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Lithofacies and Sedimentology of Baghanwala Formation (Early–Middle Cambrian), Eastern Salt Range, Pakistan

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Abstract. A detailed sedimentological study of the Baghanwala formation from, the Sikkiwala Kas (58.5 m) and the Choa Saidan Shah-Khewra section (30 m) in the eastern salt range was carried out, six lithofacies were identified: sandstone interlaminated with mudstone (LF1), medium to coarse-grained sandstone (LF2), fine-grained sandstone interbedded with mudstone (LF3), medium grained sandstone with flaser, wavy and lenticular bedding (LF4), sandstone intercalated with siltstone and mudstone with salt pseudomorph (LF5) and mudstone with sandstone intercalations (LF6). A variety of sedimentary structures has been recorded. These include salt pseudomorph, ripple marks, trace fossils, mud cracks, lenticular, wavy and flaser bedding. The sandstone facies are composed of thin, channelised bedding which were mainly deposited in shallow marine environment. The remaining part exhibits relatively higher porosity as evidenced by the study of thin sections. Therefore, LF2 and LF3 of the Baghanwala formation have the potential to be considered as a candidate of reservoir quality based on petrography and well logs. This part appears to be a good reservoir and may be exploited for its hydrocarbon potential in the subsurface in the eastern Potwar.

Keywords: Baghanwala formation, silciclastic succession, sandstone reservoir, cambrian

Introduction

The name Baghanwala formation has been formalized by Stratigraphic committee of Pakistan from the "Baghanwala Group" of Noetling (1894) (Shah, 1979; Fatmi, 1973). Previously known as "Baghanwala stage" of Pascoe (1959), (Shah, 1979). The formation was first investigated by Fleming (1852) who called it "Salt Pseudomorph Shales" (Shah, 2009; 1980; 1979). Wynne (1878) gave the name "Pseudomorph Salt Crystal Zone" (Shah, 2009). Followed by Holland (1926) who termed it "Salt Pseudomorph Beds" (Shah, 2009). The name also replaces the "Salt Pseudomorph* Shales" (*Salt pseudomorph means "false shape halite" crystals, with outer geometry similar to halite and clay/silt composition) of Gee (1945) as reported by Shah (2009).

The Baghanwala formation extends from the Eastern salt range absent in central but reappears near Chiddru (Raza and Bender, 1995; Khan and Khan, 1979a & b). Its deposition took place during early-middle Cambrian and is influenced by several environmental factors (Khan and Khan, 1979a).

The Baghanwala formation is well developed in the eastern salt range (Ghazi *et al*., 2020; Khan *et al*., 2018). The distribution of the formation in the salt range is identical to that of Kussak and Jutana formation (Khan and Shah, 2020; Ali, 2009; Ghauri, 1979; Shah, 1979). In the central salt range the Permian unconformity is present on such a level that only the portion is present in Makrach. The formation is 116 m at Baghanwala Village, 55 m at Sikkiwala Kas, 26 m at Choa-Khewra Section. The exposures are also present on the eastern side of the Nilawahan Ravine (Ghazi *et al*., 2020 and 2015; Khan and Khan, 1979a). The lateral facies change of this formation in Trans Indus Ranges is known as Khisor formation (Shah, 1979).

In subsurface, it is reported from several wells drilled in the Potwar basin and Punjab plains (Ahmed *et al.*,

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2020; Yasin *et al*., 2020; Jadoon *et al*., 2005; Kadri, 1995).

Regional geological setting. The salt range marks the boundary between the Potwar Basin to the north and Punjab Plains to the south (Gee, 1989). The Jehlum river defines its eastern limit, whereas the Indus river marks the western (Ghazi *et al*., 2020; Ghazi *et al*., 2015).

The salt range thrust front stretch east-west and is about 170 Km long. The Kalabagh fault separates the salt range from the trans Indus ranges in the west (Fig. 1).

The oldest rock exposed in the salt range is Precambrian followed by Jehlum Group, which is disconformably overlain by Permian to Eocene rocks in age (Fig. 2).

The Baghanwala formation shales and interbedded sandstones (Fig. 3) in the Potwar basin and salt range area mark the top of the Cambrian stratigraphic sequence.

During the Cambrian time, a shallow sea extended along the salt range region (Kemal, 1991). The Baghanwala formation conformably overlies the Jutana formation. Based on the conformable contact with the Jutana formation late early to early middle Cambrian has been assigned to the formation (Khan and Khan, 1979a) (Fig 4 to 6).

Materials and Methods

The Baghanwala formation is exposed in eastern salt range, Punjab, Pakistan (Ali, 2009). The Baghanwala formation is well exposed in the eastern salt range, which is mainly composed of mudstones and sandstones. Detailed section measurement of Baghanwala formation in eastern salt range was carried out in areas the Sikkiwala Kas (Lat. 32°47′04″: Long. 73°12′02″) and the Choa-Khewra Section (8 Km from Choa Saidan Shah; Lat. 32°39′43″: Long. 72°59′22″) (Fig. 1).

Results and Discussion

Lithofacies analysis. Six lithofacies have been identified within the Baghanwala formation at the studied localities (Fig. 3). The term Lithofacies has been shortend here for LF, and lithofacies are written as LF1. Sandstone interlaminated with mudstone (LF1), medium to coarse-grained sandstone (LF2), fine-grained sandstone interbedded with mudstone (LF3), medium-grained sandstone with flaser, wavy and lenticular bedding (LF4), sandstone intercalated with siltstone and mudstone (LF5) and mudstone with sandstone intercalations (LF6).

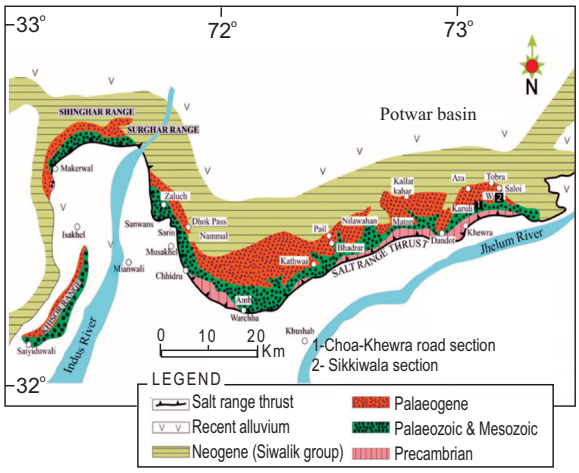

Fig. 1. Location of studied section in salt range (1) Choa Khewra road section, (2) Sikkiwala section, eastern salt range, Pakistan, modified after Khan *et al*. (2018).

A variety of sedimentary structures has been recorded: salt pseudomorph, ripple marks, trace fossils, mud cracks (Fig. 5B) lenticular, wavy and flaser bedding. These sedimentary structures have been added to interpret the depositional environment of the formation.

Sandstone interlaminated with mudstone lithofacies (LF1). ***Description.*** This lithofacies is about 15%-23% of total rock volume and consists of sandstone and carbonaceous mudstone (Fig. 4A, 6B and D). The sandstone varies from yellowish red to red and the mudstone varies from gray to black. The sedimentary structures include lenticular, wavy and flaser bedding. Its thickness varies from 7.5-8 m in Sikkiwala Kas and about 5.5-6 m in Choa Saidan Shah-Khewra.

Interpretation. The overall fine-grained size of this lithofacies indicates deposition in a relatively low energy environment. This lithofacies belongs to lagoonal to intertidal environment (Reading, 1986).

Medium to coarse-grained sandstone (LF2). ***Description.*** This lithofacies is about 16%-18% of total rock volume and consists of sandstone which is medium to coarse-grained (Fig. 4B, C, D and 6C). Fresh colour varies from white in the lower part to grayish brown in the upper part. Weathered colour is brick red to yellowish-red. The sandstone is friable and well sorted. The sedimentary structures include flaser bedding and erosional surfaces. Its thickness varies from 8-8.5 m in the Sikkiwala Kas and about 4-4.5 m in the Choa Saidan Shah-Khewra Section.

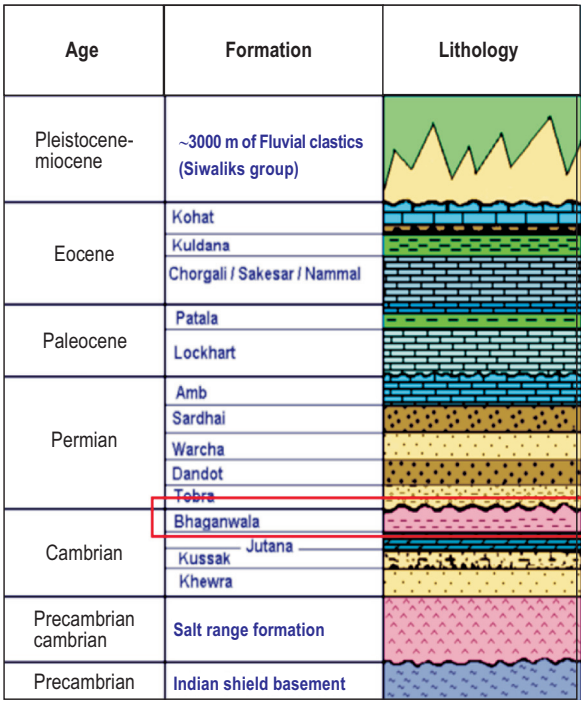

Fig. 2. Generalized stratigraphy of eastern salt range and Potwar basin (Jadoon *et al*., 2005).

Interpretation. The coarser-grained sandstone was deposited in a tidal inlet. Relatively coarse sand and mudclasts floor the channel and form a basal lag to the channel sequence, while medium-grained sandstone was deposited on the flanks of the inlet (Reading, 1986).

Fine-grained sandstone interbedded with mudstone (LF3). ***Description.*** This lithofacies is about 13% of total rock volume and consists of sandstone which is fine-grained (Figs. 5B and D). The colour of the sandstone is red. The mudstone varies in colour from grayish black to yellowish gray. The sedimentary structures include ripple marks. Its thickness varies from 7 m in the Sikkiwala Kas and about 3-3.3 m in the Choa Saidan Shah-Khewra Section.

Interpretation. The mudstone was deposited in relatively calm conditions. Overall this lithofacies represents deposition in a lagoonal environment. Mudcracks also testify to subaerial exposure of this lithofacies (Reading, 1986).

Medium grained sandstone with flaser, wavy and lenticular bedding (LF4). ***Description.*** This lithofacies is about 16%-18% of total rock volume and consists of

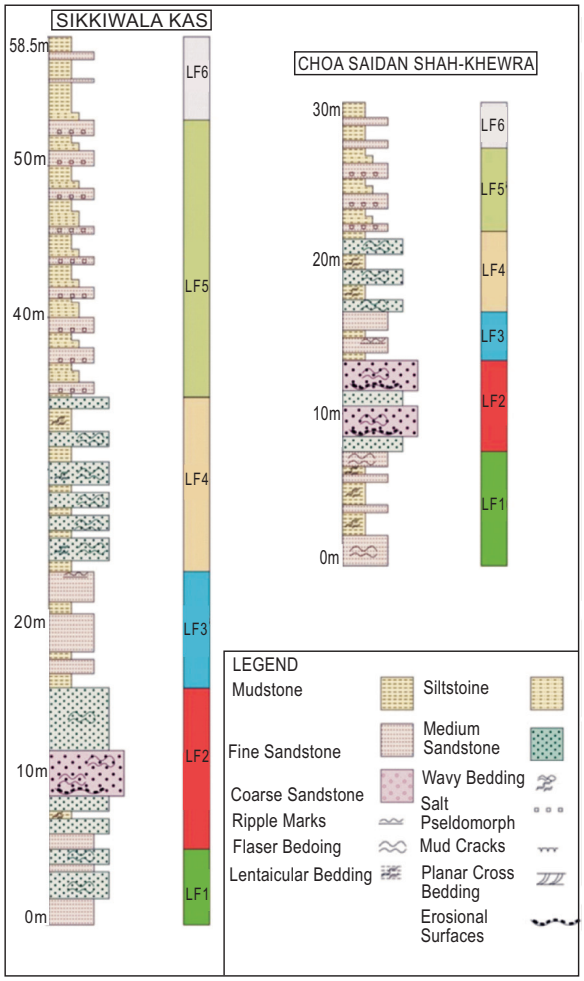

Fig. 3. Shows the Lithostratigraphic sections of Baghanwala formation in the Sikkiwala section and the Choa Khewra road section.

sandstone which is medium grained (Figs. 4F, 5A and 6E). Its colour varies from yellowish red to red. The sedimentary structures include flaser, wavy and lenticular bedding. Its thickness varies from 9.5-10 m in the Sikkiwala Kas and about 3.5-4 m in the Choa Saidan Shah- Khewra section.

Interpretation. The presence of flaser, wavy and lenticular bedding indicates a repeated alteration in sediment transport conditions. This lithofacies represent an example of intertidal facies dominated by clays and sands and exhibiting flaser, wavy and lenticular bedding (Reading, 1986).

Sandstone intercalated with siltstone and mudstone (LF5). ***Description.*** This lithofacies is about 20%-31%

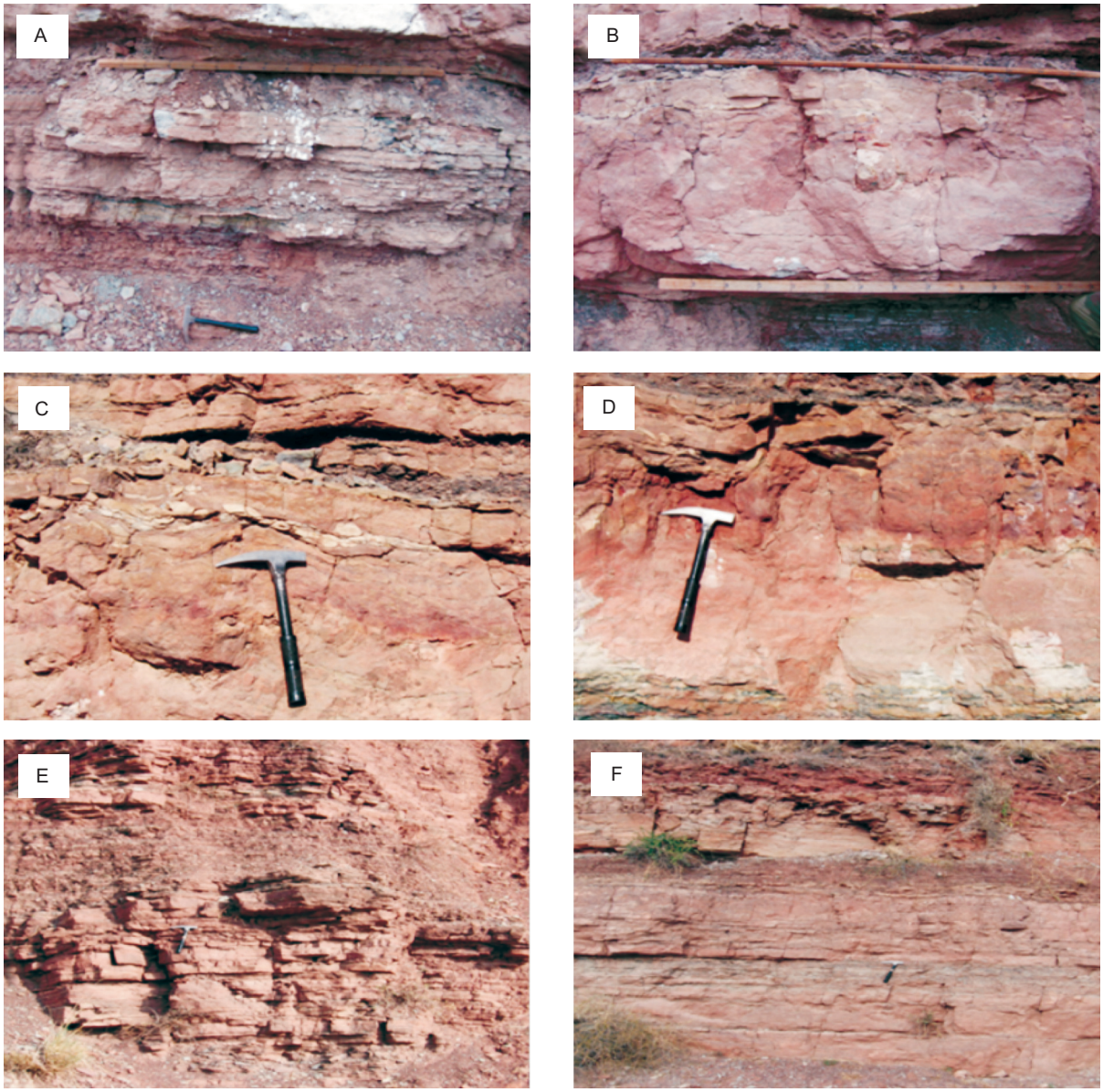

Fig. 4. Shows the Lithofacies of Baghanwala formation Choa Khewra road section. **(A)** Interlaminated sandstone and mudstone lithofacies (LF1), **(B)**, **(C)**, **(D)** sandstone lithofacies (LF2), **(E)** sandstone/siltstone/mudstone with salt pseudomorph lithofacies (LF5), **(F)** sandstone/mudstone with flaser and lenticular bedding lithofacies (LF4).

of total rock volume and consists of sands, silts and clays (Figs. 4F and 6F). Its colour varies from yellowish red to red. The salt pseudomorph is the characteristic feature of this lithofacies. Its thickness varies from 16.5-17 m in the Sikkiwala Kas and about 4.5-5 m in the Choa Saidan Shah-Khewra section.

Interpretation. The intercalation of sandstone/ siltstone/ mudstone is evidence of cyclic deposition of this lithofacies (Reading, 1986). A salt pseudomorph is the characteristic feature of this lithofacies. These are formed in higher salinity conditions then normal to form cubic crystals of halite. Later on, these crystals were dissolved by water and removed. The empty spaces of the crystals were filled with silt or clay and were preserved. This lithofacies represents deposition in an environment which was very sensitive to climatic conditions. This

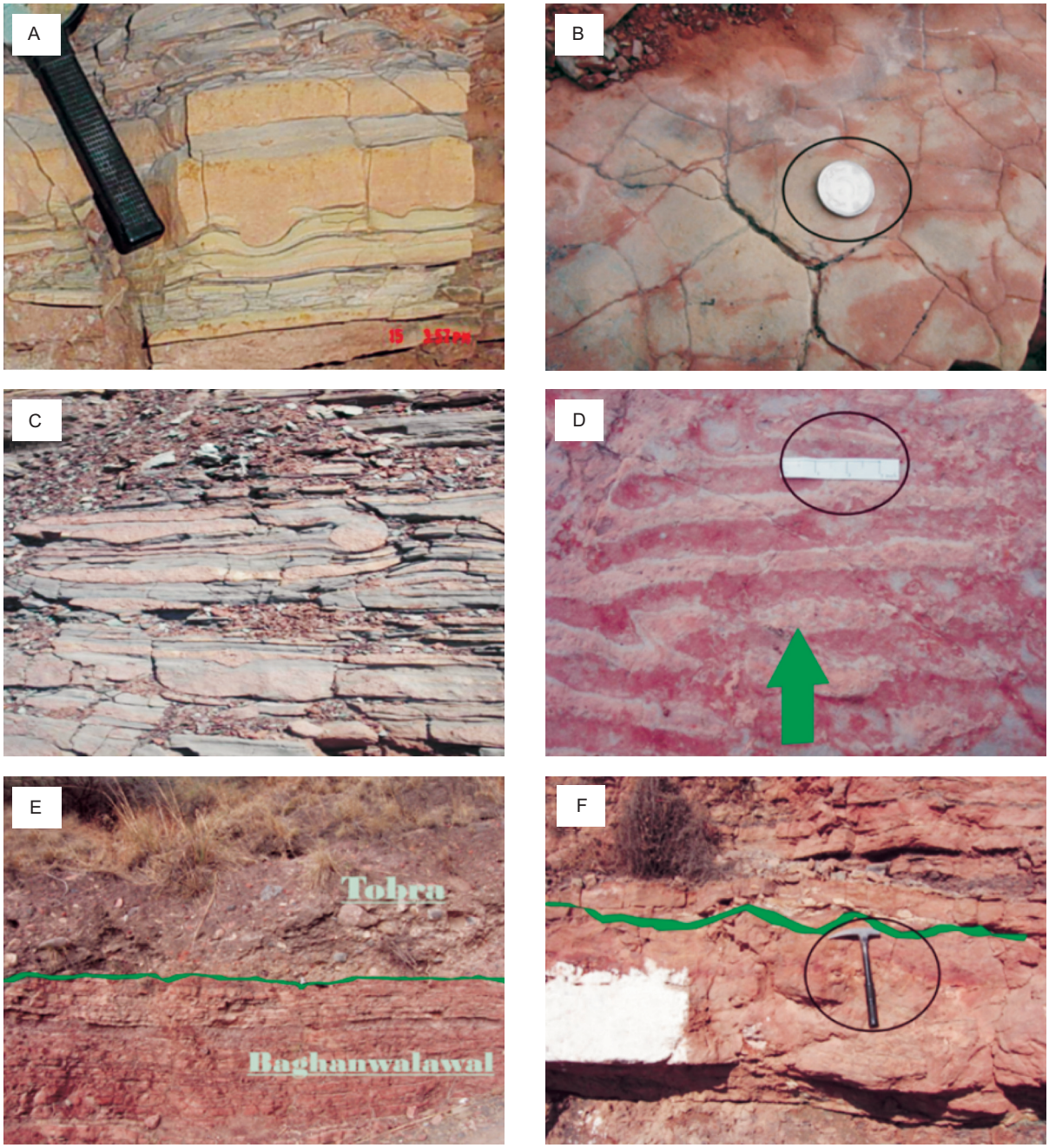

Fig. 5. Shows the sedimentary structures of Baghanwala formation Choa Khewra road section and Sikkiwala Kas sections, **(A)** Wavy bedding in LF4, **(B)** Mud Cracks in LF3, **(C)** Lenticular bedding in LF4, **(D)** Ripple marks in LF3 (arrow show direction of flow), **(E)** Contact relationship between Baghanwala formation and Tobra formation, **(F)** Erosional surfaces in LF2.

lithofacies represents deposition in a supratidal flat environment (Mackenzie *et al*., 1988).

Mudstone with sandstone intercalations (LF6). ***Description.*** This lithofacies is about 7-10% of total rock volume and consists of mudstone which is grayish red to red. Its thickness varies from 3.5-4 m in Sikkiwala Kas (Fig. 6F) and about 2-2.5 m in Choa Saidan Shah-Khewra Section.

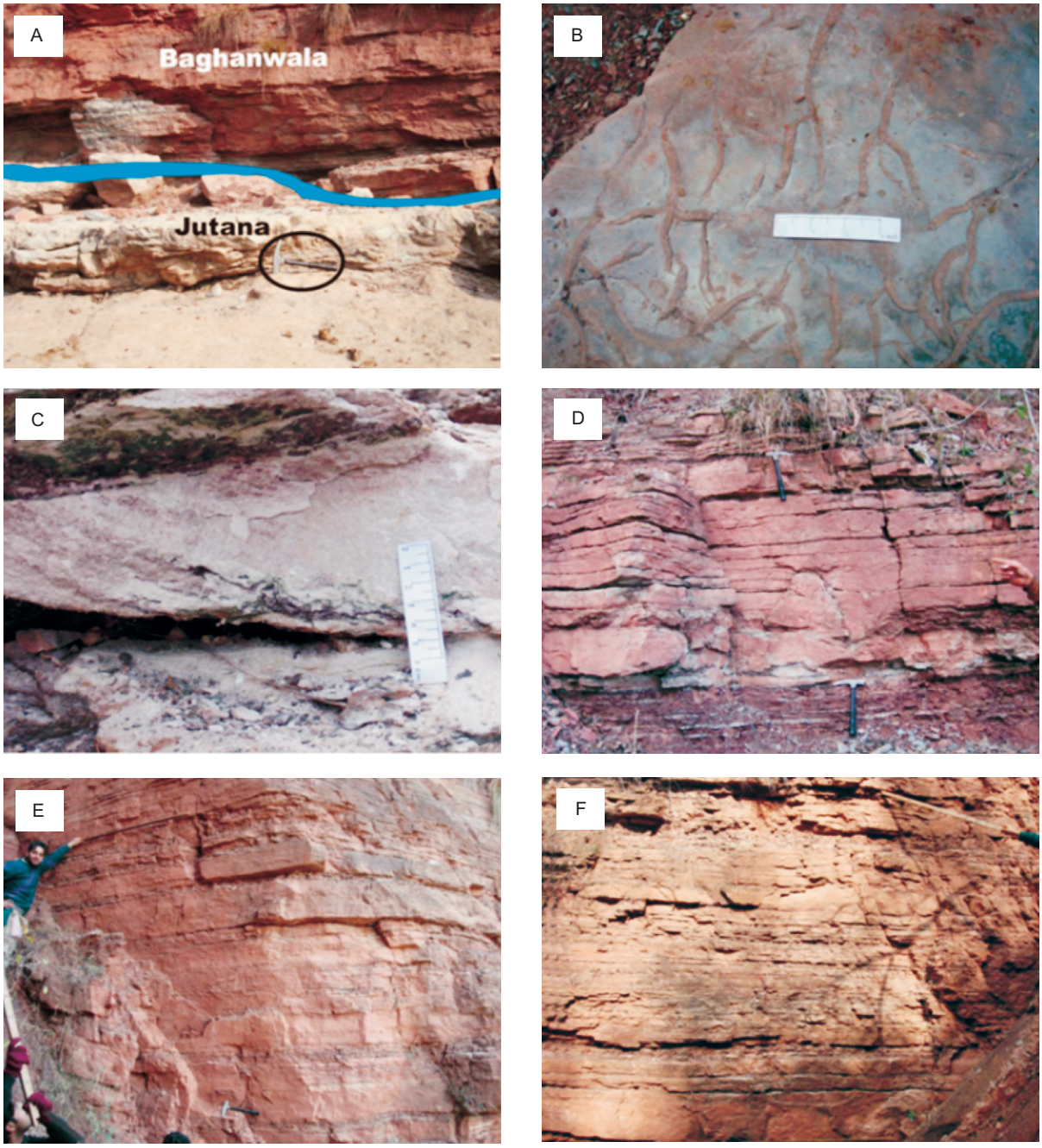

Fig. 6. Shows the Lithofacies of Baghanwala formation at Sikkiwala Kas section. **(A)** Contact relationship between Baghanwala formation and Jutana formation, **(B)** Interlaminated sandstone and mudstone lithofacies (LF1), **(C)** sandstone lithofacies (LF2), **(D)** LF1 and LF2, **(E)** Sandstone/mudstone with flaser and lenticular bedding lithofacies (LF4) & **(F)** Sandstone/siltstone/mudstone with salt pseudomorph lithofacies (LF5).

Interpretation. The lamination and finer grain size indicate deposition out of suspension in a low energy environment. The laminated may be attributed to a lagoonal environment (Reading, 1986; Leeder, 1982).

Petrography. The sandstones of the Baghanwala formation ranges in composition from, quartz arenite (Khan and Khan, 1979b), lithic arkose, subarkose/ sublitharenite, and sublitharenite (Fig. 7A, C, D, F).

Quartz, feldspar and rock fragments are the main constituents of the Baghanwala Formation. Quartz 85%, Feldspar 10%, Rock fragments 5%. Other minerals include muscovite, biotite, hematite, zircon and rutile. Cementing materials are carbonates, hematite, clays and quartz.

Quartz. It is the most mineral in the Baghanwala Formation, constitutes about 85% quartz (Fig. 7A). Grains have inclusions of heavy minerals like rutile and zircon. Both polycrystalline and monocrystalline varieties are recorded.

Polycrystalline grains have sutured contacts and are metamorphic while straighter ones is from the igneous origin (Carozzi, 1960).

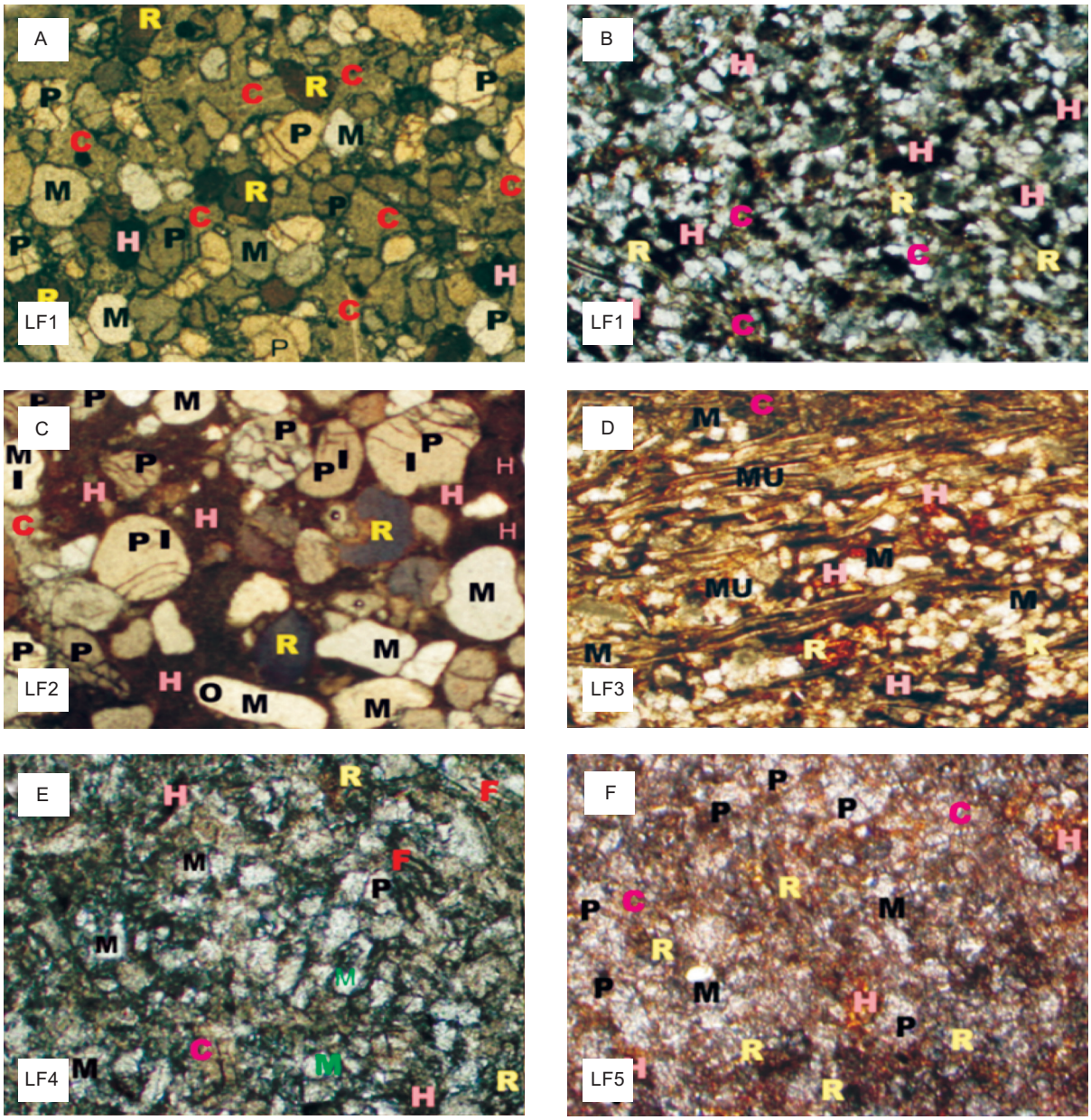

Fig. 7. **(A)** Quartz arenite (LF1) (10x) XPL, **(B)** Quartz arenite (LF1) XPL (4x), **(C)** Quartz arenite (LF2) (10x) XPL, **(D)** Sub litharenite/Subarkose (LF3) PPL (10x), **(E)** Sublitharenite (LF4) PPL, **(F)** Sub litharenite (LF5) PPL.

Feldspars. The feldspar grains are present both as orthoclase and plagioclase varieties (Fig. 7E). Alteration of feldspar into clay minerals is recorded.

Types of cement. The material include carbonates, iron oxide, silica and clays. Quartz grains are embedded in carbonate and in a few cases, they are present in iron oxide matrix. The quartz grains are coated with iron oxide cement. Carbonate minerals constitute the dominant cementing material (Fig. 7B). The percentage of carbonate minerals varies greatly. Silica is also present as cement which is in optical continuity with grains. Chert is also noted as a cement variety. Feldspar grains embedded in matrix. Clay minerals also serve as cementing material. Clay varieties include chlorite, illite and glauconite.

Accessory. Micas are present both as muscovite and biotite. Biotite occurs as small flakes altered to chlorite, while muscovite occurs as thin and elongate flakes.

Iron minerals are present throughout the formation and are dominant in the upper parts imparting a brownish-red colour to the sandstone units.

Reservoir potential. In the salt range, the reservoir potential particularly the primary intergranular porosity of the sandstones in the Baghanwala formation was damaged due to authigenic precipitation of calcite or iron oxides but secondary intergranular porosity was formed during late diagenesis due to the dissolution of early diagenetic authigenic cement. The medium to coarse-grained sandstone (LF2) exhibits relatively higher porosity as evidenced by a study of thin sections (Fig. 8). Therefore the lower part of the Baghanwala formation has the potential to be considered as a candidate of reservoir quality based on a study of thin sections and well logs.

Oil sector data show that the porosity of Baghanwala formation is quite variable and ranges from 2.5% to 9% in some Potwar basin. The Baghanwala formation is reported from several wells drilled in the Potwar province and Punjab plains (Kadri, 1995; Kemal *et al*., 1991).

The discovery of natural gas in the eastern Potwar has motivated the prospect of further discoveries in this formation. The discovery of natural gas in the Potwar basin is an indicator of the potential of this sandstone as a reservoir. Intermittent deposition occurred, sealing them off from the main body of sand, and covering the reservoir sands. This, together with the mudstone seals, creates nearly ideal reservoir properties. This

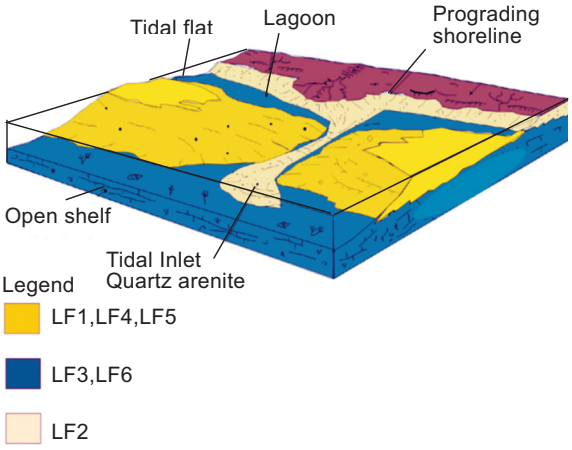

Fig. 8. Proposed schematic depositional environments of the Baghanwala form, LF1, LF4 and LF5 formed in tidal flat setting, while LF2 form in tidal channels. LF3 and LF6 are deposited in lagoonal or quite water environment.

was established in the Potwar basin, and a better understanding of which could lead to future discoveries.

These properties in the Baghanwala formation can be more promising in the eastern and western Potwar Plateau and Punjab plains.

Conclusion

Several factors support that the sandstone present in the Baghanwala formation to be an effective reservoir of hydrocarbons. These include direct studies on lithofacies and microfacies. Cementation has occluded much of the primary porosity in these sandstones. However, the reservoir potential of these rocks is related to the original depositional environment and is observed within the medium to coarse-grained sandstone (LF2) by the good vertical connectivity of sand beds. The Baghanwala formation sandstone should be investigated further to evaluate oil and gas potential.

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Conflict of Interest. The authors declare they have no conflict of interest.

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