMB 3A facies.

Plate 3



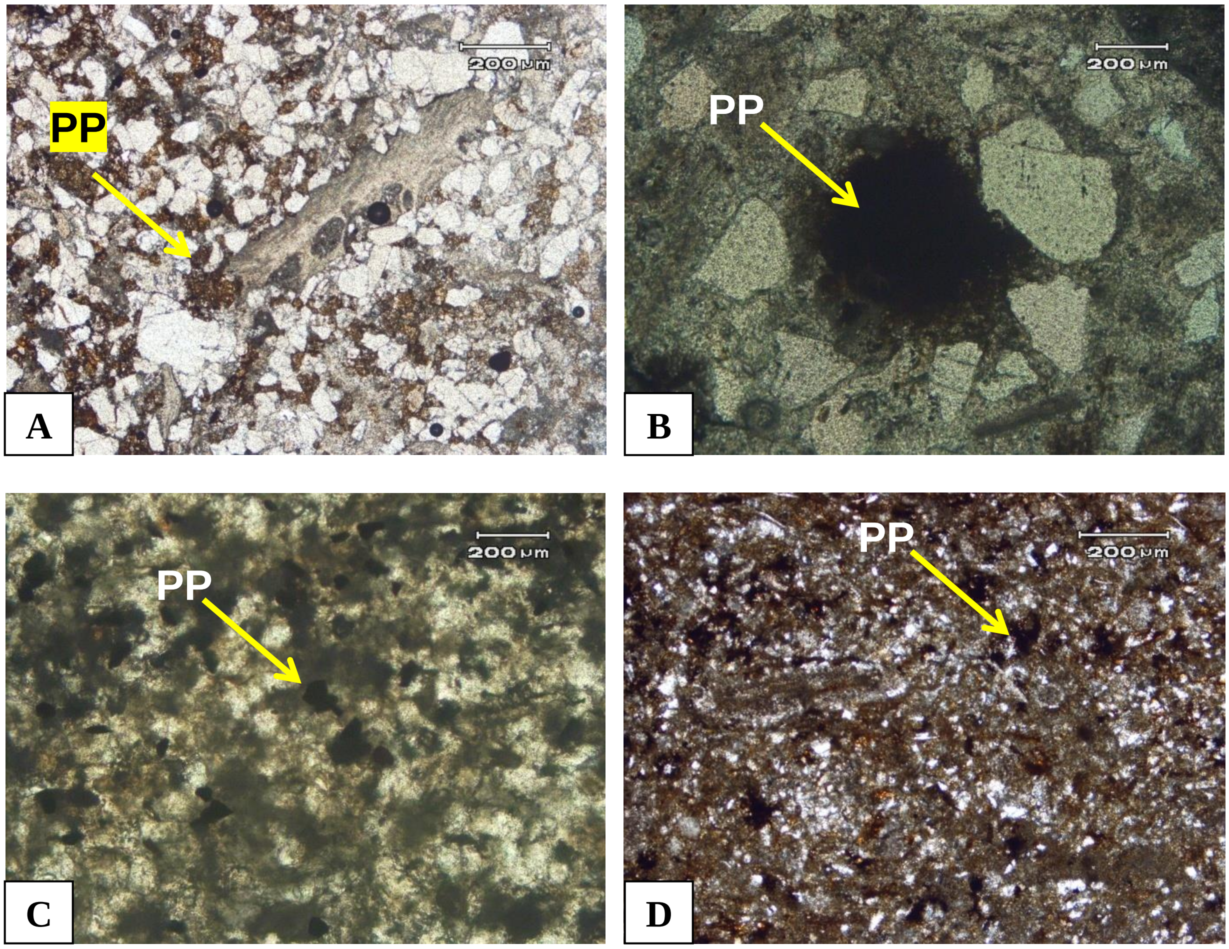
A. Photomicrograph displaying Acicular cement (AC) in the AMB 3B facies.
B. Photomicrograph displaying Fibrous cement (FC) in the AMB 3B facies.
C. Photomicrograph displaying Acicular cement (AC) in the AMB 4 facies.
D. Photomicrograph displaying Fibrous cement (FC) in the AMB 4 facies.

Plate 4



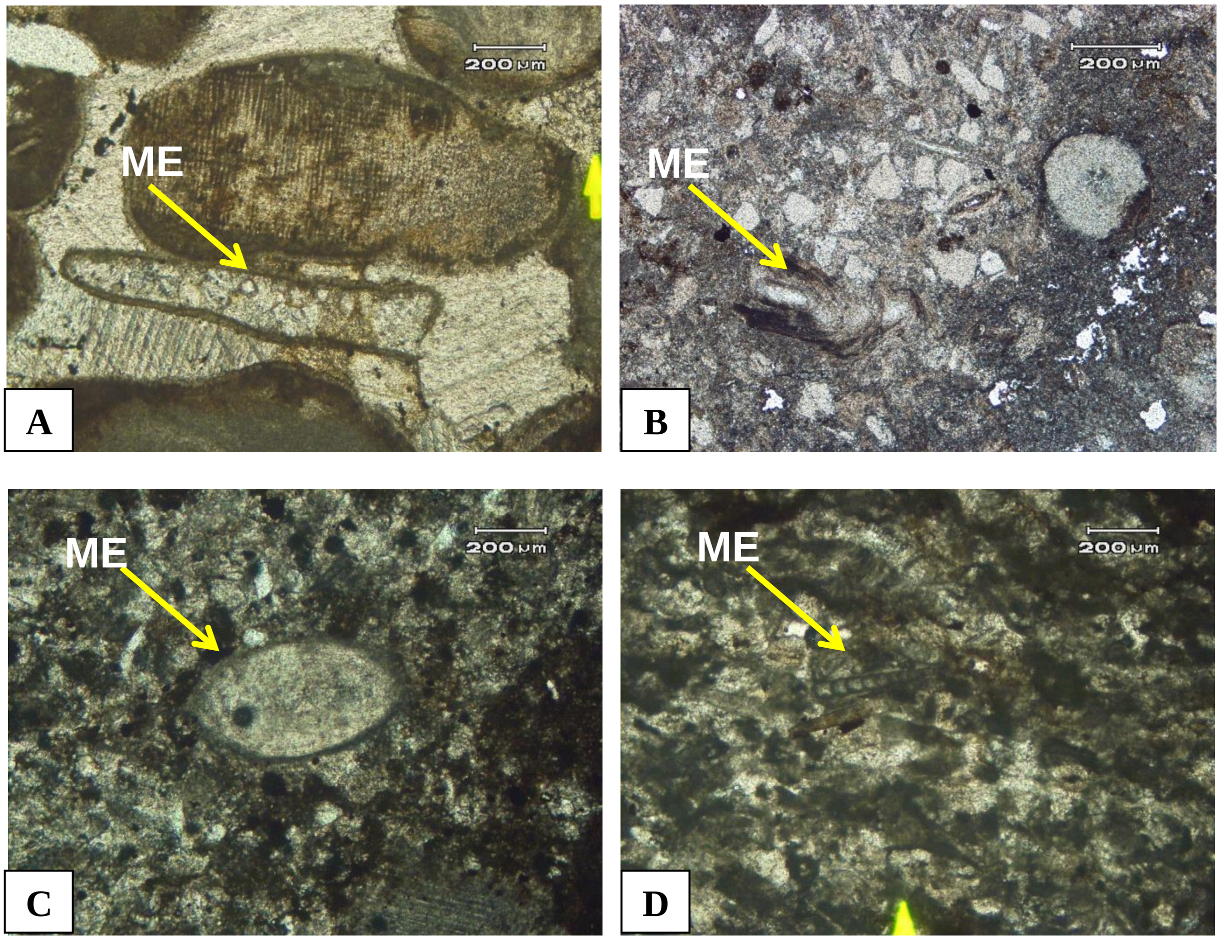
A. Photomicrograph displaying Syntaxial overgrowth cement (SC) in the AMB 4 facies.
B. Photomicrograph displaying Dissolution (DISS) phenomenon in the AMB 1 facies.
C. Photomicrograph displaying Pyrite precipitation (PP) in the AMB 1 facies.
D. Photomicrograph displaying Dissolution (DISS) phenomenon in the AMB 2 facies.

Plate 5



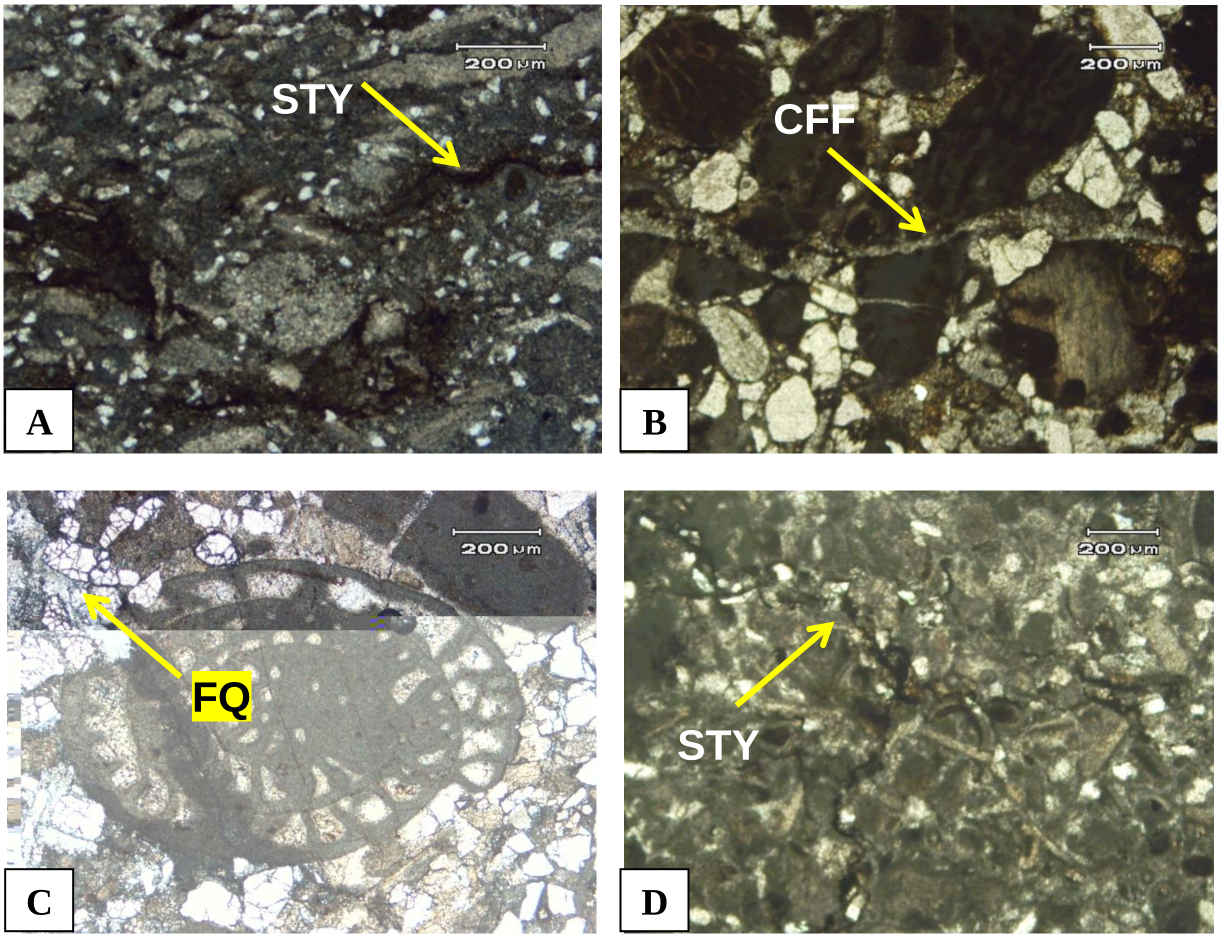
A. Photomicrograph displaying Pyrite precipitation (PP) in the AMB 2 facies.
B. Photomicrograph displaying Pyrite precipitation (PP) in the AMB 3B facies.
C. Photomicrograph displaying Pyrite precipitation (PP) in the AMB 4 facies.
D. Photomicrograph displaying Pyrite precipitation (PP) in the AMB 4 facies.

Plate 6



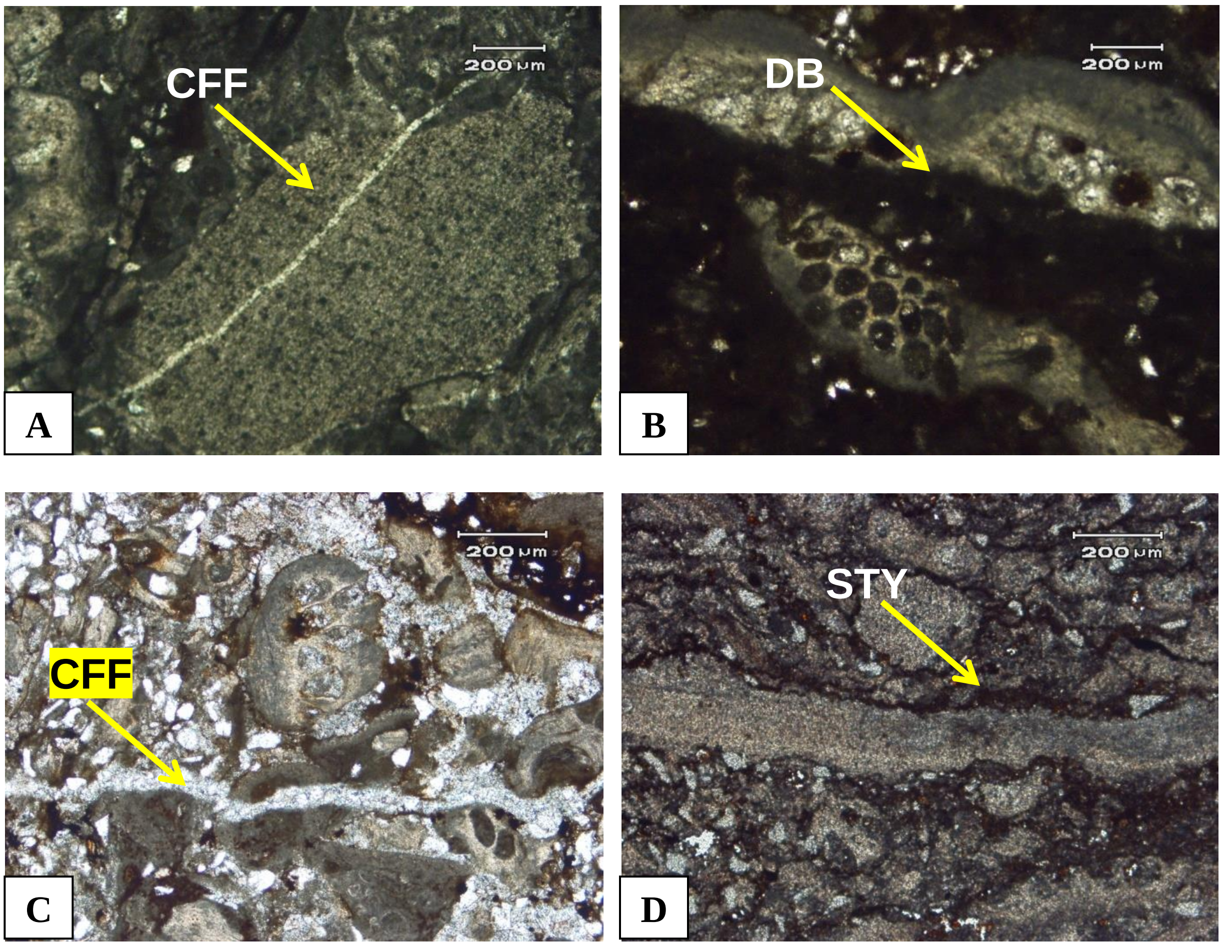
A. Photomicrograph displaying Micrite envelope (ME) in the AMB 1 facies.
B. Photomicrograph displaying Micrite envelope (ME) in the AMB 2 facies.
C. Photomicrograph displaying Micrite envelope (ME) in the AMB 3B facies.
D. Photomicrograph displaying Micrite envelope (ME) in the AMB 4 facies.

Plate 7



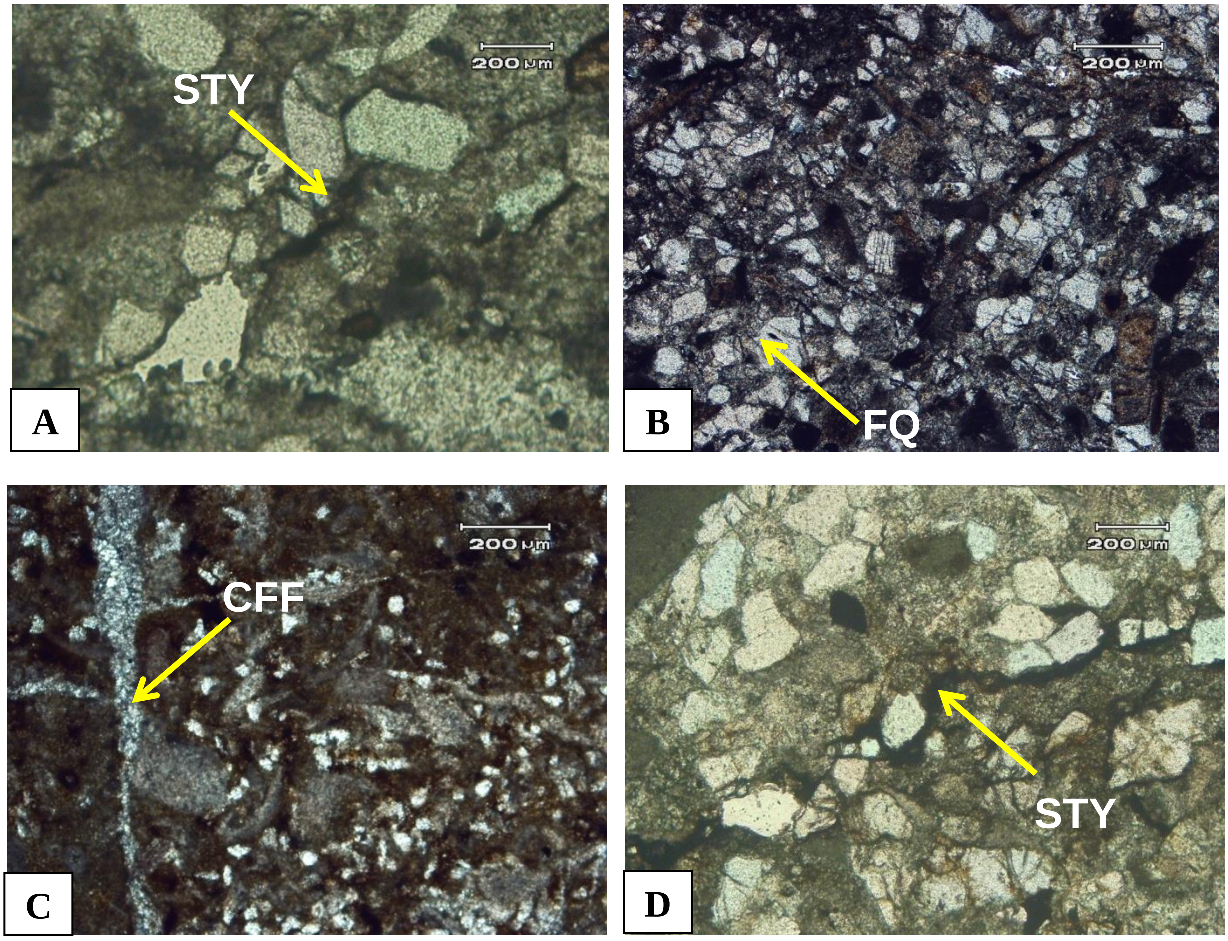
A. Photomicrograph displaying Stylolites (STY) in the AMB 1 facies.
B. Photomicrograph displaying calcite filled fractures (CFF) in the AMB 1 facies.
C. Photomicrograph displaying Fractured Quartz grains (FQ) in the AMB 1 facies.
D. Photomicrograph displaying Stylolites (STY) in the AMB 2 facies.

Plate 8



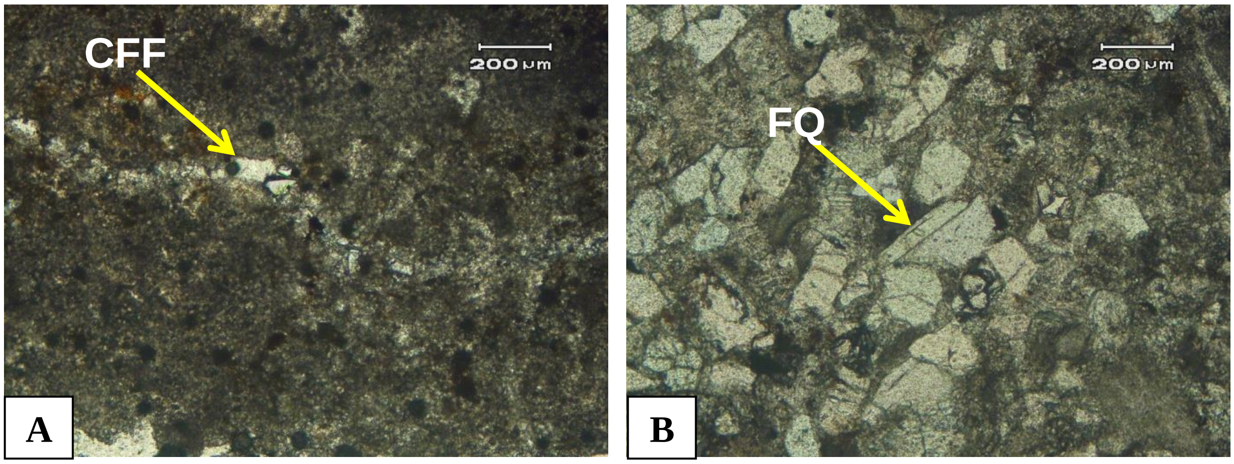
A. Photomicrograph displaying calcite filled fractures (CFF) in the AMB 2 facies.
B. Photomicrograph displaying deformed Bioclasts (DB) in the AMB 2 facies.
C. Photomicrograph displaying calcite filled fractures (CFF) in the AMB 3A facies.
D. Photomicrograph displaying Stylolites (STY) in the AMB 3A facies.

Plate 9



A. Photomicrograph displaying Stylolites (STY) in the AMB 3B facies.
B. Photomicrograph displaying Fractured Quartz grains (FQ) in the AMB 3B facies.
C. Photomicrograph displaying calcite filled fractures (CFF) in the AMB 3B facies.
D. Photomicrograph displaying Stylolites (STY) in the AMB 4 facies.

Plate 10



A. Photomicrograph displaying calcite filled fractures (CFF) in the AMB 3B facies.
B. Photomicrograph displaying Fractured Quartz grains (FQ) in the AMB 3B facies.

4.1.2. Stage 2: Shallow burial diagenesis

As the sedimentation continued, the strata were pushed down into a shallow burial diagenetic phase. The presence of pore-filling cement (granular cements) and recystallized calcite cements that are particular of shallow burial phase are identified throughout the thin sections. The Syntaxial overgrowth around echinoderm grain has also been identified (Plate 2D). According to Choquette and James (1987), and Tucker and Wright (1990) it is associated with burial diagenesis, however, can also be associated with other environments (e.g., Flügel, 1982, 2004). Physical deformations of bioclasts and quartz have also been identified in the microfacies that are also typical of shallow burial phase (Plate 7C).

In the Zaluch Nala, recystallized calcite cement and deformation of quartz grains and bioclasts are common throughout all the microfacies (Plate 7C). Granular cement and syntaxial overgrowth cement have also been identified (Plate 2D). In the Kalawahan section recrystallization of bioclasts and recrystallized calcite cement are common throughout the microfacies. Features of physical deformation are only recognized in the AMB 2 facies i.e. deformed bioclasts (Plate 2B). In the Ghundai Nala AMB 1 and AMB 3A microfacies are absent. Recrystallization of bioclasts and syntaxial overgrowth cements are recognized in the AMB 2 and AMB 4 microfacies (Plate 2D).

4.1.3. Stage 3: Deep burial diagenesis

Further overburden of the sediments pushes the strata down to hundreds of meters. At this point the rock has been lithified to such an extent where physical compaction is less affective. Instead, chemical compaction processes become operative after sufficient burial under a few hundreds of meters of sediments (Choquette and James, 1987).

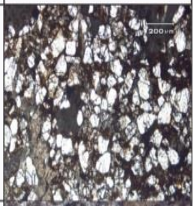
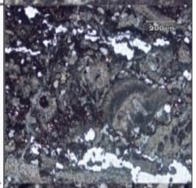
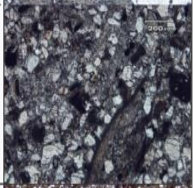
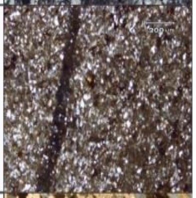
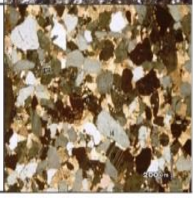
Stylolites having pyrite precipitation along them and fracture filled calcite have been identified from the thin section of the identified microfacies. These features are particular of late stage diagenesis and have been indentified from all the microfacies throughout all the three sections i.e. Zaluch Nala, Kalawahan section and Ghundai Nala.

4.2. Reservoir potential: Porosity evolution

Porosity evolution through carbonate reservoirs are a product of different diagenetic processes that happens through the reservoir (Moore, 1989; Flügel, 2004). The natural tendency in carbonate reservoirs is that most of the primary porosity is modified by diagenetic processes (Flügel, 2004). The three major environments in which porosity modification and evolution occurs are marine, meteoric and burial diagenetic environments (Moore, 1989). The marine environment in which most carbonate sediment originate is characterized by normal or modified marine pore fluids generally supersaturated with respect to most carbonate mineral (Bathurst, 1975). Marine environments are therefore the favorable sites of porosity destruction by marine cementation. The distribution of these cements varies within the marine system and is controlled by factors like fluid movements, available porosity and permeability and rate of sedimentation (Moore, 1989). Meteoric environment is characterized by pore fluid that is either supersaturated or undersaturated, however, mostly undersaturated with respect to metastable carbonate species aragonite and magnesium calcite (Bathurst, 1975). The meteoric environment therefore has a potential of porosity generation through the process of dissolution, as well as porosity destruction by pervasive cementation (Moore, 1989). The subsurface is characterized by fluids that may be a mixture of both marine and meteoric water (Folk, 1974) or a mixture of chemically complex brines that resulted from long term rock-water interaction under elevated pressures and temperatures (Stossell and Moore, 1983). Because of this extensive rock-water interaction the subsurface pore fluid is supersaturated with respect to the most stable carbonate species calcite and dolomite (Choquette and James, 1987). However, under elevated pressure and temperature conditions, pressure solution is an important porosity destruction phenomenon often aided by cement precipitation in the adjacent pore spaces due to the general supersaturated nature of the pore fluids (Moore, 1989).

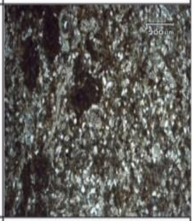
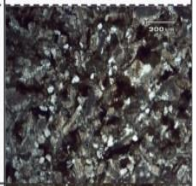
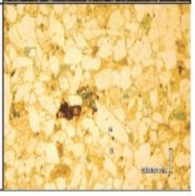
The diagenetic alteration has gone porosity modification in response to the different diagenetic events within the microfacies of Zaluch Nala, Ghundai Nala and Kalawahan Section (tables 1-3). The analysis of these diagenetic events reveals the reservoir potential of the Amb Formation as: The AMB 1 and AMB 2 are characterized by micritization, early marine and shallow burial cementation, pyrite precipitation, dissolution, recrytallization of calcite, bioclastic and quartz deformation, and presence of stylolites along with calcite filled fractures. The early marine and shallow burial cementation, pyrite precipitation, and presence of styloites along with calcite filled fractures reduce the porosity of the rock. However, the micritization within the microfacies and dissolution increase the porosity. Thus, the AMB 1 and AMB 2 are placed within the fair porosity zone. This porosity within the AMB 1 and AMB 2 is decreased in Kalawahan Nala due to unavailability of micritization and is placed in poor porosity zone. The AMB 1 is absent within Ghundai Nala. Similarly, the AMB 3A, AMB 3B and AMB 4 are characterized by micritization, early marine and shallow burial cementation, pyrite precipitation, recrytallization of calcite, bioclastic and quartz deformation, and presence of stylolites along with calcite filled fractures. The microfacies did contain the micritization, however, the porosity is occluded due to the remaining process. Thus, it is placed within the poor porosity zone. The AMB 3A is absent from the Ghundai Nala. The porosity if compared with other section reveals that AMB 3A, AMB 3B and AMB 4 within Kalawahan section is within poor porosity zone due to minimum micritization of the skeletal grains. In Ghundai Nala the AMB 3B and AMB 4 contain micritization. The AMB 3B of Ghundai Nala do not contains any shallow burial event that places the facies within fair porosity zone while AMB 4 is placed within poor porosity zone. The sandstone microfacies AMB 5 in all studies section are loose and closely packed grains. The diagenesis like compaction, calcite cement, iron oxidation, silica cementation, and fractured quartz is noted from various places. However, it indicates a good hydrocarbon reservoir potential in the study area.

Table 1. Shows porosity modification to different stages of diagenesis in Zaluch Nala (Negligible 0-5%, poor 5-10%, fair 10-15%, good 15-20% and Excellent greater than 20% after Hyne 2001).

Facies	Stages of Diagenesis	Porosity Evolution Modification (Time Unscaled)	Reservoir Potential	Photographs
Amb 1	Early Marine	Micritization, Early Marine Cementation, Pyrite Precipitation	Fair	
	Shallow Burial	Shallow Marine Cementation, Recrystallization, Quartz and Bioclastic Deformation, Dissolution		
	Deep Burial	Stylolites, Calcite Filled Fractures		
Amb 2	Early Marine	Micritization, Early Marine Cementation, Pyrite Precipitation	Fair	
	Shallow Burial	Shallow Marine Cementation, Recrystallization, Quartz and Bioclastic Deformation, Dissolution		
	Deep Burial	Stylolites, Calcite Filled Fractures		
Amb 3A	Early Marine	Micritization, Early Marine Cementation, Pyrite Precipitation	Poor	
	Shallow Burial	Shallow Marine Cementation, Recrystallization, Quartz and Bioclastic Deformation		
	Deep Burial	Stylolites, Calcite Filled Fractures		
Amb 3B	Early Marine	Micritization, Early Marine Cementation, Pyrite Precipitation	Poor	
	Shallow Burial	Shallow Marine Cementation, Recrystallization, Quartz and Bioclastic Deformation		
	Deep Burial	Stylolites, Calcite Filled Fractures		
Amb 4	Early Marine	Micritization, Early Marine Cementation, Pyrite Precipitation	Poor	
	Shallow Burial	Shallow Marine Cementation, Recrystallization, Quartz and Bioclastic Deformation		
	Deep Burial	Stylolites, Calcite Filled Fractures		
Amb 5	Early Marine	Loosely Pack, Early Marine Cementation: Silica Cement with Iron Oxides at places	Good	
	Shallow Burial	Compaction : with Fractured Quartz at Places		
	Deep Burial	Not Found		

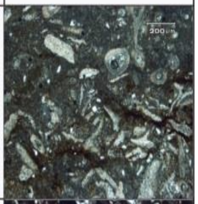
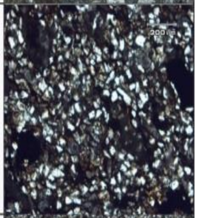
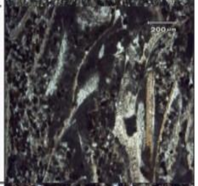
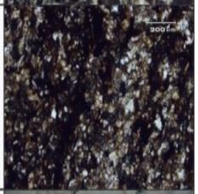
Indicates Porosity Generation Processes (green) **Indicates Porosity Reduction Processes** (yellow)

Table 2. Shows porosity modification to different stages of diagenesis in Ghundai Nala (Negligible 0-5%, poor 5-10%, fair 10-15%, good 15-20% and Excellent greater than 20% after Hyne 2001).

Facies	Stages of Diagenesis	Porosity Evolution Modification (Time Unscaled)	Reservoir Potential	Photographs
Amb 1	Early Marine	Not Found		
	Shallow Burial			
	Deep Burial			
Amb 2	Early Marine	Micritization; Early Marine Cementation; Pyrite Precipitation	Fair	
	Shallow Burial	Shallow Marine Cementation; Recrystallization; Dissolution		
	Deep Burial	Stylolites; Calcite Filled Fractures		
Amb 3A	Early Marine	Not Found		
	Shallow Burial			
	Deep Burial			
Amb 3B	Early Marine	Micritization; Early Marine Cementation; Pyrite Precipitation	Fair	
	Shallow Burial	Not Recognized		
	Deep Burial	Stylolites; Calcite Filled Fractures		
Amb 4	Early Marine	Micritization; Early Marine Cementation; Pyrite Precipitation	Poor	
	Shallow Burial	Shallow Marine Cementation; Recrystallization		
	Deep Burial	Stylolites; Calcite Filled Fractures		
Amb 5	Early Marine	Loosely Pack; Early Marine Cementation: Silica Cement with Iron Oxides at places	Good	
	Shallow Burial	Compaction : with Fractured Quartz at Places		
	Deep Burial	Not Found		

Indicates Porosity Generation Processes (green) **Indicates Porosity Reduction Processes** (yellow)

Table 3. Shows porosity modification to different stages of diagenesis in Kalawahan Nala (Negligible 0-5%, poor 5-10%, fair 10-15%, good 15-20% and Excellent greater than 20% after Hyne 2001).

Facies	Stages of Diagenesis	Porosity Evolution Modification (Time Unscaled)	Reservoir Potential	Photographs
Amb 1	Early Marine	Early Marine Cementation; Pyrite Precipitation	Poor	
	Shallow Burial	Shallow Marine Cementation; Recrystallization; Dissolution		
	Deep Burial	Stylolites; Calcite Filled Fractures		
Amb 2	Early Marine	Early Marine Cementation; Pyrite Precipitation	Poor	
	Shallow Burial	Shallow Marine Cementation; Recrystallization; Bioclastic Deformation; Dissolution		
	Deep Burial	Stylolites; Calcite Filled Fractures		
Amb 3A	Early Marine	Minimu Micritization; Early Marine Cementation; Pyrite Precipitation	Poor	
	Shallow Burial	Shallow Marine Cementation; Recrystallization		
	Deep Burial	Stylolites; Calcite Filled Fractures		
Amb 3B	Early Marine	Minimum Micritization; Early Marine Cementation; Pyrite Precipitation	Poor	
	Shallow Burial	Shallow Marine Cementation; Recrystallization		
	Deep Burial	Stylolites; Calcite Filled Fractures		
Amb 4	Early Marine	Minimum Micritization; Early Marine Cementation; Pyrite Precipitation	Poor	
	Shallow Burial	Shallow Marine Cementation; Recrystallization		
	Deep Burial	Stylolites; Calcite Filled Fractures		
Amb 5	Early Marine	Loosely Pack; Early Marine Cementation: Silica Cement with Iron Oxides at places	Good	
	Shallow Burial	Compaction : with Fractured Quartz at Places		
	Deep Burial	Not Found		

Indicates Porosity GenerationProcesses

Indicates Porosity Reduction Processes

5. Conclusions

In this study a three stratigraphic sections namely Zaluch Nala, Ghundai Nala and Kalawahan sections in the Salt Range area are selected. The lithofacies variation exists in the Amb Formation and siliciclastic-carbonate mixed lithologies are reported. Measured stratigraphic thickness of the Amb Formation in the Zaluch Nala Section is 50.1 m, 16.5 m in the Ghundai Nala and 30.5 m in the Kalawahan sections respectively. There are six different microfacies, which were defined based on macro and micro level studies and were abbreviated as AMB 1, AMB 2, AMB 3A, AMB 3B, AMB 4 and AMB 5. Based on the recognition of micritization, dissolution, cementation, pyritization, recrystallization, physical and chemical compaction, and fracturing in these microfacies, three stages of diagenesis i.e., marine, shallow and deep burial are interpreted. This in turn suggested that the AMB 1 and AMB 2 have a fair porosity while the AMB 3A, AMB 3B and AMB 4 have poor porosity. The AMB 5 has good porosity. These porosities fluctuated within studied section and are different from Kalawahan Section: AMB 1, AMB 2, AMB 3A, AMB 3B and AMB 4 which have poor porosity and Ghundai Nala: AMB 1 and AMB 3A are absent, AMB 3B has fair porosity, and AMB 4 has poor porosity.

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References

Balme, B.E., 1970. Palynology of the Permian and Triassic strata in the Salt Range and Surghar Range, West Pakistan. In: Kummel, B., Tiechert, C. (Eds.), Stratigraphy Boundary Problems: Permian and Triassic of West Pakistan. University of Kansas Special Publication, 4, 305-453.

Bathurst, R.G.C., 1975. Carbonate Sediments and their diagenesis. Developments in sedimentalogy, Elsevier, Amsterdam.

Choquette, P.W., James, N. P., 1987. Diagenesis No. 12: Diagenesis in Limestone-3. The deep burial environment, Geoscience Canada, 14(1), 3-35.

Douglas, R.C., 1968. Morphologic studies of fusulinids from Lower Permian of West Pakistan. American Association of Petroleum Geologists Bulletin, 52, 525-526.

Dunbar, C.O., 1933. Stratigraphic significance of the fusulinds of the Lower Productus Limestone of the Salt Range. Geological Survey of India Records, 66(4), 405-413.

Dunham, R.J., 1962. Classification of carbonate rocks according to depositional texture. In: Ham, W.E. (Ed.), Classification of carbonate rocks. American Association of Petroleum Geologists Memoir, 1, 108-121.

Fatmi, A.N., 1973. Lithostratigraphic units of Kohat-Potwar Province, Indus Basin. Geological Survey of Pakistan Memoirs, 10, 1-80.

Fatmi, A.N., 1974. Lithostratigraphic units of the Kohat-Potwar province, Indus Basin, Pakistan. Geological Survey of Pakistan Memoirs, 10, 1-80.

Flügel, E., 1982. Microfacies of carbonate rocks: analysis, interpretation and application. Springer-Verlag, New York.

Flügel, E., 2004. Depositional Model, Facies zones and Standard Microfacies. In: Microfacies of Carbonate Rocks Analysis, Interpretation and Application. Springer-Verlag, Berlin (Germany).

Folk, R., 1974. The natural history of crystalline calcium carbonate: effect of magnesium content and salinity. Journal of the Sedimentary Petrology, 44, 40-53.

Grant, R.E., 1970. Brachiopods from Permian-Triassic boundary beds and age of Chhidru Formation, West Pakistan. In: Kummel, B., Tiechert, C. (Eds.), Stratigraphy Boundary Problems: Permian and Triassic of West Pakistan. University of Kansas Special Publication, 4, 117-150.

Hyne, N.J., 2001. Nontechnical Guide to Petroleum Geology, Exploration, Drilling and Production, 2ndEdition, PennWell.

James, N.P., Choquette, P.W., 1983. Diagenesis 6: Limestones: the seafloor diagenetic environment. Geosciences Canada, 10, 162-179.

Jaswal, T.M., Lillie, R.J., Lawrance, R.D., 1997. Structure and evolution of the northern Potwar deformed zone, Pakistan. American Association of Petroleum Geologists Bulletin, 81, 308-328.

Kazmi, A.H., Rana, R.A., 1982. Tectonic Map of Pakistan. Geological Survey of Pakistan, Quetta.

Kendall, A.C., Tucker, M.E., 1973. Radiaxial fibrous calcite: a replacement after acicular aragonite. Sedimentology, 20, 365-390.

Kummel, B., Tiechert, C., 1970. Stratigraphy and Paleontolgy of the Permian Triassic Boundary Beds, Salt Range and Trans Indus Ranges, West Pakistan. In: Kummel, B., Tiechert, C. (Eds.), Stratigraphy Boundary Problems: Permian and Triassic of West Pakistan. University of Kansas Special Publication, 4, 2-110.

Mertmann, D., 2003. Evolution of the marine Permin carbonate platform in the Salt Range, Pakistan. Journal of Paleogeography, Paleoclimatology, Paleoecology, 191, 373-384.

Moore, P.F., 1989. The lower Kasskaskia sequence-Devonian. In: Ricketts, B.D. (Ed.), Western Canada Sedimentary Basin: A Case History. Canadian Society of Petroleum Geologists, Special Publication, 30, 139-164.

P.J.R.G. (Pakistan Japanese Research Group), 1985. Permian and Triassic strata in the Salt Range and Surghar Range, Pakistan. In: Nakazawa, K., Dickins, J.M. (Eds.), The Tethys, 221-312.

Pettijohn, F.J., Potter, P.E., Seiver, R., 1987. Sand and Sandstone (second edition). Springer-Verlag, New York.

Scholle, P.A., Ulmer-Scholle, D.S., 2003. A color guide to the petrography of carbonate rocks: Grains, textures, porosity and diagenesis. The American Association of Petroleum Geologist Memoir, 77.

Shah, M.I., 1977. Stratigraphy of Pakistan. Memoirs of the Geological Survey of Pakistan. Ministry of Petroleum and Natural Resources of Pakistan.

Stossell, R.K., Moore,. C. H., 1983. Chemical constraints and origins of four groups of Gulf Coast reservoir fluids. American Association of Petroleum Geologists Bulletin, 67, 896-906.

Teichert, C., 1966. Stratigraphic nomenclature and correlation of the Permian “Productus Limestone”, Salt Range, West Pakistan. Geological Survey of Pakistan Records, 15, 1-19.

Tucker, M.E., Wright, V.P., 1990. Carbonate Sedimentology. Blackwell Publishing, New Jersey.

Waagen, W., 1889-91. Salt Range fossils: Geological results: Memoirs of Palaeontologia Indica, 13(4), 242.

Wardlaw, B.R., Pogue, K.R., 1995. The Permian of Pakistan. In: Scholle, P. A., Peryt, T. M., Ulmer-Scholle, D.S. (Eds.), The Permian of Northern Pangea: Sedimentary Basins and Economic Resources, Springer, Berlin, Heidelberg, 215-224.