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SEDIMENTOLOGICAL ATTRIBUTES OF THE MIDDLE JURASSIC LORALAI FORMATION, KHIDIRZAI NALA SECTION, WESTERN SULAIMAN FOLD AND THRUST BELT, DISTRICT ZHOB, BALOCHISTAN, PAKISTAN

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Abstract: *This paper encompasses the detailed study on the sedimentological attributes of the Middle Jurassic Loralai Formation, Khidarzai Nala Section, Bargha Shirani, (Lat.: 31° 12´ 31° 27´N and Long.: 69° 37´ 69° 45´E) Western Sulaiman Range, District Zhob, Balochistan-Pakistan. The Middle Jurassic Loralai Formation belongs to carbonate rocks, which are widely distributed in the host area of investigated section. The present detailed sedimentological study executed on this formation is the first of its kind and covers an analysis of carbonate microfacies and diagenetic settings. The petrographic investigations revealed that its most significant microfacies include intraclastic rudstones and grainstones, skeletal, ooidal, pisoidal and peloidal grainstones, skeletal and unfossiliferous mudstones. Its diagenetic settings were, also, studied and a variety of cement types from early to late diagenetic phases were identified. An attempt has been made, as well, to highlight the significant reservoir potential of the Loralai Formation for oil and gas in the Western Sulaiman Range and adjoining areas. This potential is evident by the significant show of well-developed grainstones microfacies and secondary porosities, particularly, dissolution, moldic and vuggy porosities. The recorded fracturing and dolomitization phases have substantially enhanced the porosity of this important carbonate rock found in the measured section. Moreover, at a number of stratigraphic levels this formation has fractured limestone horizons, which belong to different fracturing phases. The phases ultimately induced and enhanced permeability by facilitating interconnections. The comprehensive field and laboratory studies revealed that the Middle Jurassic Loralai Formation was deposited in the shallow shelf settings and at different horizons it has established reservoir potential as is represented in the investigated section.*

Key words: Microfacies, diagenetic setting, Middle Jurassic, Loralai Formation, Western Sulaiman Range-Pakistan

INTRODUCTION

The only Mesozoic strata exposed in the Bargha Shirani area are comprised of Loralai Formation belonging to the Jurassic age (Table 1). The formation belongs to the Middle Jurassic carbonate rocks with its wide distribution in the host area of studied section. The Bargha Shirani area (Lat.: 31° 12´ 31° 27´N and Long.: 69° 37´ 69° 45´E) lies in the southeast of District Zhob, Balochistan (Fig. 1). The area is part of the Toposheet No. 39 E/15 Survey of Pakistan, Rawalpindi). The access to study area is much easy due to the presence of major communication links in the region around. It is located at 30km in the southeast from the Zhob town. While the Zhob town lies about 212km in the southwest of the Dera Ismail Khan on Zhob-Dera Ismail Khan Road and 340km in the northeast of Quetta on Quetta-Zhob Road. There are several jeepable shingle roads, foot tracks and streams criss crossing the study area. All these links proved much convenient to carry out fieldwork assignments in the study area. The studied section could, also, be approached by foot through beds of larger streams and those of the nalas, such that, Kapip Nala, Baghao Khawara, Karawalai Manda, Liarwali Manda, Kot Kandao Manda and Sherwai Khawara. The fieldwork was carried out from 1st November, 2006 to 5th December, 2006 in a single go. The present research work was executed to study the sedimentological attributes, such that, microfacies and diagenetic framework, of the shallow shelf Loralai Formation exposed at the Khidarzai Nala Section, Bargha Shirani area, Western Sulaiman Range, District Zhob, Balochistan-Pakistan.

The study area is relatively virgin area. Only a few workers contributed in describing the geology of this area. The Hunting Survey Corporation (1961) mapped the area on 1:250,000 scale with limited field truthing. Kazmi and Jon (1997) briefly described the structure and tectonics of the area with cross sections

Table 1 Showing Stratigraphy of the Bargha Shirani Area and Sulaiman Fold and Thrust Belt, Balochistan-Pakistan (Modified after Shah, 2002).

<table>
<tr><th rowspan="2">Era</th><th rowspan="2">Period</th><th rowspan="2">Epoch</th><th rowspan="2" colspan="2">Age</th><th colspan="2">Lower Indus Basin</th></tr>
<tr><th>Sulaiman Fold and Thrust</th><th>Study Area</th></tr>
<tr><td rowspan="23">MESOZOIC</td><td rowspan="13">CRETACEOUS</td><td rowspan="7">UPPER</td><td rowspan="2" colspan="2">MAASTRICTIAN</td><td>Pab Sandstone</td><td>Not Exposed</td></tr>
<tr><td>Fort Munro Formation</td><td>Not Exposed</td></tr>
<tr><td rowspan="4">SENORIAN</td><td>CAMPANIAN</td><td rowspan="2">Mughal Kot Formation</td><td rowspan="2">Exposed</td></tr>
<tr><td>SANTONIAN</td></tr>
<tr><td>CONIACIAN</td><td rowspan="2">Parh Limestone</td><td rowspan="2">Not Exposed</td></tr>
<tr><td>TUROMANIAN</td></tr>
<tr><td colspan="2">CENOMANIAN</td><td rowspan="3">Goru Formation</td><td rowspan="3">Exposed</td></tr>
<tr><td rowspan="6">LOWER</td><td colspan="2">ALBIAN</td></tr>
<tr><td colspan="2">APTIAN</td></tr>
<tr><td rowspan="4">NEOCOMIAN</td><td>BARREMIAN</td><td rowspan="4">Sembar Formation</td><td rowspan="4">Exposed</td></tr>
<tr><td>HAUTERIVIAN</td></tr>
<tr><td>VALANGINIAN</td></tr>
<tr><td>BERRIASIAN</td></tr>
<tr><td rowspan="10">JURASSIC</td><td rowspan="3">UPPER</td><td colspan="2">TITHONIAN</td><td rowspan="3" colspan="2">UNCONFORMITY</td></tr>
<tr><td colspan="2">KIMMERIDGIAN</td></tr>
<tr><td colspan="2">OXFORDIAN</td></tr>
<tr><td rowspan="3">MIDDLE</td><td colspan="2">CALLOVIAN</td><td rowspan="3">Takatu Formation</td><td rowspan="3">Not Exposed</td></tr>
<tr><td colspan="2">BATHONIAN</td></tr>
<tr><td colspan="2">BAJOCIAN</td></tr>
<tr><td rowspan="4">LOWER</td><td colspan="2">ALENIAN</td><td rowspan="4">Loralai Formation</td><td rowspan="4">Exposed</td></tr>
<tr><td colspan="2">TOARCIAN</td></tr>
<tr><td colspan="2">PLIENSBACHIAN</td></tr>
<tr><td colspan="2">SINEMURIAN/HETTAGIAN</td></tr>
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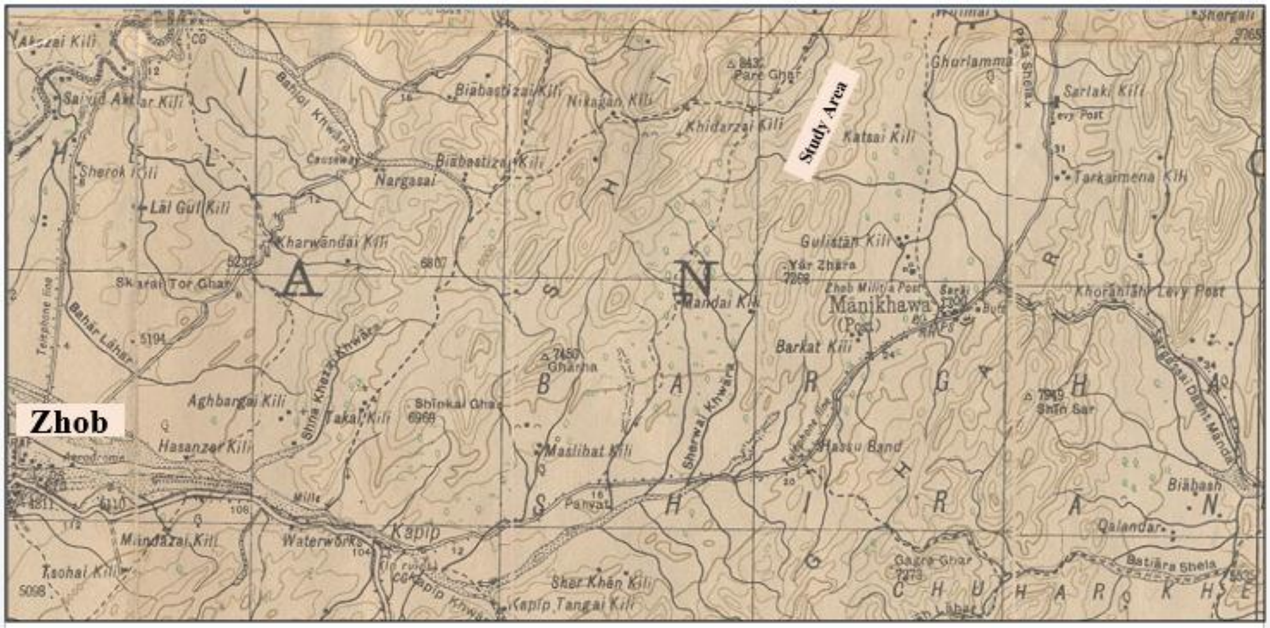


Fig. 1 Location map showing the measured section near Khidarzai Kili, Western Sulaiman Fold and Thrust Belt, District Zhob, Balochistan-Pakistan (Modified part of Topo-sheet: 39 E/15)

and maps. The Geological Survey of Pakistan and Directorate of Mineral Development, Government of Balochistan initiated a joint development project entitled “Reconnaissance Survey and Mineral Investigations in Zhob, Barkhan and Kohlu districts of Balochistan” in the year 1999-2000. The project was aimed to collect basic data on the geology and mineral resources of these districts by carrying out reconnaissance geological mapping on 1:250,000 scale (Hussain, *et al.,* 2002). According to Kadri (1995) rifting and break-up of Gondwana continued during the Jurassic period. That is why the Upper Jurassic strata is absent in the Lower Indus Basin and represent a major unconformity in this basin. The Cretaceous strata comprising of Sembar Formation, Goru Formation and Mughal Kot Formation lie directly over the Middle Jurassic rocks. The present authors carried out detailed field and petrographic investigations in the study area and produced a lot of original field data on the sedimentological attributes of the Loralai Formation.

Loralai Formation

The Loralai Formation constitutes the most important assemblage of carbonates in the Mesozoic succession of the Western Sulaiman Range. The formation belongs to the Middle Jurassic age and is well exposed throughout the area hosting the measured section (Hussain, 2005). According to Kadri (1995) the Shirinab Formation is comprised of three members, namely Spingwer, Loralai and Anjira, however, one of its member, such that, Loralai has been raised to the formation status in the study area (Hussain, 2001). The Loralai Member of Kadri (1995) is taken as Loralai Formation in this paper by the present authors. The shale contents are dominant in the formations present in all around the study area except the Loralai Formation. The Mesozoic rocks of the Sulaiman Range are several thousand metres thick and are mostly shallow water marine sedimentary rocks of dominantly carbonates and minor argillaceous contents (Shah, 2002). The exposures of limestones of the Loralai Formation at the Khidarzai Nala Section are ridge forming and produce characteristic dip slopes and escarpments (Fig. 2). The Loralai Formation is equivalent to the Samana Suk Formation, which is recognizable over a wide area of northern Pakistan (Shah, 1977) and is distributed in the Trans Indus Ranges, Cis-Indus Salt Ranges, Kohat Tribal Range, Samana Range, Kala Chitta Range and southern Hazara mountains (Kazmi and Jan, 1997 and Bender and Raza, 1995). The formation is, also, co-related with the Chiltan Formation (Murree Brewery Gorge Section, near Quetta) and Mazar Drick Formation of the Sulaiman Fold and Thrust Belt-Pakistan (Sheikh, *et al.,* 2005). It is equivalent of the Chiltan Formation to the south in the Kirthar Range as well (Sheikh, *et al.,* 2002). The age assigned by Williams (1959) and Woodward (1959) is Early Jurassic. However, the Hunting Survey Corporation (1961) recorded Toarcian fossils from lower levels in the limestones of Loralai Formation (Shah, 2002).

Fig. 2 Field photograph showing shale breaks in limestones of the Loralai Formation, Khidarzai Nala Section, Western Sulaiman Fold and Thrust Belt, District Zhob, Balochistan-Pakistan.

GEOLOGICAL SETTING

The study area is located in the Western Sulaiman Range, Lower Indus Basin (Jadoon, *et al.*, 1993). The area owes its origin to the collision between Indo-Pakistani Plate and Eurasian Plate in the Paleocene that resulted in subduction of Indo-Pakistan Plate under the Eurasian Plate (Powel, 1979). The main collision phase of the Himalayan uplift initiated due to collision of the northern margin of Indo-Pakistani Plate with Eurasian Plate, followed by an oblique collision of the northwestern margin of Indo-Pakistan with Afghan Microplate in Miocene time (Bender and Raza, 1995). The Sulaiman Fold and Thrust Belt was developed in response to this convergence with huge thickness of sediments. The area hosting the measured section falls in the northern part of Sulaiman Foreland Fold and Thrust Belt, Lower Indus Basin in the north east part of Balochistan. It is bounded by Zhob Valley Thrust in the west, left-lateral Manikhawa Fault in the east and Pezu Wrench Fault in the north. The study area separates the Sulaiman Foreland Fold and Thrust Belt from the Kohat Basin. The Chinjan-Zakariazai Thrust bounds the study area in the south near its western limits (Kazmi and Jan, 1997 and Bender and Raza, 1995). On its north eastern side the Mughal Kot Fault is located (Kazmi and Jan, 1997). In the study area a number of small and large thrust faults are found in a mess of competent and incompetent strata.

MATERIALS AND METHODS

The present work is based on the original field data collected during the detailed field work. Twenty (20) samples were collected from the measured section depending on the variations observed from bed to bed, while fourteen (14) samples were selected for petrographic investigations. The laboratory techniques, comprising analysis of thin sections using petrographic microscope, chemical staining with Alizarin Red S and Potassium Ferricyanide and digital photomicrography, have been applied to describe its sedimentological attributes. The laboratory petrographic investigations, executed for the first time by these authors, produced a lot of original data on the microfacies and diagenetic framework of the Loralai Formation. The Zamari Tangi (Lat.: 30° 32' 10" N and Long.: 68° 18' 40" E), Loralai District, Balochistan, has been designated its type locality, where it is 424m thick. While further towards north; it is reduced to the thickness of 6m only (Woodward, 1959). In the study area the main exposures of this formation are found in the NW of Baghao Khawara and Near Khidarzai village.

Field Observations

In the measured section the formation is striking N 42° E and dipping 45° NW. The strike direction changes as it extends northwards. In the Khidarzai Nala Section it is 54.47m thick and is predominantly a limestone with fair proportion of dolomite and dolomitic limestone/dolomitic patches, marl and subordinate shale. The shales of varigated colour, as a subordinate component, are present in thin interbeds and as intercalations at certain horizons (Fig. 2). The interbedded shale is greenish gray, platy, flaky, fissile and calcareous. The limestones are thin to medium to thick bedded and massive limestones of yellowish gray on weathered surface and gray to dark gray colour on fresh surface. Calcite veins, dolomitic patches and some marly beds were, also, observed in this section. The limestones are fractured, which were filled later on by calcite. Generally the rock is medium to coarse grained. The bed thickness increases from bottom to top. In the lower part of this rock dolomitic patches, flute casts, calcite skin (on joint surface), ripple marks, calcite veins, oolites, pisolites, cross-bedding, raindrops, solution weathering, pits, concretions, solution cavities and graded bedding are found. In the middle part of this rock unit calcite veins, dolomitic patches, conjugate set of joints, cross bedding, ripples, flute casts, calcite skin (on joint) surface, oolites, gradded bedding, sole marks (groove marks) were noted. In the upper part of this rock calcite veins, iron concretions, dolomitic patches, solution cavities, large pebbles, vertical fractures, cross-bedding, rock cleavage, and graded bedding were observed. A pebbly horizon in the upper part of the formation was observed also. In addition at different levels of this section intra-formational folding, faulting and stromatolites were found.

Petrography

The limestones are mainly micritic, however, at certain levels oosparitic (ooidal grainstones) and pelsparitic (peloidal grainstones) are found particularly in its upper part. Pisoids, pelloids and ooids are found as well and they are collectively 60 to 70%. The grain size of ooids ranges from 1.5 to 2.6mm. The shape of ooids is circular to elliptical and sub-rounded. Calcite is, also, present and ranges from 10 to 15%. Calcite veins are present as well. Ferruginous material is found also and ranges from 10 to 15%. Cleavage in recrystallized calcite was, also, noted.

Sedimentological Attributes

The tudied sedimentological attributes include: microfacies analysis and diagenetic fabric. These are described in the following:

Microfacies Analysis

The microfacies analysis of the Middle Jurassic Loralai Formation was carried out by following the microfacies classification scheme of carbonate rocks suggested by Dunham (1962). To interpret limestone facies composed of large size grains Embry and Klovan (1971) scheme has been adopted, in which the microfacies having grain-supported texture with clasts larger than 2mm diameter in size are termed as rudstones (Scoffin, 1987). The petrographic investigations manifested that the most significant microfacies found in the Loralai Formation are intraclastic rudstones, a number of grainstone types, bioclastic mudstones and unfossiliferous mudstones. The faunal diversity could have not been observed in the studied microfacies of the Loralai Formation from this section.

Rudstones: The present investigation revealed only one type of this microfacies, which is described in the following:

Intraclastic Rudstones: It is comprised of intraclasts of large size, i.e., more than 2mm diameter. Occasionally small size ooids are found also in association with intraclasts (Plate A, Fig. 1).

Grainstones: A number of grainstones have been recorded in present section of the Loralai Formation at its several horizons, particularly in its upper part (Shah, 2002). The petrographic analysis manifested that its most significant grainstone microfacies include intraclastic grainstones, bioclastic grainstones, ooidal grainstones, pisoidal grainstone and peloidal grainstones. Other allochem grains, like, grapestones and intraclasts are, also, found in association with grainstones. The grapestones, which are actually aggregate grains and are formed by the agglutination of other types of carbonate material, are found occasionally in grainstones of this formation. In the investigated section the grapestones with very low frequency of appearance have been recorded in association with other types of grains as shown in Plate A, Fig. 2 and Plate B, Fig. 4. The grainstones in association with intraclasts are, also, found (Plate B, Fig. 3). However, the frequency of their appearance in the grainstones of the Loralai Formation is low. The following microfacies of grainstones have been recorded as an outcome of petrographic analysis:

Intraclastic Grainstones: These grainstones are present at different horizons of the Loralai Formation, exposed in this section (Plate A, Fig. 2 and Fig. 3). A chemically compacted intraclastic grainstone is shown in Plate A, Fig. 3.

Plate A

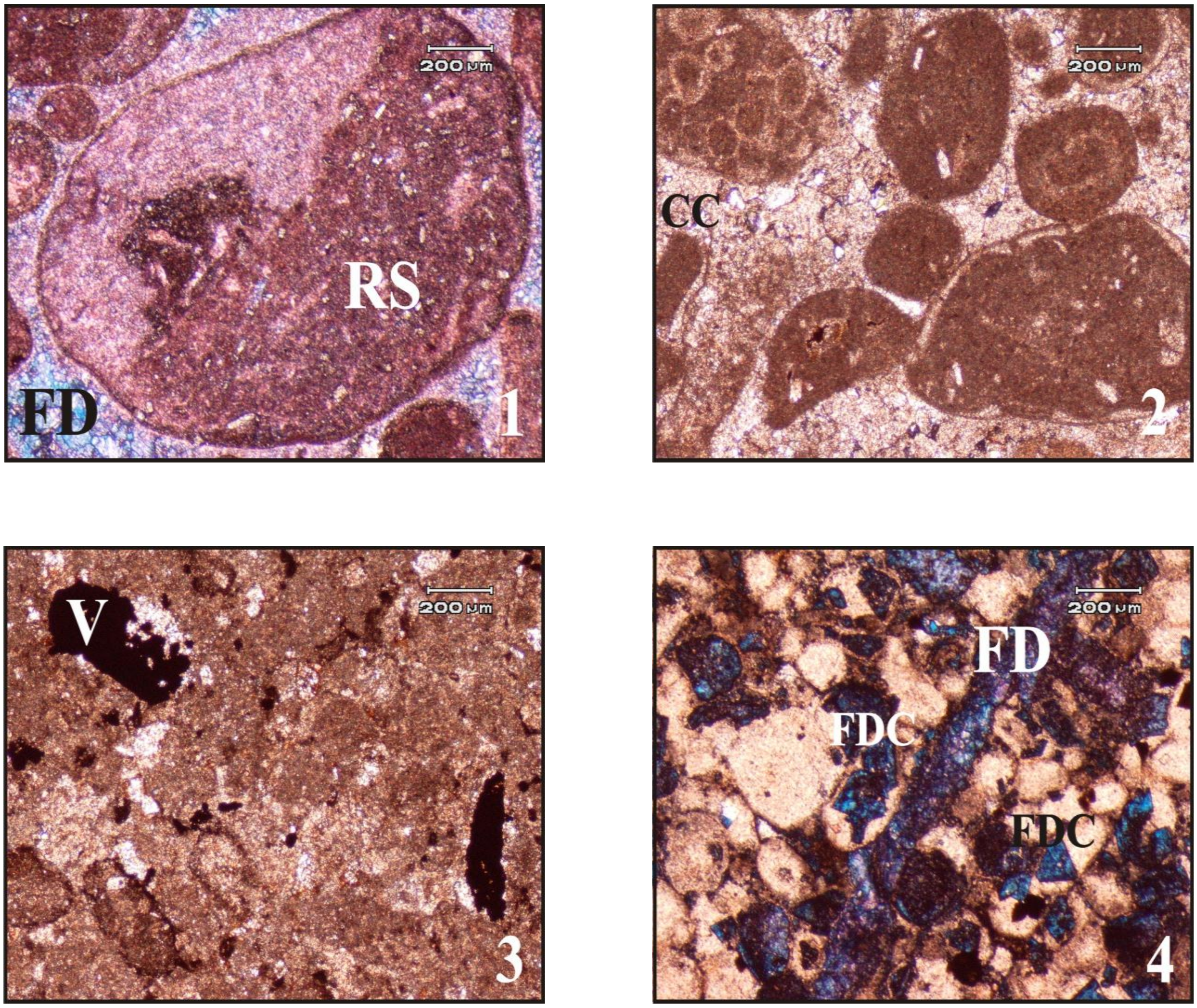


Fig. 1 Photomicrograph showing a partially dolomitized intraclastic rudstone (RS). The intergranular calcite cement is dolomitized as ferroan dolomite (FD) at places. (200, PPL, stained). Sample KZN-4M

Fig. 2 Photomicrograph showing an intraclastic grainstone along with columnar (CC) cement (200, PPL, unstained). Sample KZN-7

Fig. 3 Photomicrograph showing a chemically compacted intraclastic grainstone with vuggy (V) porosity (200, PPL, unstained). Sample KZN-11U

Fig. 4 Photomicrograph showing a partially dolomitized bioclastic grainstone. The skeletal grains are indeterminate. Partially developed crystals of ferroan dolomite (FD) are present. A fracture filled with ferroan dolomite (FD) cement is cross cutting this microfacies (200, PPL, stained). Sample KZN-6T

Plate B

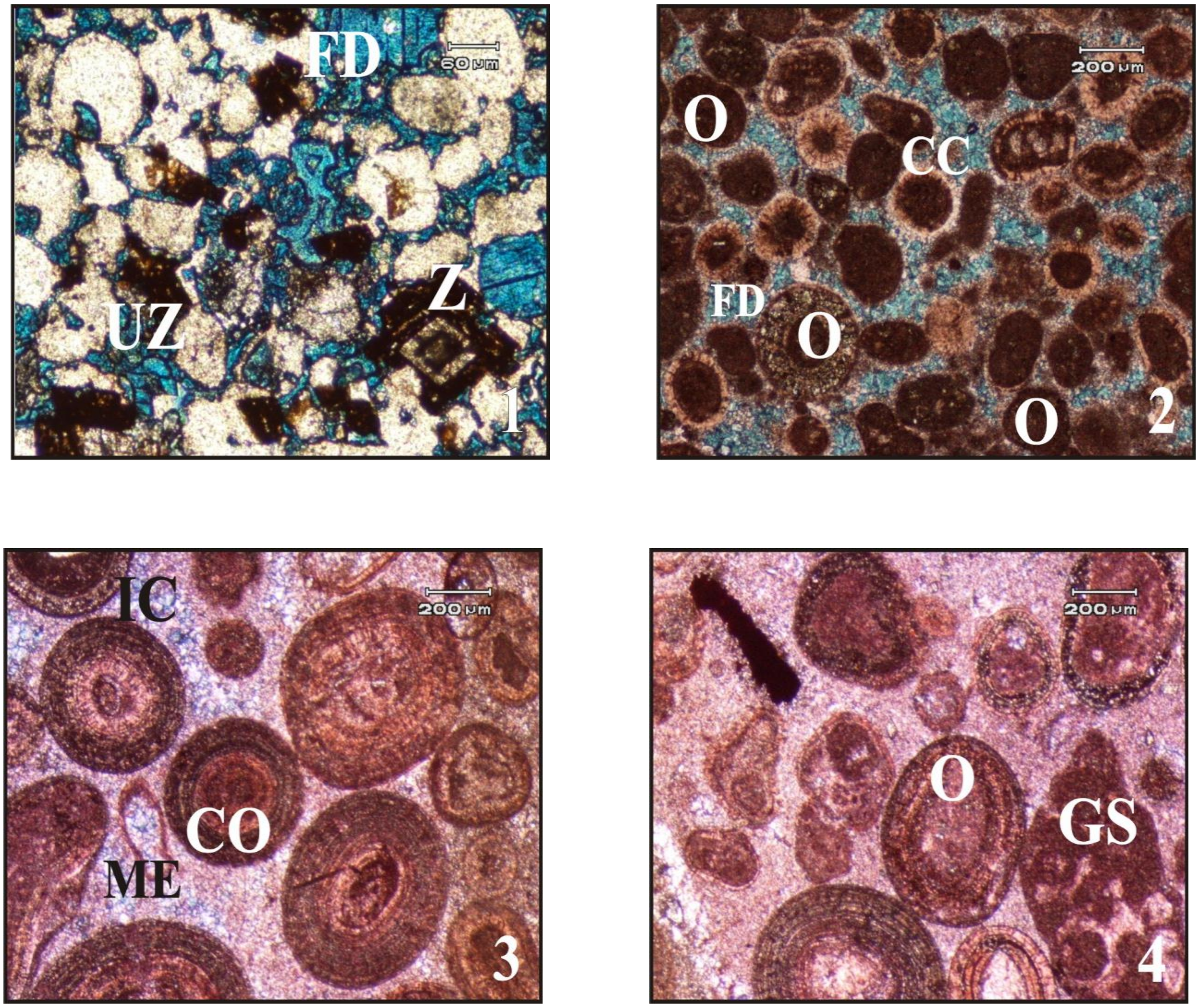


Fig. 1 Photomicrograph showing a pervasively dolomitized bioclastic grainstone with interganular ferroan dolomite (FD) cement. The skeletal grains are indeterminate. Partially developed crystals of un-zoned (UZ) and a well-developed large crystal of zoned (Z) ferroan dolomite are present (200, PPL, stained). Sample KZN-19B
Fig. 2 Photomicrograph showing a slightly chemically compacted ooidal (O) grainstone with inter-granular ferroan dolomite (FD) cement and columnar calcite (CC) cement. The concentric (a few) and radial ooids are present (200, PPL, stained). Sample KZN-14B
Fig. 3 Photomicrograph showing an ooidal grainstone with inter-granular cement (IC), micritic envelope (ME) and concentric ooids (CO). The size of ooids vary greatly. Inter-granular sparry cement is partially (ferroan) dolomitized (200, PPL, stained). Sample KZN-4M
Fig. 4 Photomicrograph showing an ooidal grainstone (O) with associated grapestone (GS). It, also, displays vuggy porosity (200, PPL, stained). Sample KZN-4M

Bioclastic Grainstones: This type of grainstones are comprised of skeletal shells and fragments of organisms, however these bioclasts are indeterminate due to partial dolomitization (Plate A, Fig. 4 and Plate B, Fig. 1).

Ooidal Grainstones: Ooids present in these grainstones have, generally, concentric laminar microfabrics (Plate B, Fig. 3). However, ooids with superimposed radial microstructure are, also, found in these grainstones (Plate C, Fig. 1). Occasionally intraclasts and grapestones are found as well (Plate B, Fig. 3). Ooidal grainstones in association with grapestones are, also, found (Plate B, Fig. 4).

Pisoidal Grainstones: The pisoidal grainstones are found at a few levels in this section (Plate C, Fig. 2). This microfacies is composed of very large micritized faecal pellets and/or peloidal grains.

Peloidal Grainstones: The peloidal grainstones have been recorded at a number of levels in this section (Plate C, Fig. 3). This microfacies is composed of faecal pellets and peloids, which are micritized. The other carbonate grains are, also, found in associations with these grainstones (Plate B, Fig. 4).

Mudstones: Mudstones, both unfossiliferous and fossiliferous, have been observed at different horizons of the Loralai Formation exposed at the Khidarzai Nala Section. The observed mudstones at places are highly fractured, stylolitized and partially dolomitized (Plate D, Fig. 2). The detail is given below:

Bioclastic Mudstones: The fossiliferous mudstones with skeletal grains have been found in Plate D, Fig. 1. A fracture filled with ferroan dolomite is criss-crossing this mudstone.

Unfossiliferous Mudstones: The observed mudstones at places are highly fractured and stylolitized. The medium amplitude stylolites are found with stylocummolate mainly comprising iron mineralization and zoned dolomite (Plate D, Fig. 2 and Fig. 3).

Diagenesis

The diagenetic settings of the Loralai Formation, Khidarzai Nala Section were perceived through the petrographic analysis, supplemented with chemical staining techniques. The formation, under investigation, is partially, as well as, pervasively dolomitized in places, which is one of the most significant diagenetic character of this formation. The low frequency of appearance of stylolites and fractures, the presence of pelloids, pisoids and various kinds of ooides at different levels are, also, its important characters. The effect of chemical compaction is found medium to high and modifications made by dissolution are very few. A few features of brittle deformation have been recorded as well. The observed diagenetic features in the Loralai Formation, exposed at this section are described as follows:

Micritic Envelopes: The micritic envelopes commonly develop around fauna which are originally composed of aragonite. It is the first diagenetic phase, which takes place in the marine diagenesis of limestones. These envelopes serve to define and preserve the outline and morphology of the carbonate grains over which these envelops develop (Plate B, Fig. 3). These envelopes commonly develop on grains, originally composed of aragonite. While aragonite is a metastable carbonate mineral. It dissolves in the first phase of diagenesis of carbonate sediments and is replaced by calcite. These envelopes, found in the Loralai Formation of the Khidarzai Nala Section are similar to those described by Kendal and Skipwith (1969) from the recent carbonate sediments and those illustrated from the Jurassic and Carboniferous Limestones by Bathurst (1964). The micritic envelopes are found on skeletal and non-skeletal grains in different microfacies. An example from the studied section is shown in Plate B, Fig. 3.

Fractures and Stylolites: Atleast three phases of fracturing were observed in the studied section (Plate C, Fig. 1 and Plate D, Fig. 1). The fractures of various sizes filled most frequently with ferroan dolomite have been recorded in Plate C, Fig. 1 and Plate D, Fig. 1. Like fractures the stylolites are, also, common. A low amplitude stylolite with stylocummolate developed in a mudstone microfacies is shown in Plate D, Fig. 2.

Small to medium to large size fractures are commonly found at various levels in the measured section. The mudstones microfacies particularly bear fractures, while other microfacies have, also, been found bearing factures at certain horizons (Plate C, Fig. 1 and Fig. 4 and Plate D, Fig. 1) with a few phases of fracturing sometimes. Almost all fractures are filled with ferroan dolomite (Plate C, Fig. 1 and Plate D, Fig. 1).

The stylolitization has, also, been recorded at different levels of this formation, which are commonly of low amplitude and are found mostly in the mudstones (Plate D, Fig. 2). It is noted that the stylocummolate is comprised of iron and zoned dolomite as shown in Plate D, Fig. 3.

Cements: The **c**ementation is an important diagenetic process in the continuous modification of the carbonate sediments, which endows strength and stability (lithification) to the concerned microfacies. The persistently cemented microfacies always resist physical, as well as, chemical compaction and fracturing episodes. Early diagenetic cements are recognized as fibrous aragonite, while intergranular cement, dog tooth (circumgranular equent) cement, dolomite cement, drusy mosaic cement and columnar cement precipitate at later diagenetic stages. The following cement types have been recorded at different horizons and in different microfacies of the Loralai Formation exposed at the studied section:

Circumgranular Cements: The following two types of this cement have been observed in this section:

Dog Tooth Cement: It is circumgranular equant cement, which precipitates as later diagenetic cements, like, dolomite cement, drusy mosaic cement, etc. Its example is shown in Plate B, Fig. 2.

Circumgranular Columnar Cement: According to Tucker (1988) the circumgranular columnar cement commonly develops in the mixed meteoric or marine phreatic environments. This type of cement found in the investigated formation is shown in Plate A, Fig. 2.

Intergranular Cement: The intergranular cement, found at different levels of the Loralai Formation, is mostly dolomitized and equant in texture (Plate B, Fig. 3). It is the next phase of carbonate diagenesis (Sheikh, 1992). At certain levels of this formation sparry dolomite cement with drusy mosaic of meteoric phreatic environment has, also, been noted in the studied section. It has been recorded in a number of grainstones (Plate A, Fig. 1 and 2 and Plate B, Fig. 3 and 4).

Drusy Calcite Cement: It crystallizes in cavities and open fractures and is termed as cavity filling cement. The crystals of this cement are of small size at margins of cavity and gets larger towards the centre of cavity as per available accommodation space. It has been recorded in different microfacies of the Loralai Formation. This cement might be sparry calcite or dolomite. However, in this section it is partially dolomitized, while dolomite is ferroan dolomite. An example is shown in Plate C, Fig. 4.

Dolomitization: During the course of diagenetic processes the dolomitization of limestones is a common feature of carbonate rocks and it has been noted in the case of Loralai Formation as well. It is observed that the dolomitization is fairly extensive and has been developed at various levels of this formation in the measured section as cement and as well as replacement. It has developed, also, along stylolites (Plate D, Fig. 2) and in fractures (Plate C, Fig. 1 and Plate D, Fig. 1). At certain horizons ferroan dolomite is found as well (Plate A, Fig. 4, Plate D, Fig. 1 and Plate C, Fig. 1). In the studied section the following types of dolomitization have been recorded:

Pervasive Dolomitization: Extensive dolomitization in limestones is termed as the process of pervasive dolomitization. This type the process of dolomitization is not texture selective only, it attacks fabric of the rock and whole of the rock is got dolomitized (Plate B, Fig. 1).

Microdolomitization: In this type of dolomitization the developed crystals of dolomite are of very small size (Plate D, Fig. 4). Sometimes these crystals are so small in size that larger magnification is required to observe these crystals.

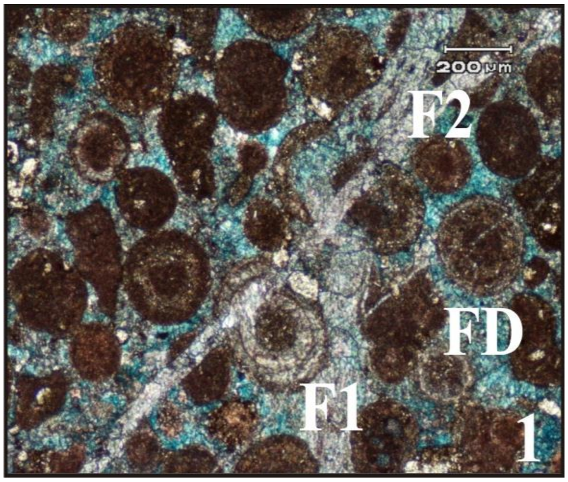
Zoned Dolomitization: The zoning developed in dolomites during diagenesis indicates that the geochemical composition of the percolating water, charged with Mg ions, remained changing continuously. The crystals of zoned dolomite are shown in Plate B, Fig. 1 and Plate D, Fig. 3.

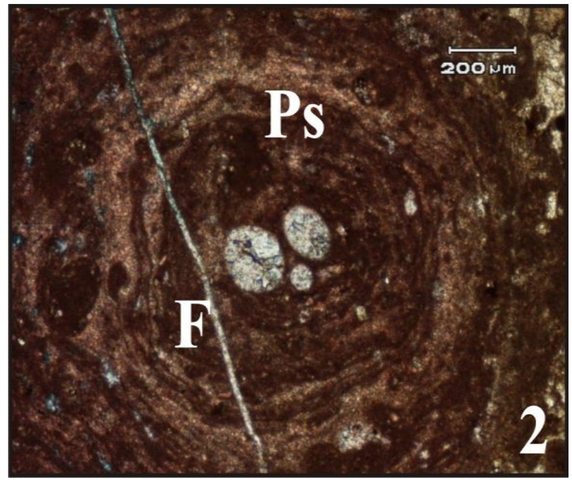
Porosity Fabric: In the studied section all the recorded fractures are filled with calcite (Plate C, Fig. 2), dolomite (Plate C, Fig. 1) or ferroan dolomite (Plate D, Fig. 1). Not a single open fracture could be found in this section. However, various types of solution porosity has been noted, like, vuggy porosity (Plate B, Fig. 4) and mouldic porosity.

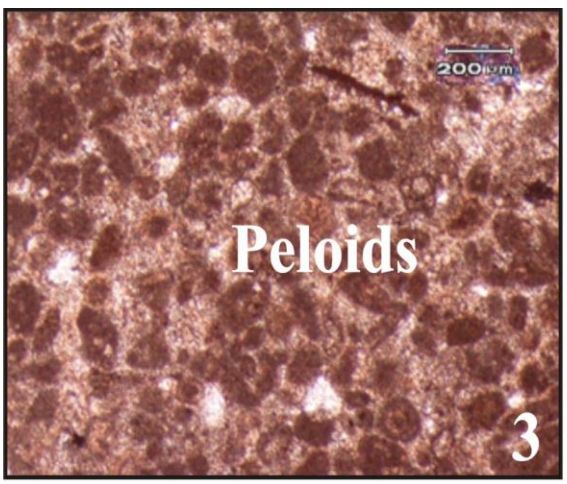
Diagenetic Events

The determined sequence of diagenetic events in the Loralai Formation, exposed at this section, is described here. The development of micritic envelopes is the first diagenetic phase, which takes place in the marine diagenesis of limestones. The dissolution of aragonite is the second phase inwhich the aragonite dissolves in the faunal grains having aragonitic mineralogy and is precipitated as sparite. In the next phase of the diagenetic history of carbonate rocks, only dolomitization of matrix takes place and component grains (allochems) are not dolomitized. The physical compaction of the carbonate sediments is the next diagenetic event. Under this diagenetic process the inter-grain space reduces, which results in the overall reduction of porosity of the rock (Plate A, Fig. 3). In case of poorly cemented sediments the component grains may break due to physical compaction process. As a result of this compaction fractures are produced and ultimately the porosity and permeability of the rock is enhanced. The next phase is that of chemical compaction. As a result of increasing compaction due to increasing overburden

Plate C







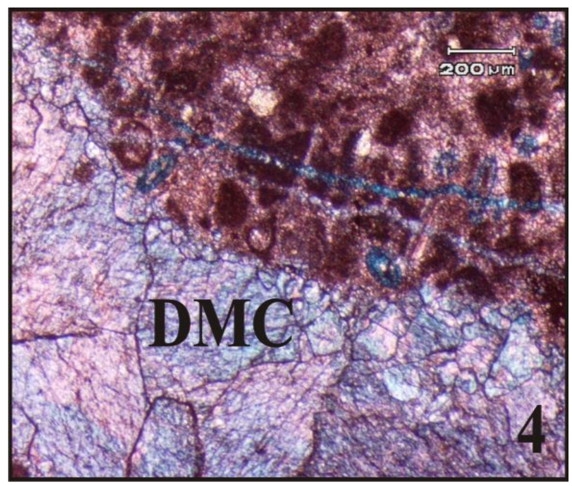


Fig. 1 Photomicrograph showing two episodes (F1 and F2) of fracturing. The small fracture is younger than larger fracture cross cutting it in an ooidal grainstone with inter-granular ferroan dolomite (FD) cement (200, PPL, stained). Sample KZN-20

Fig. 2 Photomicrograph showing a pisoidal (Ps) grainstone. A small fracture (F) is cross cutting it (200, PPL, stained) Sample KZN-17

Fig. 3 Photomicrograph showing a peloidal grainstone with inter-granular dolomite cement (200, PPL, unstained). Sample KZN-4L

Fig. 4 Photomicrograph showing a peloidal grainstone with two small fractures filed by ferroan dolomite and drusy masaic (DMC) cement (200, PPL, stained). Sample KZN-4L

Plate D

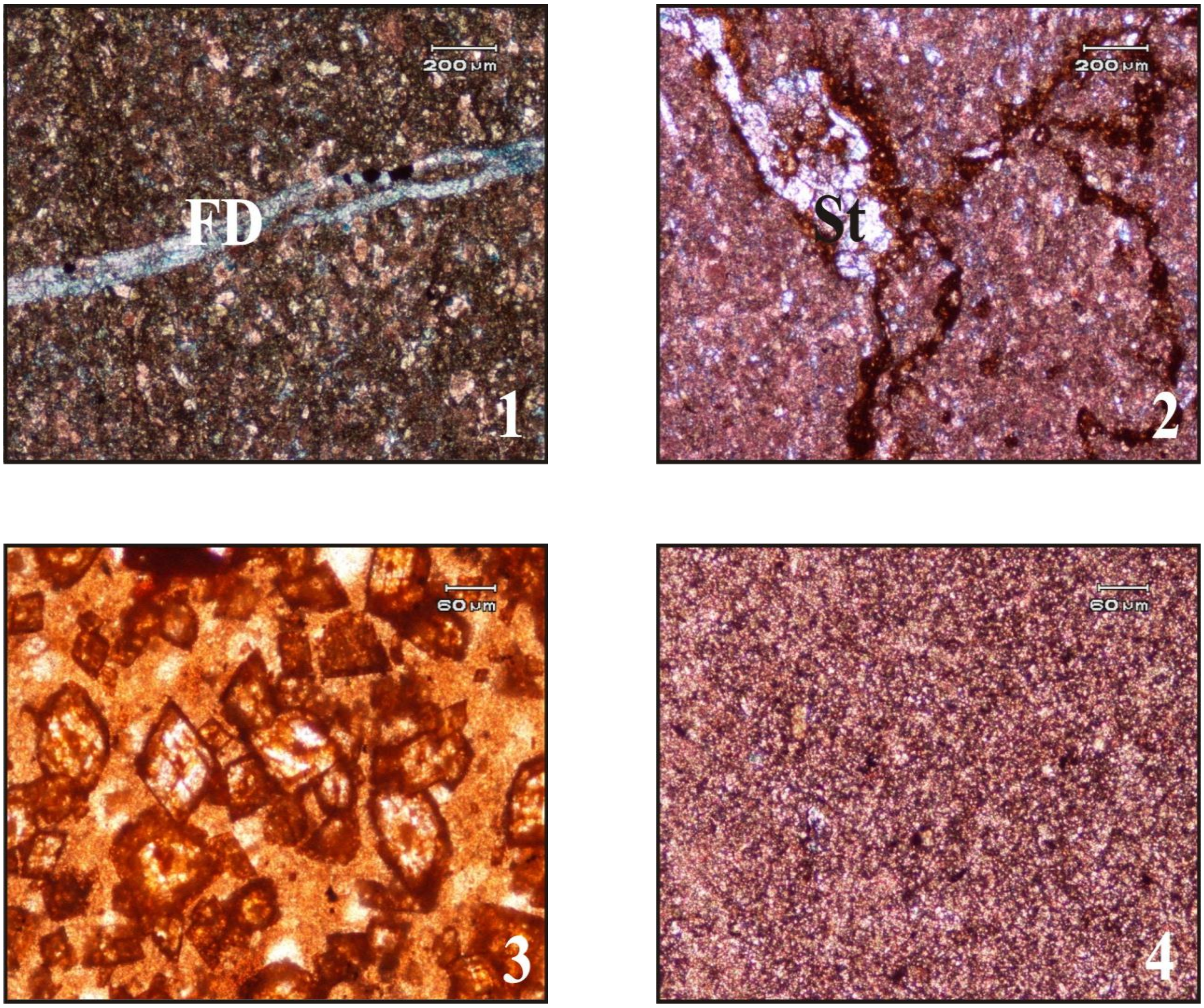


Fig. 1 Photomicrograph showing a partially dolomitized bioclastic mudstone along with a (ferroan) dolomitized (FD) fracture (200, PPL, stained). Sample KZN-13B

Fig. 2 Photomicrograph showing a highly stylolitized mudstone with dolomitic stylocummolate (St). The mudstone is partially dolomitized as well (200, PPL, stained). Sample KZN-11M

Fig. 3 Photomicrograph showing a part from the dolomitic stylocummolate in a partially dolomitized mudstone. Almost all the dolomite crystals are zoned (60, PPL, unstained). Sample KZN-11M

Fig. 4 Photomicrograph showing microdolomite facies (60, PPL, stained). Sample KZN-8 and/or tectonic stresses, first the grain to grain contacts take place and then simple grain contacts developed into sutured grain contacts. Later on dissolution of grains starts at these stressed contacts. The stylolitization is the last diagenetic event and is the end product of chemical compaction. It is actually manifestation of a diagenetic phenomenon, named as pressure-dissolution (Plate D, Fig. 2). The stylolites, also, serve as conduits and might enhance permeability (Scoffin, 19870).

RESULTS AND DISCUSSION

The Loralai Formation is taken as the most important assemblage of carbonates in the Mesozoic succession of the Western Sulaiman Range. The formation belongs to the Middle Jurassic age (Hussain, 2005). In the measured section the formation is predominantly a limestone along with fair amount of dolomite, dolomitic limestone or dolomitic patches and marl and subordinate shale as well. The shales of variegated colour, as a subordinate component, are present in thin interbeds and as intercalations at certain horizons. The limestones are fractured which were filled later on by calcite and found as calcite veins. In the lower part of this rock dolomitic patches, flute casts, calcite skin (on joint surface), ripple marks, calcite veins, cross-bedding, raindrops, solution weathering, pits, concretions, solution cavities and graded bedding were recorded. In the middle part of this rock unit calcite veins, dolomitic patches, conjugate set of joints, cross bedding, ripples, flute casts, calcite skin (on joint) surface, gradded bedding, sole marks (groove marks) were observed. In the upper part of this rock calcite veins, iron concretions, dolomitic patches, solution cavities, large pebbles, vertical fractures, cross-bedding, rock cleavage, and graded bedding were found.

The petrographic studies revealed that The Middle Jurassic Loralai Formation is mainly composed of rudstones and grainstones and the component of micritic microfacies is recorded as relatively lesser and as minimum componant. The determined package of microfacies manifests that it was deposited in the shallow shelf with restricted and high energy environment. This package of sediments is represented by commonly fossiliferous limestones, however, due to frequent dolomitization these fossils are indeterminate. Bioclasts larger than 2mm are frequently found in it with oversized pores/vuggy solution porosity. The field observations and petrographic investigations show lack of open fractures and confirm presence of filled fractures. It seems apparently that the inerconnectivity is not facilitated by these post depositional features. However, in contrast to it the highly enhanced solution porosity fabric effectively interconnects the micropores of rud/grainstones. While the interconnectivity of pores is, also, improved by number of stylolitic conduits (Scoffin, 1987) and by the solution channels formed along filled fractures due to dissolution in some of diagenetic phases. The predominant component of rudstones and grainstones microfacies component and well-developed solution porosity fabric found and recorded in the microfacies support the reservoir character of these Middle Jurassic limestones.

CONCLUSIONS

The present research findings ensue the following conclusions, based on the detailed field and laboratory analyses:

- The deposition of the Loralai Formation has mostly taken place in the shallow shelf environment.
- The coarse grained microfacies are identifiable in the studied section at different stratigraphic horizons and are predominant.
- Indications of physical and chemical compaction have been found at various levels of this formation.
- The phenomenon of stylolitization is recorded at different horizons in this formation and signs of tight packing have been noticed as well. Mg liberated from the pelloids due to compaction at an early stage caused precipitation of dolomite as styloccumulate along stylolites.
- The presence of coarse grained microfacies and dolomites are very significant features for considering Loralai Formation as a potential reservoir rock in and around the area hosting studied section.
- Dolomitization and micro-dolomitization has been noted along with ferroan dolomite as inter-granular cement and as cement precipitated in fractures. At some later stage Fe^{++} is incorporated into this dolomite and results in the formation of ferroan dolomite. The recorded zoned dolomite indicates the changes in the geochemical composition of formation water during the dolomitization phase in the due course of diagenetic events.
- The presence of fractures, stylolitization and significant dolomitization noted in this formation provide further qualification to it as a potential reservoir rock for hydrocarbons.
- Moreover at various stratigraphic levels in the studied section the sufficiently developed reservoir quality in it suggests that the Loralai Formation is the best candidate in this area to be targeted for the exploration of oil and gas commercial accumulations.

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